TEXAS WATER CONSERVATION ASSOCIATION

DEVELOPMENT OF USE-BASED CHLOROPHYLL CRITERIA FOR RECREATIONAL USES OF RESERVOIRS

FINAL

JUNE 2005

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Support Also Provided By:
Texas Association of Metropolitan Sewerage Agencies
National Association of Clean Water Agencies

820-0101

FINAL REPORT

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LIST OF ABBREVIATIONS

ac	acre
ac-ft	acre-feet
APAI	Alan Plummer Associates, Inc.
avg	average
BRA	Brazos River Authority
CRP	Clean Rivers Program
DO	dissolved oxygen
EPA	U. S. Environmental Protection Agency
ft	feet
GBRA	Guadalupe-Blanco River Authority
H_2SO_4	sulfuric acid
LCRA	Lower Colorado River Authority
ln	log normal
m	meter
mm	millimeters
max	maximum
mg/L	milligrams per liter
min	minimum
ml	milliliters
NO_2	nitrite
NO_3	nitrate
NTU	nephelometric turbidity units
SARA	San Antonio River Authority
SOP	Standard Operating Procedure
SRA	Sabine River Authority
std	standard
SWQM	Surface Water Quality Monitoring
TCEQ	Texas Commission on Environmental Quality
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TP	total phosphorus
TRA	Trinity River Authority
TRWD	Tarrant Regional Water District
TSS	total suspended solids
TWCA	Texas Water Conservation Association
ug/L	micrograms per liter
USGS	U.S. Geological Survey
VSS	volatile suspended solids

FINAL REPORT

DEVELOPMENT OF USE-BASED CHLOROPHYLL CRITERIA FOR RECREATIONAL USES OF RESERVOIRS

CHAPTER I

INTRODUCTION

In 2002, the U.S. Environmental Protection Agency (EPA) mandated that states develop numeric nutrient water quality standards for lakes, streams, and estuaries. The Texas Commission on Environmental Quality (TCEQ), the agency responsible for the development of these standards, has established a plan for developing nutrient standards. This plan specifies that major reservoirs will be the first waterbodies for which nutrient standards will be considered.

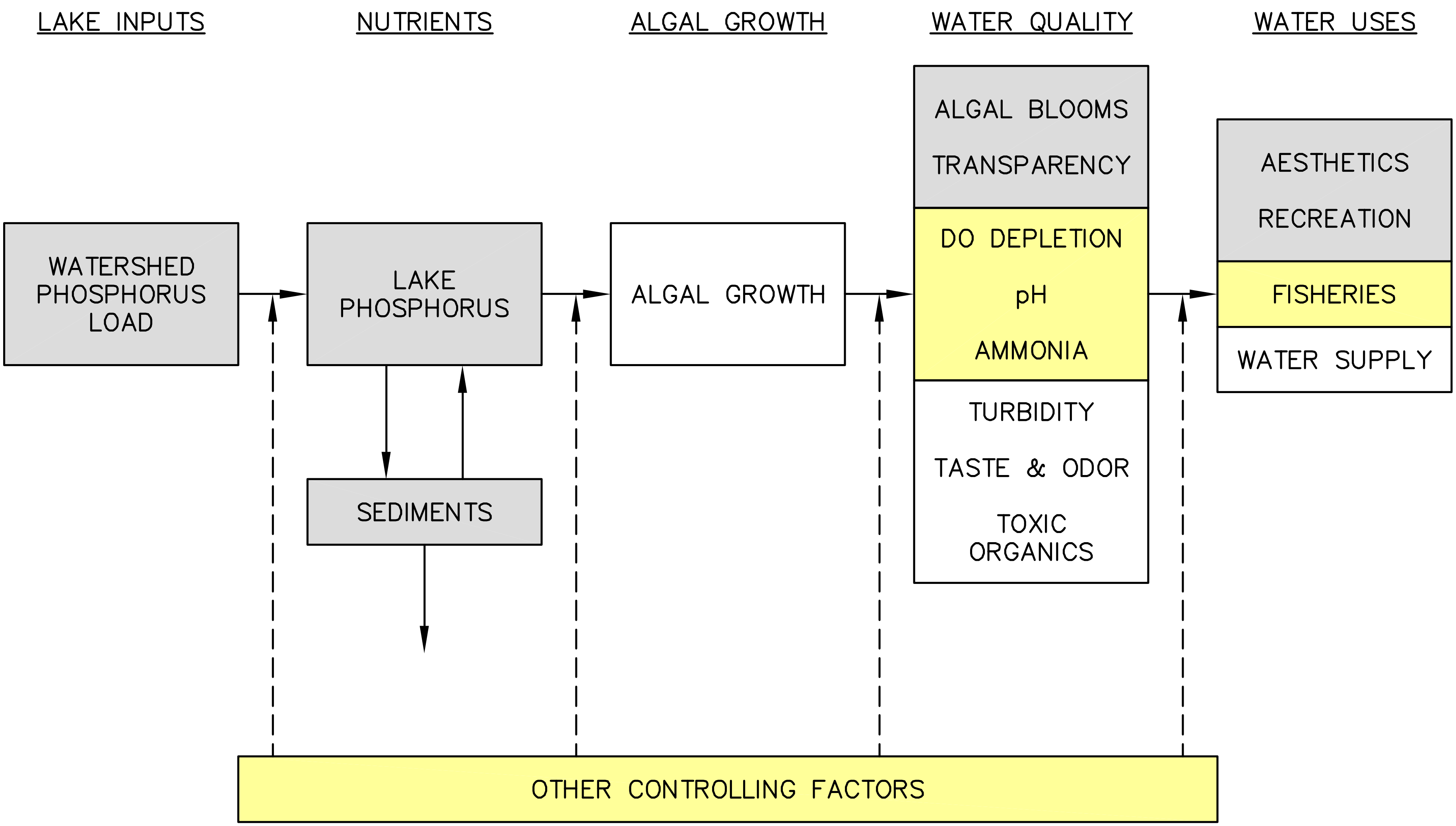
The Federal Clean Water Act, in Section 303(c)(2)(A), specifies that, whenever a state revises or adopts a new water quality standard, the standard "shall consist of the designated uses of the navigable waters involved and the water quality criteria for such waters based upon such uses." Potential uses of reservoirs include contact recreation, non-contact recreation, fisheries, public water supply, and aquatic life and wildlife support. The purpose of this study is to provide data to the TCEQ that can be used to determine criteria that are supportive of recreational uses. Criteria for recreational uses can then be evaluated in conjunction with criteria supportive of other uses when determining a recommended water quality standard.

The primary manner in which high nutrient concentrations can affect contact and non-contact recreational uses is when the nutrients produce dense growths of algae and/or aquatic vegetation, which are aesthetically undesirable. In some cases, dense growths of vegetation can physically interfere with the use of waters for swimming, skiing, or boating. Use of waters for a public water supply can be adversely impacted if there are algal blooms that result in unpleasant tastes and odors in the treated water. Fisheries, up to a point, are positively affected by increased primary production resulting from increased nutrient loads. In addition, the standing crop of largemouth bass, an ambush predator of high fishery value in Texas, has been shown to be positively correlated with the proportion of reservoir area occupied by rooted aquatic vegetation. However, when eutrophication begins to reduce dissolved oxygen concentrations significantly, fisheries can be adversely affected.

This study recommends that the nutrient water quality standards for reservoirs be based on chlorophyll-*a*, since the density of planktonic algae is most frequently the nutrient-related condition affecting the desirability of reservoirs for recreational uses. Implementing these

standards will, ultimately, require an understanding of the relationships between watershed loadings of nitrogen and phosphorus, light attenuation, algal growth, and use impairment due to algal growth. Figure I-1 presents a summary of these relationships, as they relate to phosphorus loads to a reservoir.

This study was a collaborative effort. It was sponsored by the Texas Water Conservation Association, with support from the National Association of Clean Water Agencies and the Texas Association of Metropolitan Sewerage Agencies. Participants in the study were as follows: Brazos River Authority (BRA), Guadalupe-Blanco River Authority (GBRA), Lower Colorado River Authority (LCRA), Sabine River Authority (SRA), San Antonio River Authority (SARA), Tarrant Regional Water District (TRWD), and Trinity River Authority (TRA). Consultants assisting in the effort were William W. Walker, Jr., Ph.D., and Alan Plummer Associates, Inc., (APAI).



From: William W. Walker, Jr., Ph.D.

FIGURE I–1
CAUSAL PATHWAYS LINKING PHOSPHORUS LOADS TO WATER USES

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CHAPTER II

STUDY DESIGN

The basic approach taken in this study was to collect simultaneous data on users' perceptions of whether recreational use was impaired (and, if so, the extent of the impairment) and water quality data. Several other researchers have conducted similar studies to identify the level at which algal growth is objectionable to recreational users of reservoirs (for example, Heiskary & Walker, 1988; Smeltzer & Heiskary, 1990). These researchers concluded that algal bloom frequency is the most significant nutrient-related condition for recreational users. However, they have also found that bloom frequency can be correlated to a growing-season mean chlorophyll-*a* concentration, which is a more practical parameter for a regulatory criterion.

DESCRIPTION OF STUDY RESERVOIRS

Eight reservoirs were selected for the study. The study reservoirs represent a wide range of conditions with respect to size, drainage area, trophic status, primary uses, and ecoregion location. The eight reservoirs are Canyon Lake, Cedar Creek Reservoir, Granger Lake, Lake Bridgeport, Lake Fork Reservoir, Lake Georgetown, Lake Livingston, and Lake Travis. A summary of the size of each reservoir and the ecoregion(s) in which each reservoir is located is presented in Table II-1. Figure II-1 is a map of the geographical locations of the study reservoirs and ecoregion boundaries.

Canyon Lake, located in the Central Texas Hill Country, serves as a water supply reservoir and provides flood control on the Guadalupe River. Water clarity is excellent, and the reservoir is a popular location for boating, fishing, skiing, and scuba diving.

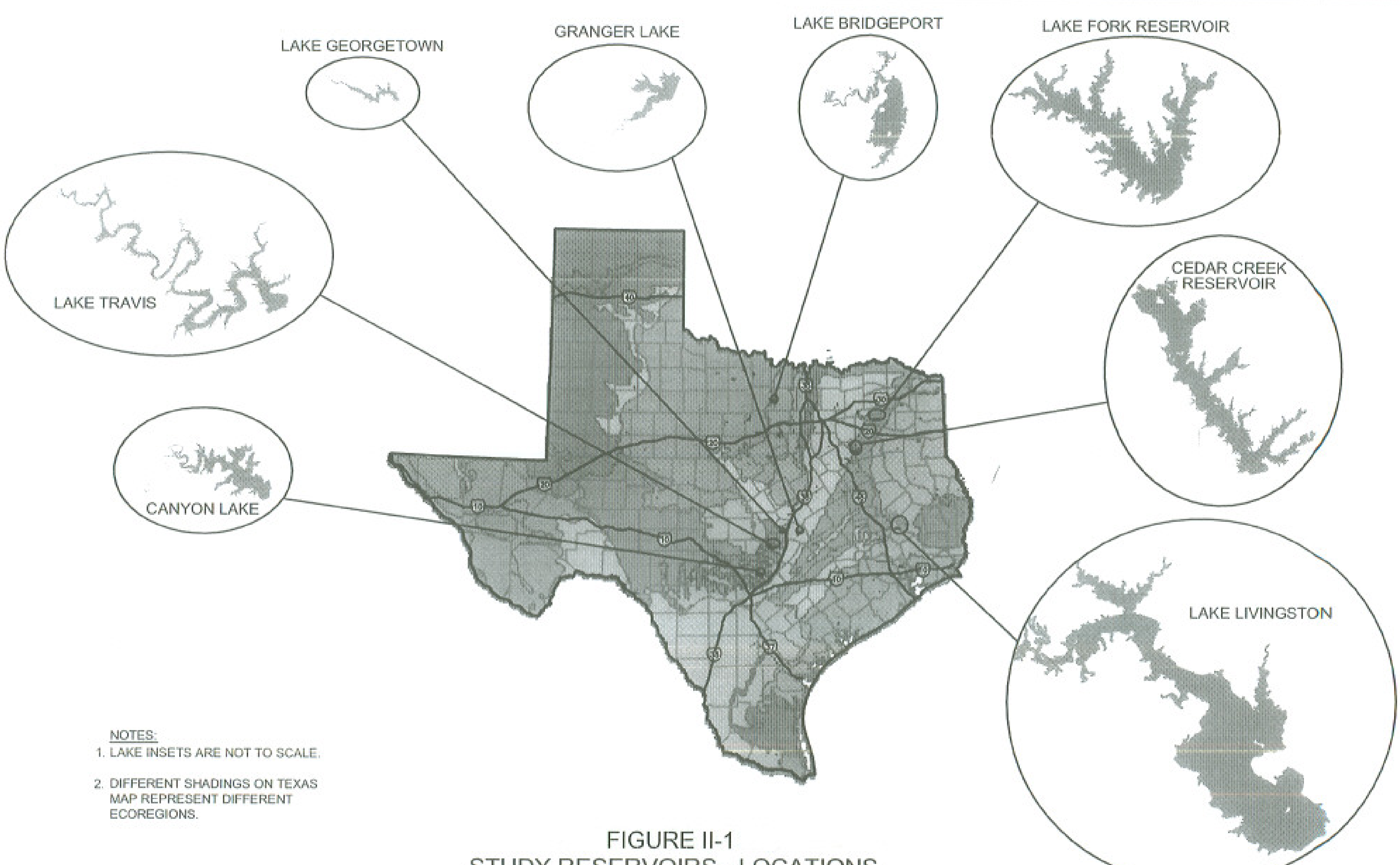
Cedar Creek Reservoir, in northeast Texas, serves as a water supply reservoir and is used for a wide range of recreational activities. This reservoir is one of two reservoirs studied that exhibit high levels of chlorophyll-*a*.

Granger Lake, located in Central Texas, provides public water supply. It is also popular for crappie and white bass fishing. This reservoir maintains a high level of suspended inorganic material that substantially reduces water clarity.

TABLE II-I

DESCRIPTION OF STUDY RESERVOIRS

Reservoir	Level III Ecoregion	Surface Area (acres)	Volume (acre-feet)
Canyon Lake	Edwards Plateau	8,230	378,781
Cedar Creek Reservoir	Texas Blackland Prairies/East Central Texas Plains	32,623	637,180
Granger Lake	Edwards Plateau/Texas Blackland Prairies	4,009	54,280
Lake Bridgeport	Central Oklahoma/Texas Plains	11,649	366,236
Lake Fork Reservoir	Texas Blackland Prairies/South Central Plains	27,690	604,927
Lake Georgetown	Edwards Plateau	1,297	37,010
Lake Livingston	Texas Blackland Prairies/South Central Plains	83,277	1,741,867
Lake Travis	Edwards Plateau	18,622	1,131,650



NOTES:

1. LAKE INSETS ARE NOT TO SCALE.
2. DIFFERENT SHADINGS ON TEXAS MAP REPRESENT DIFFERENT ECOREGIONS.

FIGURE II-1
STUDY RESERVOIRS - LOCATIONS

02/23/05-11:29 M:\Projects\820\0101\Acad\FIGURE II-2.dwg.dwg BrianD

Lake Bridgeport, located northwest of the Dallas/Fort Worth metropolitan area, serves as a source of public water supply, provides water supply for a power plant, is used for fishing and contact recreation, and provides limited flood control. Waters in Lake Bridgeport tend to be of moderately high clarity.

Lake Fork Reservoir, east of the Dallas/Fort Worth metropolitan area, provides public water supply and is known as one of the best largemouth bass fisheries in Texas. The waters in this reservoir are moderately clear.

Lake Georgetown, in Central Texas, provides public water supply and is used for contact recreation, non-contact recreation, and fishing. The waters of Lake Georgetown have high clarity.

Lake Livingston, located in East Texas, is a source of public water supply and is used for contact recreation, non-contact recreation, and fishing. Lake Livingston is the second reservoir studied that exhibits high levels of chlorophyll-*a*.

Lake Travis, located in the Central Texas Hill Country, provides public water supply and agricultural water supply, provides flood control for the Colorado River, and is extensively used for contact and non-contact recreation, as well as fishing. The waters have very high clarity.

STATION LOCATIONS

Each reservoir was sampled at two locations: one site was in the main body, and one site was in a cove or the headwater. A map of each reservoir showing the locations of sampling sites is presented in Appendix A.

The following criteria were used as the basis for selection of the monitoring locations:

- The water depth at the monitoring station should be at least 10 feet.
- The monitoring site is in the proximity of users who can respond to the survey (marina, park, subdivision, etc.).
- The sites selected should not have significant stands of aquatic vegetation.

USER SURVEYS

The user survey is designed to document the user's opinion of the physical condition of the waterbody based on its appearance and to document the user's perception of how suitable the water conditions are for recreational use and/or aesthetic enjoyment. The user survey is conducted at a time and location that generally correspond to the time and location that water quality data are collected.

A copy of the survey form is included in Appendix B. The two main questions presented in the survey are as follows:

1) Please circle the **one** response that best describes the **physical condition** of the lake water **today**:
   a) No algae, or crystal clear water
   b) A little algae visible
   c) Definite algal greenness
   d) Very green; some scum present and/or mild odor apparent
   e) Pea-soup green with one or more of the following: massive floating scums on lake or washed up on shore, strong foul odor, or fish kill

2) Please circle the **one** response that best describes your **perception** of how suitable the lake water is for recreation and aesthetic enjoyment **today**:

   a) Beautiful, could not be any nicer
   b) Very minor aesthetic problems; excellent for swimming, boating enjoyment
   c) Swimming and aesthetic enjoyment slightly impaired
   d) Desire to swim and level of enjoyment of the lake substantially reduced
   e) Swimming and aesthetic enjoyment of the lake nearly impossible

The survey also asks how many times a year the respondent visits the lake and their primary recreational activity for that day.

An attempt was made to collect seven surveys at each monitoring station during each monitoring event. Two of the surveys were to be completed by the staff collecting the water quality samples. The other five surveys were to be completed by members of the general public. The surveys were to be completed on the same day that the water quality samples were collected. No surveys were to be conducted before 10 A.M., and the sampling staff were encouraged to verify that the persons completing the survey had already been on, or near, the area of the lake where the sample was collected.

WATER QUALITY DATA

Following is a summary of the water quality parameters measured for this study, methods used, and preservation techniques. The parameters measured in the laboratory, methods used, and laboratory reporting limits are summarized in Table II-2. The methods and equipment used for field measurements are summarized in Table II-3. Because of the importance to this study of the measurements of chlorophyll-*a* and pheophytin, special procedures were adopted for these analyses. These procedures are described in a separate section below.

General Water Quality Measurements

The laboratories performing the general water quality analyses for each reservoir are identified on Table II-4. All but a few of the samples collected for laboratory analyses were depth-composited grab samples. Equal volumes of sample [500 milliliters (ml) each] were collected at depths of 1 foot (ft), 3 ft and 6 ft and combined into a single sample for analyses. Field measurements of dissolved oxygen (DO), pH, temperature, and specific conductivity also were made at depths of 1 ft, 3 ft, and 6 ft. The only samples that were not depth composites were the samples collected at Canyon Lake in 2003. These samples were surface grab samples and surface field measurements.

Samples collected for nitrogen and phosphorus analyses were preserved with sulfuric acid (H_2SO_4) and analyzed within 28 days. Samples collected for suspended solids analyses were preserved on ice and analyzed within 7 days.

Field duplicate samples were collected periodically for chlorophyll-*a* and pheophytin analyses. The duplicate samples also were analyzed by the LCRA laboratory.

Chlorophyll-*a* and Pheophytin

There were concerns about using chlorophyll as a water quality standard because of uncertainties regarding whether all aspects of the sampling and analytical methods are sufficiently defined to produce consistent results and whether historical data are comparable to recent data. In fact, shortly before the beginning of this study, the Texas Commission on Environmental Quality (TCEQ) contracted with the SRA for a study to determine whether there are steps in the sampling/analysis process that need to be controlled more rigorously and, if so, which steps those are. The results of this study are summarized in Appendix E. Appendix E also

TABLE II-2

LABORATORY WATER QUALITY ANALYSES

Laboratory Analysis	Method	Laboratory Reporting Limit
Nitrogen, Nitrate+Nitrite	EPA 353.2, EPA 353.3, or SM 4500-NO_3 E	0.04 mg/L
Nitrogen, Nitrate	EPA 300.0	0.02 mg/L
Nitrogen, Nitrite	EPA 300.0, in combination with EPA 353.2 or EPA 353.3	0.02 mg/L
Nitrogen, Total Kjeldahl	EPA 351.2 or SM 4500-N_{org} D	0.2 mg/L
Phosphorus, Total	EPA 365.2, EPA 365.4, or SM 4500-P E	0.06 mg/L
Chlorophyll-*a*	EPA 445.0, EPA 446.0, or SM 10200-H	2 µg/L
Pheophytin	EPA 445.0, EPA 446.0, or SM 10200-H	2 µg/L
Suspended Solids, Total	EPA 160.2 or SM 2540 D	1 mg/L
Suspended Solids, Volatile	EPA 160.4 or SM 2540 E	4 mg/L
Turbidity**	EPA 180.1	0.5 NTU

**Samples for Lake Bridgeport and Cedar Creek Reservoir were analyzed using a Hach Field Turbidity Meter.

TABLE II-3

FIELD WATER QUALITY MEASUREMENTS

Field Measurement	Method		Monitoring Equipment					
			BRA	**GBRA**	**LCRA**	**SRA**	**TRA**	**TRWD**
Secchi-disc Depth	TCEQ SOP*		200 mm black/white	200 mm black/white	200 mm black/white	200 mm black/white	200 mm black/white	200 mm black/white
Dissolved Oxygen	EPA 360.1 or TCEQ SOP*		Hydrolab	YSI 600 XLM	YSI 600 XLM	Hydrolab	YSI 600 XLM	Hydrolab Surveyor 4
pH	EPA 150.1 or TCEQ SOP*		Hydrolab	YSI 600 XLM	YSI 600 XLM	Hydrolab	YSI 600 XLM	Hydrolab Surveyor 4
Temperature	EPA 170.1 or TCEQ SOP*		Hydrolab	YSI 600 XLM	YSI 600 XLM	Hydrolab	YSI 600 XLM	Hydrolab Surveyor 4
Specific Conductivity	SM 2510 or TCEQ SOP*		Hydrolab	YSI 600 XLM	YSI 600 XLM	Hydrolab	YSI 600 XLM	Hydrolab Surveyor 4

*Surface Water Quality Monitoring Procedures, Volume 1: Physical and Chemical Monitoring Methods for Water, Sediment, and Tissue. Dec. 2003 (RG-415)

TABLE II-4

LABORATORY PERFORMING GENERAL WATER QUALITY ANALYSES

Reservoir	2003 Samples	2004 Samples
Canyon Lake	Guadalupe-Blanco River Authority and Brazos River Authority	Guadalupe-Blanco River Authority and STL*
Cedar Creek Reservoir	TRAC**	TRAC**
Granger Lake	Brazos River Authority	Brazos River Authority
Lake Bridgeport	TRAC**	TRAC**
Lake Fork Reservoir	Sabine River Authority and Brazos River Authority	Sabine River Authority and Analab***
Lake Georgetown	Brazos River Authority	Brazos River Authority
Lake Livingston	Trinity River Authority both Lake Livingston and Central Regional Wastewater System	Trinity River Authority both Lake Livingston and Central Regional Wastewater System
Lake Travis	Lower Colorado River Authority	Lower Colorado River Authority

*STL Laboratories in Austin, Texas
**TRAC Laboratories in Denton, Texas.
***Analab Laboratories in Kilgore, Texas

includes the Standard Operating Procedure for the determination of chlorophyll-*a* that was used by SRA during the study.

In recognition of this, at the outset of the study, all information on sampling and analytical procedures that may need to be rigorously controlled was compiled, and protocols for those procedures were established. Specific aspects of the approved method that were rigorously controlled for this study included the following:

- Samples were field-filtered. The filters containing the collected samples were frozen with dry ice in the field and maintained in a frozen state until analyzed. Samples were analyzed within 14 days.
- The acidification period was maintained as close to 90 seconds as was feasible.
- A micropipette rather than an eyedropper was used to acidify the samples.

For each sampling event, approximately 500 ml of sample were filtered through a glass-fiber filter. The filter was then folded twice, wrapped in aluminum foil, enclosed in a plastic bag, and placed on dry ice for shipment to the LCRA laboratory. All analytical results used in the subsequent data evaluations are the results provided by the LCRA laboratory.

SAMPLING PERIODS AND FREQUENCY

During 2003, samples were collected twice each month during the months of June through September at most sites. In 2004, samples were collected twice each month during the months of April through September. Whenever possible, samples were collected a minimum of two weeks apart. An effort was made not to collect samples that may have been influenced by stormwater runoff.

Periodically, SRA split samples with LCRA, and both SRA and LCRA analyzed the samples for chlorophyll-*a* and pheophytin. The purpose of this was to determine inter-laboratory variability.

CHAPTER III

SUMMARY OF DATA

Data collection began in June 2003 and was completed in September 2004. Sampling events were conducted during June through September in the first year, and April through September in the second year. A total of 1,806 valid recreational user surveys were completed; and over 5,700 water quality measurements were obtained, including 296 measurements of chlorophyll-*a*. The numbers of surveys obtained at each reservoir and each year are shown in Table III-1. Ninety-five percent of the surveys can be correlated with water quality data.

Except for one sampling event at Cedar Creek Reservoir in June 2003, surveys were collected on the same day as water quality samples. In the case of the sampling event on Cedar Creek Reservoir, due to a problem with transporting the samples, water quality samples for laboratory analyses were re-collected on the day following the initial sample collection. (The survey forms were completed on the day that the initial sample was collected).

WATER QUALITY IN RESERVOIRS

Water quality in the various study reservoirs differs significantly in terms of transparency and concentrations of suspended solids, nitrogen, phosphorus, and chlorophyll-*a*. A summary of the water quality data for each reservoir is presented in Appendix C. In this report, unless specified otherwise, analyses reported as being below the detection limit were included in calculations at a value equal to one-half of the detection limit.

General Water Quality

A summary of water quality data for each reservoir is presented in Table III-2. Mean summer values for total nitrogen, total phosphorus, DO, and pH at each reservoir are presented. All DO and pH measurements (1 ft, 3 ft, and 6 ft) were included when computing these averages. The mean values include data from both main body and cove/headwater stations.

The phosphorus concentrations measured in 2003 at Granger Lake, Lake Fork Reservoir and Lake Georgetown were substantially different than the concentrations measured in 2004 at these reservoirs. The 2004 values appear to be more consistent with other characteristics of these reservoirs. Therefore, only 2004 data are included in the averages reported in Table III-2.

TABLE III-1

NUMBER OF USER SURVEYS BY RESERVOIR

Reservoir	2003	2004	Total
Canyon Lake	96	117	213
Cedar Creek Reservoir	129	145	274
Granger Lake	72	70	142
Lake Bridgeport	124	175	299
Lake Fork Reservoir	84	151	235
Lake Georgetown	72	67	139
Lake Livingston	124	190	314
Lake Travis	93	97	190
Total	**794**	**1012**	**1806**

TABLE III-2

RESERVOIR CHARACTERISTICS
NUTRIENTS, DISSOLVED OXYGEN, pH

Reservoir	Total Nitrogen (mg/L)	Total Phosphorus (mg/L)	DO (mg/L)	pH
Canyon Lake	0.70	0.05	8.6	8.1
Cedar Creek Reservoir	1.26	0.10	7.8	8.4
Granger Lake	0.62	0.10	7.0	8.1
Lake Bridgeport	0.77	0.06	7.4	8.1
Lake Fork Reservoir	0.95	0.04	7.6	7.7
Lake Georgetown	0.35	0.11	7.4	8.1
Lake Livingston	1.34	0.24	9.3	8.4
Lake Travis	0.36	0.01	8.2	8.4

A comparison of the mean summer transparencies in the main body of each reservoir is presented in Figure III-1. The reservoirs are ordered on Figure III-1 from least transparent on the left to most transparent on the right. In general, study reservoirs located west of Interstate Highway 35 have higher transparencies than reservoirs located in the east and northeast areas of the state. The study reservoirs with the highest transparency are located in the Edwards Plateau ecoregion.

A comparison of the mean summer suspended solids concentrations in the main body of each reservoir is presented on Figure III-2. The relative proportions of inorganic solids and volatile (organic) solids in each reservoir are shown. It can be observed on Figure III-2 that the total concentration and the percentage of inorganic suspended solids in Granger Lake are substantially different than in the other reservoirs. Granger Lake exhibits substantially higher inorganic suspended solids.

Comparisons of mean summer total nitrogen concentrations and total phosphorus concentrations in each reservoir are presented in Figure III-3 and Figure III-4, respectively. Data are presented for both the main body station and the cove or headwater station in each reservoir. The reservoirs exhibit a wide range of nutrient concentrations. As in Table III-2, only 2004 data for phosphorus have been used for Granger Lake, Lake Fork Reservoir, and Lake Georgetown.

Chlorophyll-*a* and Pheophytin

Summaries of the chlorophyll-*a* and pheophytin data obtained by this study are presented in this section. The concentrations of chlorophyll-*a* in each reservoir are presented, as well as a comparison of the data obtained by this study to historical data for chlorophyll-*a* for each of the reservoirs, an evaluation of whether data on pheophytin are needed, and the results of the study of inter-laboratory variability.

Chlorophyll-*a* Concentrations in Reservoirs

A comparison of the mean summer chlorophyll-*a* concentrations in each reservoir is presented on Figure III-5. Values are shown for both the main body station and the cove or headwater station in each reservoir.

The reservoirs are arranged on Figure III-5 in the same order as on Figure III-1, which presents transparency data for each reservoir. As can be observed, the general trend is that, as

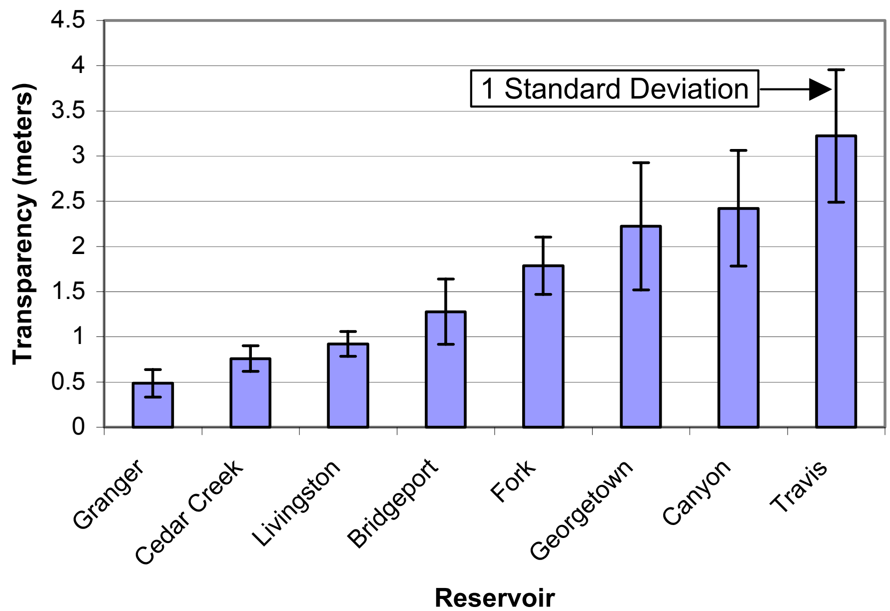


FIGURE III-1
MEAN SUMMER RESERVOIR TRANSPARENCY
MAIN BODY

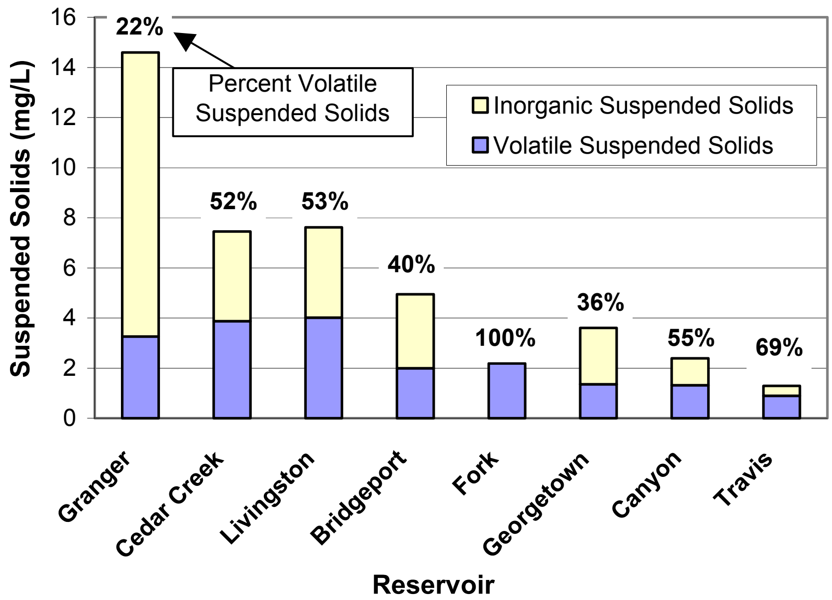


FIGURE III-2

MEAN SUMMER RESERVOIR SUSPENDED SOLIDS CONCENTRATIONS MAIN BODY

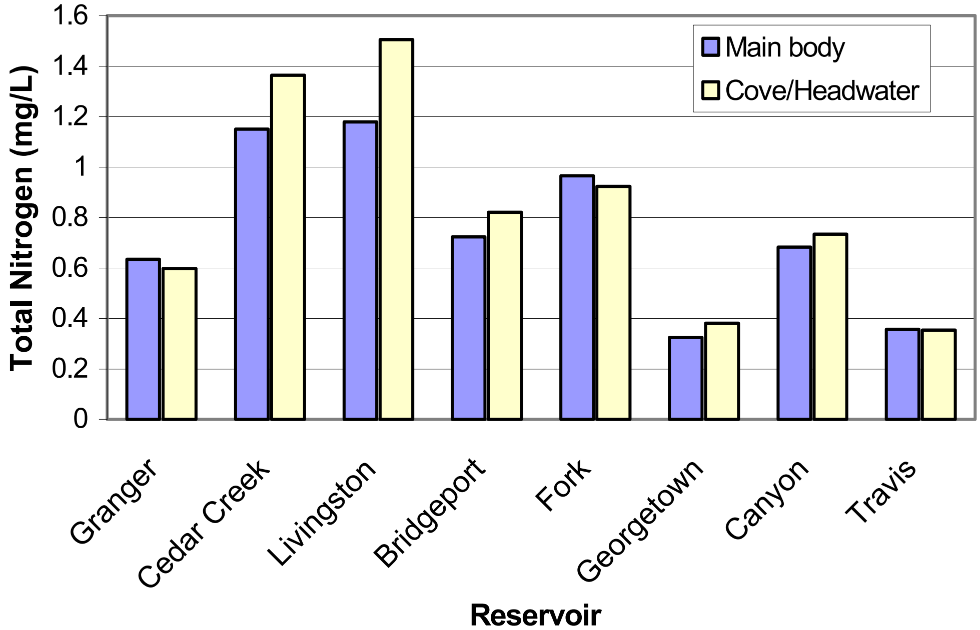


FIGURE III-3

MEAN SUMMER RESERVOIR NITROGEN CONCENTRATIONS MAIN BODY AND COVE/HEADWATER

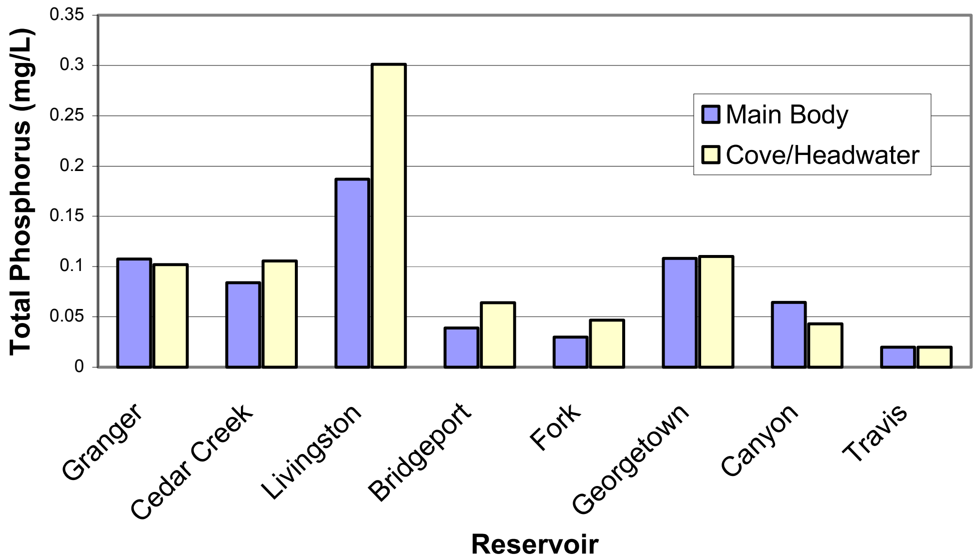


FIGURE III-4

MEAN SUMMER RESERVOIR PHOSPHORUS CONCENTRATIONS MAIN BODY AND COVE/HEADWATER

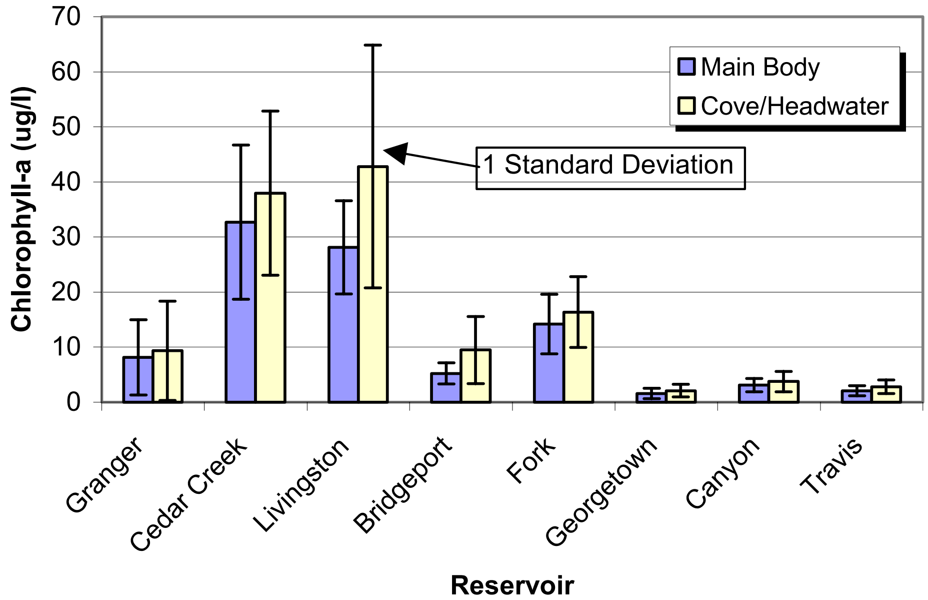


FIGURE III-5

MEAN SUMMER CHLOROPHYLL-*a* CONCENTRATIONS
MAIN BODY AND COVE/HEADWATER

chlorophyll-*a* increases, transparency decreases. The most notable exception to this trend is Granger Lake. As previously noted, the low transparency in Granger Lake is due to inorganic suspended solids rather than algal growth. In fact, the high concentrations of solids probably discourage algal growth by limiting light penetration.

Both algae and suspended solids contribute to reductions in transparency. However, in most of the reservoirs studied, the concentration of suspended solids is low, and algae is the more dominant factor.

Data have also been compiled on the range of chlorophyll-*a* concentrations exhibited at each reservoir. Both main body and cove/headwater stations were included in this summary. The results are presented on Table III-3.

Comparison to Historical Data

When this study was initiated, there was a concern that it might be difficult to use chlorophyll-*a* as the nutrient water quality standard. There was a concern that the analytical method may have changed sufficiently that historical data would not be comparable to recent data. If this were true, there might not be sufficient data available in the TCEQ database to characterize reservoir quality accurately. Therefore, data from this study were compared to historical data in the TCEQ Surface Water Quality Monitoring (SWQM) database. In general, TCEQ data collected between 1993 and 2003 were used. However, the period of record in the TCEQ database varies from reservoir to reservoir. The results of this comparison are presented in Table III-4. As can be observed in Table III-4, the historical data and data from this study are generally comparable. The only reservoirs for which the data are somewhat different are Cedar Creek Reservoir and Lake Livingston. In both cases, the average chlorophyll-*a* concentrations reported by this study are a little higher than the average concentrations based on TCEQ data.

Significance of Pheophytin Measurements

When this study was initiated, it also was not clear whether pheophytin should be included in the evaluation and subsequent water quality standards. Therefore, all samples collected for this study were analyzed for both chlorophyll-*a* and pheophytin. An evaluation was conducted to

TABLE III-3

MAXIMUM AND MINIMUM CHLOROPHYLL-*A* CONCENTRATIONS COMBINED DATA FOR MAIN BODY AND COVE/HEADWATER SITES

Reservoir	Maximum Chlorophyll-*a* (ug/L)	Minimum Chlorophyll-*a* (ug/L)*
Canyon Lake	7	1
Cedar Creek Reservoir	64	10
Granger Lake	36	1
Lake Bridgeport	32	3
Lake Fork Reservoir	27	5
Lake Georgetown	5	1
Lake Livingston	115	8
Lake Travis	5	1

*Values reported as < 2.0 ug/L are included in the summary as 1.0 ug/L

TABLE III-4

COMPARISON OF MEAN SUMMER RESERVOIR CHLOROPHYLL-*a* MAIN BODY THIS STUDY AND TCEQ DATABASE

Reservoir	TCEQ*			This Study		
	Mean** Chlorophyll-*a* (ug/L)	Std. Dev.	N	Mean Chlorophyll-*a* (ug/L))	Std. Dev.	N
Canyon Lake	2	2	17	3	1	15
Cedar Creek Reservoir	24	16	20	33	14	20
Granger Lake	3	2	9	8	7	17
Lake Bridgeport	5	2	25	6	2	17
Lake Fork Reservoir	13	10	25	14	5	19
Lake Georgetown	2	1	9	2	1	16
Lake Livingston	20	12	26	28	8	20
Lake Travis	3	4	22	2	1	19

*Values reported as < 0.5 ug/L or < 0.25 ug/L not included in the analysis
Values reported as < 1.0 ug/L included in analysis as 0.5 ug/L
Values reported as < 2.0 ug/L included in analysis as 1.0 ug/L

**Data averaged for the period 1993–2003

determine the relative significance of the pheophytin data thus compiled. The average pheophytin concentration in each reservoir was determined as well as the percent of the sum of the chlorophyll-*a* and pheophytin concentrations that was represented by pheophytin. Data from main body and cove/headwater stations were combined for this evaluation. The results of the evaluation are presented on Figure III-6. As shown on Figure III-6, the concentrations of pheophytin are either low in terms of absolute magnitude or are a very small percentage of the total chlorophyll/pheophytin pigments that are present. Therefore, neither assessments of reservoir quality nor correlations of user survey results with chlorophyll-*a* concentrations are significantly changed by including the results of pheophytin analyses. It was concluded that assessments of reservoir quality and nutrient water quality standards can be based on chlorophyll-*a* only.

Inter-laboratory Variability

During 2003, as the results of the analyses of chlorophyll-*a* and pheophytin by SRA were compared to the LCRA results, the importance of specific method refinements became clear. Table III-5 presents data that illustrate how the method refinements produced a more reasonable agreement between the results obtained by the two laboratories. For the first three samples analyzed, as shown in Table III-5, LCRA and SRA had significantly different results. These differences were concluded to be due to the fact that LCRA used a micropipette to acidify the samples, and SRA used an eyedropper. The time between acidification and measurement was also found to be important. The results for the subsequent samples were obtained after SRA implemented all of the refined protocols used by LCRA. As shown in Table III-5, substantially better agreement in the analytical results was obtained after those changes were made.

USER SURVEYS

The user surveys received were analyzed to determine the characteristics of the users that filled out the surveys at each reservoir. The characteristics of the users with respect to frequency of visits to the reservoir are summarized in Table III-6. The types of activities in which the survey respondents were participating at each reservoir are summarized in Table III-7.

As shown in Table III-7, the total number of reservoir use activities identified exceeds the total number of surveys completed. This is because, even though the survey form asks respondents to identify their “primary” activity, some respondents identified multiple activities.

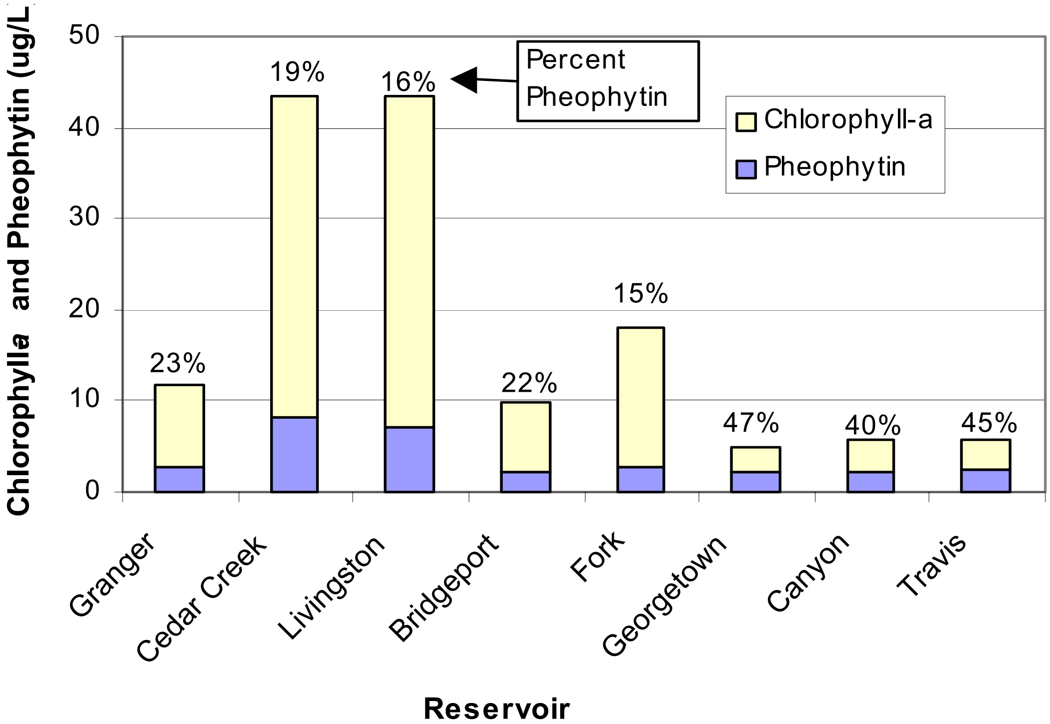


FIGURE III-6

MEAN SUMMER RESERVOIR CHLOROPHYLL-*a* AND PHEOPHYTIN CONCENTRATIONS

MAIN BODY

TABLE III-5

ANALYSES OF SPLIT SAMPLES BY LCRA AND SRA

Year	Sample Number	Chlorophyll-*a* + Pheophytin (ug/L)			
		LCRA Result	SRA Result	|SRA – LCRA|	Relative Percent Difference (RPD)
2003	1*	13.5	19.7	6.2	37.3%
	2*	13.0	24.2	11.2	60.2%
	3*	9.0	48.6	39.6	137.5%
	4	15.6	15.7	0.1	0.6%
	5	12.7	17.3	4.6	30.7%
	6	12.3	16.5	4.2	29.2%
	7	19.0	21.2	2.2	10.9%
	8	18.2	20.3	2.1	10.9%
2004		Chlorophyll-*a* (ug/L)			
	1	10.3	6.4	3.9	46.7%
	2	10.6	12.2	1.6	13.1%
	3	7.3	7.9	0.6	7.9%
	4	7.9	7.9	0.0	0.0%
	5	9.4	9.8	0.4	4.2%
	6	9.4	9.6	0.2	2.1%
	7	14.8	14.5	0.3	2.0%
	8	14.8	13.2	1.6	12.1%
	9	22.3	18.6	3.7	19.9%
	10	23.0	20.0	3.0	14.0%
	11	15.8	17.5	1.7	10.2%
	12	15.4	16.7	1.3	8.1%
	13	9.4	11.1	1.7	15.3%
	14	7.4	9.8	2.4	27.9%
	15	5.2	6.0	0.8	14.3%
	16	6.8	8.8	2.0	25.6%
	17	9.5	10.3	0.8	8.1%
	18	13.4	13.5	0.1	0.7%
	19	13.2	13.2	0.0	0.0%
	20	20.8	22.6	1.8	8.3%
	21	14.6	11.7	2.9	22.1%
	22	26.1	24.1	2.0	8.0%
	23	21.9	19.2	2.7	13.1%
	24	21.7	22.9	1.2	5.4%
	25	21.4	22.1	0.7	3.2%
	26	20.4	20.5	0.1	0.5%
	27	16.0	17.7	1.7	10.1%
	28	22.6	27.3	4.7	18.8%
	29	21.6	23.3	1.7	7.6%
	30	15.2	19.4	4.2	24.3%

*Prior to method refinement.

TABLE III-6

USER GROUP CHARACTERISTICS BY FREQUENCY OF VISITS TO RESERVOIR

Reservoir	Permanent Resident	More Than Six Times Per Year	Two to Six Times Per Year	Typically Every Year	First Visit	Total by Reservoir
Canyon Lake	62	64	36	18	29	209
Cedar Creek Reservoir	105	128	21	5	13	272
Granger Lake	8	89	24	10	9	140
Lake Bridgeport	33	156	51	10	49	299
Lake Fork Reservoir	124	36	26	24	25	235
Lake Georgetown	7	88	32	7	5	139
Lake Livingston	164	68	39	17	26	314
Lake Travis	17	122	25	8	15	187
Total	**520**	**751**	**254**	**99**	**171**	**1,795**

TABLE III-7

USER GROUP CHARACTERISTICS BY PRIMARY ACTIVITY

Reservoir	Number of Users							Total Responses by Reservoir
	Swimming	Fishing	Boating	Skiing/ Windsurfing	On-shore Activity	Sampling Crew	Other	
Granger Lake	11	42	17	2	15	56	18	161
Cedar Creek Reservoir	15	82	68	8	22	64	21	280
Lake Livingston	45	113	44	13	60	56	38	369
Lake Bridgeport	17	107	27	27	15	77	31	301
Lake Fork Reservoir	10	139	14	3	4	60	17	247
Lake Georgetown	21	16	14	7	19	56	19	152
Canyon Lake	31	27	67	13	9	46	43	236
Lake Travis	46	14	51	13	12	72	18	226
Total	**196**	**540**	**302**	**86**	**156**	**487**	**205**	**1,972**

It can also be noted from Table III-7 that, if one assumes the surveys for each lake are representative of the general population of users at that lake, the primary type of recreational use varies from reservoir to reservoir. Lake Fork Reservoir is well known for the quality of the fishing, and 56% of the survey respondents engaged in recreation indicated that their primary activity that day was fishing. Only 5% of the survey respondents indicated that their primary activity was contact recreation (swimming, skiing, or windsurfing). In comparison, at Lake Travis, only 6% of the recreational respondents were primarily engaged in fishing, while 26% were engaged in contact recreation.

It is concluded from these data that, in general, reservoir users have different preferences with respect to water clarity/chlorophyll concentration based on the type of recreational use in which they are participating. The reservoirs with high clarity (low chlorophyll concentrations) have more contact recreation users both as a percentage and in terms of absolute numbers.

In addition, it appears that fishermen prefer waters with more chlorophyll. The usage of the lakes with high clarity waters by fishermen is low both as a percentage and in terms of absolute numbers. The reservoirs with moderate levels of chlorophyll appear to be most popular with fishermen.

All the surveys were collected on weekdays (Monday through Friday). It is not known whether this influenced the user population that was surveyed.

CHAPTER IV

RESULTS

The following chapter presents a series of evaluations designed to evaluate relationships between varying concentrations of chlorophyll in waters of reservoirs and users' perceptions of whether recreational uses are impaired. Dr. William W. Walker, Jr., has also performed detailed evaluations of these relationships. His work is presented in Appendix D. Some of Dr. Walker's evaluations are also included in this chapter.

The relationships have been evaluated in several different ways. For example, relationships are examined for the individual reservoirs, for groups of reservoirs with similar transparency characteristics, and for the entire, pooled dataset. In addition, variations in results, based on the type of recreational activity at the reservoir and frequency of visit to the reservoir, are evaluated.

Before conducting the evaluations of relationships, two types of data were eliminated from the database:

- The database was screened to identify surveys that identified a factor other than "algal greenness" as having the most effect on the respondent's assessment of suitability of the reservoir for recreational use. These surveys were not included in subsequent evaluations.

- An attempt was made not to collect samples when water quality was influenced by rainfall runoff. However, visual inspection of the data and reports by the sampling crews of rainfall impacts suggest that a limited number of samples at Canyon Lake, Lake Bridgeport, and Lake Livingston had increased turbidity due to recent rainfall events. These water quality samples and the corresponding survey responses were not included in subsequent evaluations.

RESULTS BY RESERVOIR

Comparisons of the users' responses regarding suitability for use versus chlorophyll-*a* concentrations for each reservoir are presented on Figure IV-1. The potential responses regarding suitability of use were as follows:

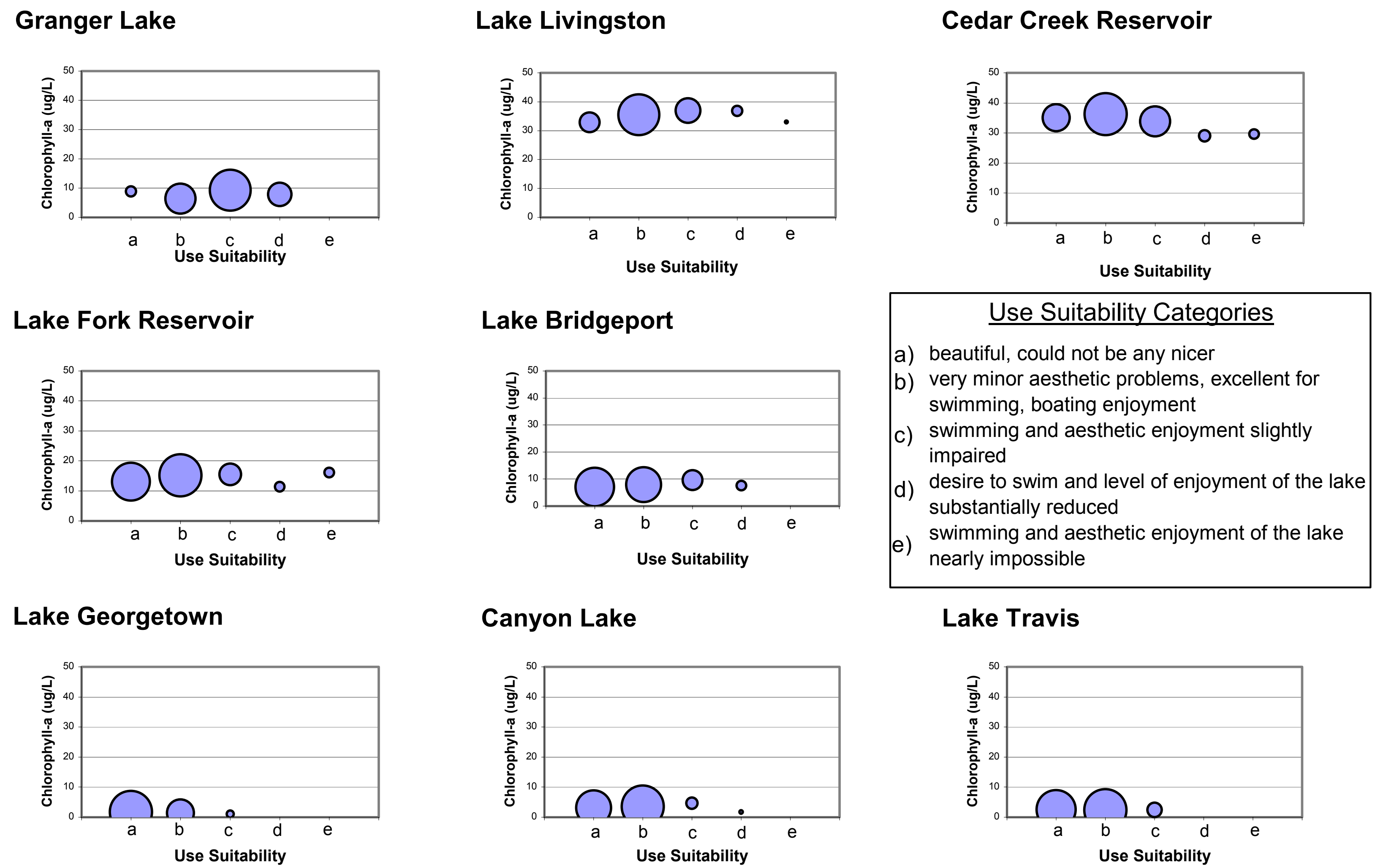


FIGURE IV-1
PERCEIVED IMPACTS ON RECREATIONAL USE VERSUS CHLOROPHYLL-a CONCENTRATIONS FOR EACH RESERVOIR

a) Beautiful, could not be any nicer

b) Very minor aesthetic problems; excellent for swimming, boating enjoyment

c) Swimming and aesthetic enjoyment slightly impaired

d) Desire to swim and level of enjoyment of the lake substantially reduced

e) Swimming and aesthetic enjoyment of the lake nearly impossible

To generate the results presented on Figure IV-1, the following calculations were performed:

- All "a" responses were compiled with their associated measurement of the chlorophyll-*a* concentration, and an average chlorophyll-*a* concentration for that dataset was calculated.

- Similarly, the average chlorophyll-*a* concentrations associated with a response of "b", a response of "c", a response of "d", and a response of "e" were computed.

- The number of responses in each category, "a" through "e", was also determined.

- The resultant data were plotted such that the horizontal axis identifies the response ("a," "b," "c," "d", or "e"), and the vertical axis identifies the average chlorophyll-*a* concentration for that response. The result is plotted as a circle. The center of the circle is placed at the average concentration, and the size of each circle is proportional to the number of respondents that classified the waterbody in that respective category ("a," "b," "c," "d,", or "e").

A review of these figures suggests that, for a given reservoir, there is a general acceptance of existing water quality. Thus, for Cedar Creek Reservoir and Lake Livingston, a majority of responders categorized the waters as either "a – beautiful, could not be nicer," or "b – very minor aesthetic problems; excellent for swimming, boating enjoyment," even though the chlorophyll-*a* concentration averages were between 30 micrograms per liter (ug/L) and 35 ug/L.

Slight trends of increasing perception of use impairment with increasing concentrations of chlorophyll-*a* can be observed in the responses for Lake Bridgeport, Lake Fork Reservoir, and Lake Livingston. In addition, the reservoirs with the higher chlorophyll-*a* concentrations (Cedar Creek Reservoir and Lake Livingston) were classified as "a" less frequently and "c" more frequently than the other reservoirs.

No trends can be discerned in the results for Canyon Lake, Lake Georgetown, and Lake Travis because there was very little variation in chlorophyll-*a* concentrations during the study period. Chlorophyll-*a* concentrations in Lake Georgetown and Lake Travis did not exceed 5 ug/L, and chlorophyll-*a* concentrations in Canyon Lake did not exceed 7 ug/L.

The survey results regarding use suitability for Granger Lake may have been influenced more by the natural turbidity of the reservoir than by chlorophyll-*a* concentrations (even though respondents were specifically asked if "algae/greenness" was the factor on which they based their assessment of use suitability). As can be observed on Figure IV-1, the majority of respondents categorized Granger Lake as "c – swimming and aesthetic enjoyment slightly impaired" or "d – desire to swim and level of enjoyment of the lake substantially reduced." The average chlorophyll-*a* concentration for these responses was less than 10 ug/L. None of the other reservoirs, even Cedar Creek Reservoir and Lake Livingston, had a majority of the responses in categories "c" and "d".

RESULTS FOR RESERVOIR GROUPS

As has previously been noted, the reservoirs studied exhibit a wide range of transparencies. The transparency characteristics of the study reservoirs are presented on Figure IV-2. In the following evaluations, the reservoirs have been grouped based on their respective transparencies.

As previously noted, Granger Lake had the lowest transparency. The transparency was always less than 1 meter (m), and the average transparency in the main body of the reservoir was 0.5 m. Also, while in the other reservoirs there is a relationship between decreased transparency and increased algal growth, the decreased transparency in Granger Lake is primarily attributable to inorganic solids. Therefore, because of its unique characteristics, Granger Lake has not been grouped with any other reservoirs.

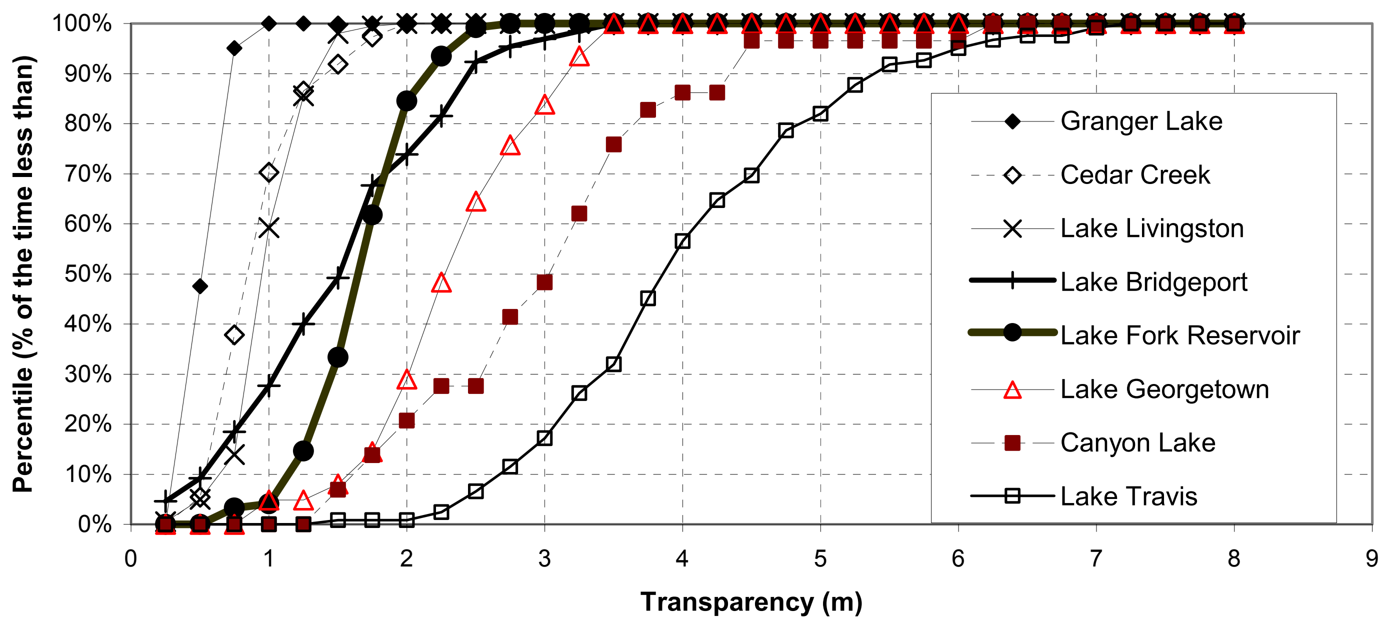


FIGURE IV-2
TRANSPARENCY CHARACTERISTICS OF RESERVOIRS

Transparency levels in Cedar Creek Reservoir and Lake Livingston are very similar. Transparency is always less than 2 m. The average transparencies in the main bodies of Cedar Creek Reservoir and Lake Livingston are 0.8 m and 0.9 m, respectively. Both of these reservoirs have relatively high concentrations of planktonic algae. The average chlorophyll-*a* concentrations in the main body waters of Cedar Creek Reservoir and Lake Livingston are 33 ug/L and 28 ug/L, respectively. Therefore, these two reservoirs have been grouped together.

Lake Bridgeport and Lake Fork Reservoir exhibit moderate levels of transparency and moderate levels of chlorophyll-*a*; so, they have been grouped together. The average transparencies in the main body waters of Lake Bridgeport and Lake Fork Reservoir are 1.3 m and 1.8 m, respectively. The average chlorophyll-*a* concentrations in the main body waters are 5 ug/L and 14 ug/L in Lake Bridgeport and Lake Fork Reservoir, respectively.

The remaining three reservoirs have high clarity and low chlorophyll-*a* concentrations. The average transparencies in the main body waters of Lake Georgetown, Canyon Lake, and Lake Travis are 2.2 m, 2.3 m, and 3.2 m, respectively. The corresponding average chlorophyll-*a* concentrations are 2 ug/L, 3 ug/L, and 2 ug/L.

Evaluations in the remainder of the report do not include data for Granger Lake since the responses for that reservoir are not believed to be related closely to chlorophyll-*a* concentrations. For the remaining three reservoir groups, relationships between chlorophyll-*a* concentrations and the respondents' perceptions of the suitability of the waters for recreational use were evaluated.

When conducting evaluations based on reservoir groups, in addition to analyzing the combined response of all participants in the survey for each reservoir group, evaluations were also conducted in which the data were divided into subsets in order to determine if there were significant differences in the responses of different user groups. For one evaluation, the data were divided into subsets based on the type of activity in which the survey respondent was engaged; and, for the other evaluation, the data were divided into subsets based on the frequency with which the respondents visited the reservoir.

<u>Evaluations of Responses by Reservoir Groups</u>

The datasets that included all users in each reservoir group were evaluated as follows. For each reservoir grouping, chlorophyll-*a* data were compiled into three subsets, and an average concentration was computed for each subset. The first subset was comprised of the

chlorophyll-*a* concentrations associated with "a" responses. The second subset was comprised of the chlorophyll-*a* concentrations associated with "b" responses; and the third subset was comprised of the chlorophyll-*a* concentrations associated with "c," "d," or "e" responses. The results of this evaluation are presented on Figure IV-3.

Evaluations of Responses Based on Activity at the Reservoir

For the purpose of this evaluation, the respondents were grouped into three categories:

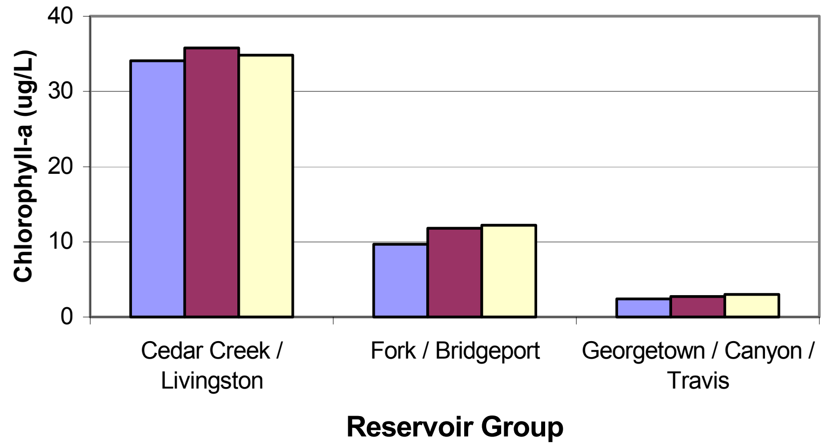
- Sampling crew
- Contact recreation users, which included those who identified their primary activity as swimming, skiing, or windsurfing
- Non-contact recreation users, which included those who identified their primary activity as fishing, boating, on-shore activity, or other

The data were then evaluated to determine whether the professional samplers characterized the waters differently than the public and whether contact recreation users characterized the waters differently than non-contact recreation users.

In some cases, survey respondents identified more than one type of recreational use, even though they were requested to identify their "primary" use. When evaluating responses based on the type of use, if there were multiple responses but contact recreation use was identified as one of the uses, that survey was assigned to the contact recreation use category.

Figure IV-4 presents the results of the evaluation to determine if the sampling crews had a different perception of the level of chlorophyll-*a* that impaired recreational use than the general public. To prepare Figure IV-4, the chlorophyll-*a* data for each reservoir group were aggregated into the following subsets:

- Less than 5 ug/L
- 5 ug/L to <10 ug/L
- 10 ug/L to <20 ug/L
- 20 ug/L to <40 ug/L
- 40 ug/L or greater



a - beautiful, could not be any nicer
b - very minor aesthetic problems, excellent for swimming, boating enjoyment
c- swimming and aesthetic enjoyment sligthly impaired
or
d - desire to swim and level of enjoyment of the lake substantially reduced
or
e - swimming and aesthetic enjoyment of the lake nearly impossible

FIGURE IV-3

RECREATIONAL SUITABILITY BASED ON CHLOROPHYLL-*A* CONCENTRATION RESULTS FOR RESERVOIR GROUPS

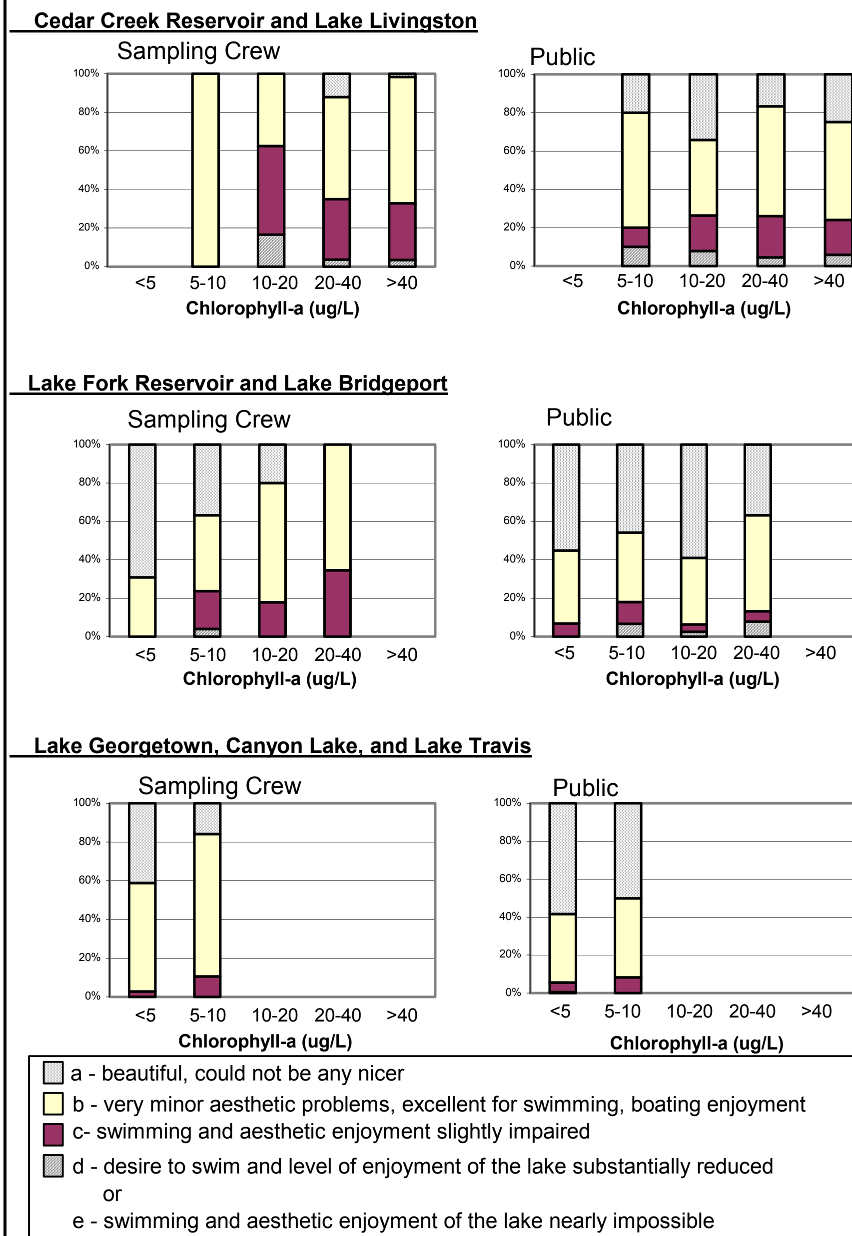


FIGURE IV-4

COMPARISON OF EVALUATION OF RECREATIONAL SUITABILITY BY SAMPLING CREW AND BY PUBLIC BASED ON RESERVOIR GROUPS

Then, each chlorophyll-a subset was evaluated to determine what percent of the samplers categorized the use suitability of the water as "a," "b," "c," "d," or "e". The same evaluation was performed for the responses of the public. As indicated on Figure IV-4, the sampling crews were more likely to identify impairment of recreational use than the general public and somewhat more consistent in identifying increased impairment as chlorophyll-a concentrations increased. However, this figure also indicates that, at equivalent concentrations of chlorophyll, the perception of use impact by the samplers varied significantly from one reservoir group to another. Thus, in Cedar Creek Reservoir and Lake Livingston, when chlorophyll-a concentrations were in the 10 ug/L – 20 ug/L range, the sampling crew classified the use suitability of the water as "d" ("enjoyment substantially reduced") almost 20% of the time. However, when chlorophyll-a concentrations were between 10 ug/L and 20 ug/L in Lake Fork Reservoir and Lake Bridgeport, the sampling crew classified the use suitability as "c" ("slightly impaired") approximately 20% of the time and did not characterize any of the waters as "d." The perceptions of the public vary somewhat from one reservoir group to another, also, but not as much as the perceptions of the samplers.

A similar evaluation was performed comparing responses of contact recreation users to responses of non-contact recreation users. The results of this evaluation are presented on Figure IV-5. The conclusions to be drawn from this evaluation are unclear. The contact recreation users exhibited a more consistent tendency to assign fewer "a's" and more "b's" as chlorophyll-*a* concentrations increased than did non-contact recreation users. However, non-contact recreation users were more inclined to assign "c," "d," or "e" classifications at all chlorophyll-*a* concentrations.

Evaluations of Responses Based on Frequency of Visits

For the purpose of this evaluation, the survey respondents were grouped into two categories:

- Frequent – Visit lake more than six times per year or are a permanent resident
- Infrequent – Visit lake six times per year or less

Responses of the sampling crews were not included in this evaluation

The evaluation was performed in the same manner as the previous comparisons of sampling crew versus the public and contact recreation users versus non-contact recreation users. The results are presented on Figure IV-6. No discernible differences exist between these two groups of users for the reservoir grouping that includes Cedar Creek Reservoir and Lake

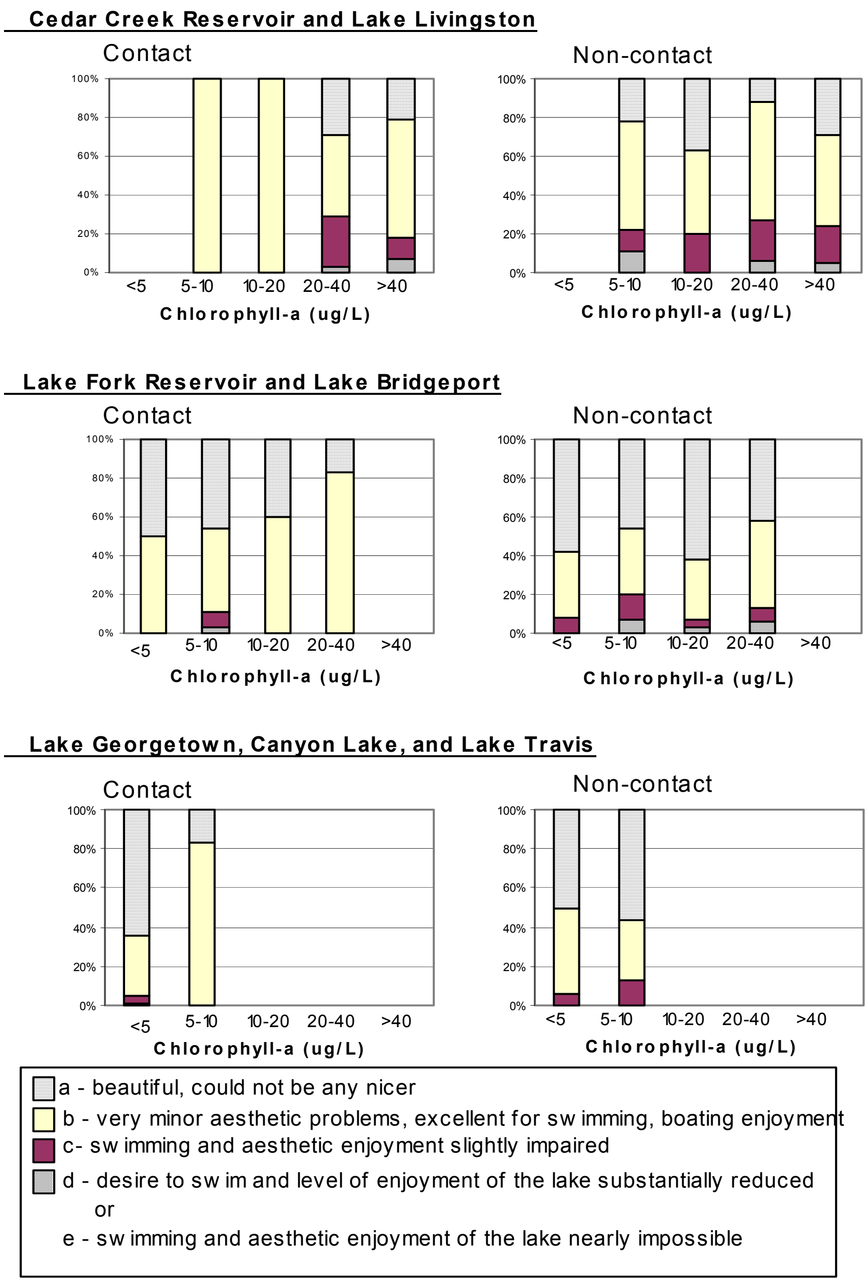


FIGURE IV-5

COMPARISON OF EVALUATION OF RECREATIONAL SUITABILITY BY CONTACT RECREATIONAL USERS VERSUS NON-CONTACT RECREATIONAL USERS BASED ON RESERVOIR GROUPS

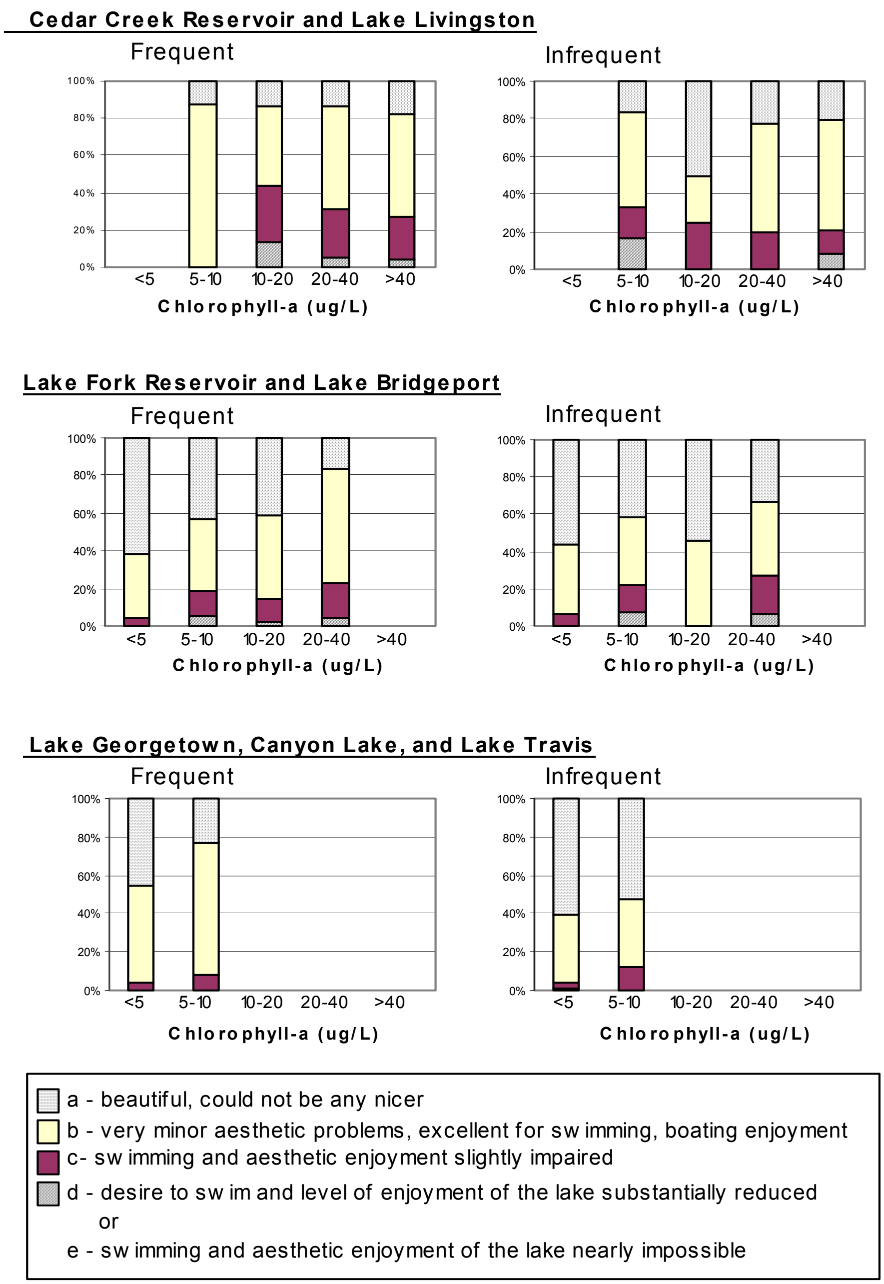


FIGURE IV-6
COMPARISON OF EVALUATION OF RECREATIONAL SUITABILITY BY FREQUENT VISITORS VERSUS INFREQUENT VISITORS BASED ON RESERVOIR GROUPS

Livingston. However, in the other two reservoir groups, the frequent visitors are slightly more likely to perceive use impacts as chlorophyll-*a* concentrations increase than are the infrequent visitors.

RESULTS BASED ON COMPLETE DATASET

Comparisons of perceptions of use suitability and chlorophyll-*a* concentrations were also conducted for a pooled dataset that included the results for all of the reservoirs except Granger Lake. As previously discussed, the responses for Granger Lake regarding suitability for recreational use are believed to have been influenced significantly by factors other than the amount of algae present.

The data were evaluated three different ways. Following are descriptions of the method and the results for each evaluation.

First Evaluation

The first evaluation using the pooled dataset was an investigation of the relationship between the average chlorophyll-*a* concentration in a reservoir (main body and cove/headwater stations) and (1) the combined percentage of the respondents that characterized the recreational use suitability of that reservoir as "c," "d," or "e" and (2) the combined percentage of the respondents that characterized the recreational suitability of that reservoir as "d" or "e." The results of this evaluation are presented on Figure IV-7. There is a strong correlation indicating that, as the chlorophyll concentration of a reservoir increases, more users perceive some degree of use impairment.

Second Evaluation

For the second evaluation, the chlorophyll-*a* concentrations were ordered from lowest to highest. Then, the data originally were aggregated into 10 percentile groups; i.e., the 10% of the data with the lowest concentrations comprised one subset; the next 10% of the data, based on the next lowest concentration group, comprised the second subset; etc. When this was done, because of the number of values below the reliable detection limit in the first subset, the first and second subsets were combined. Therefore, when responses were compared to chlorophyll concentrations, there were nine subsets, which represented the following percentile ranges: 0-19, 20-29 30-39, 40-49, 50-59, 60-69, 70-79, 80-89 and 90-100.

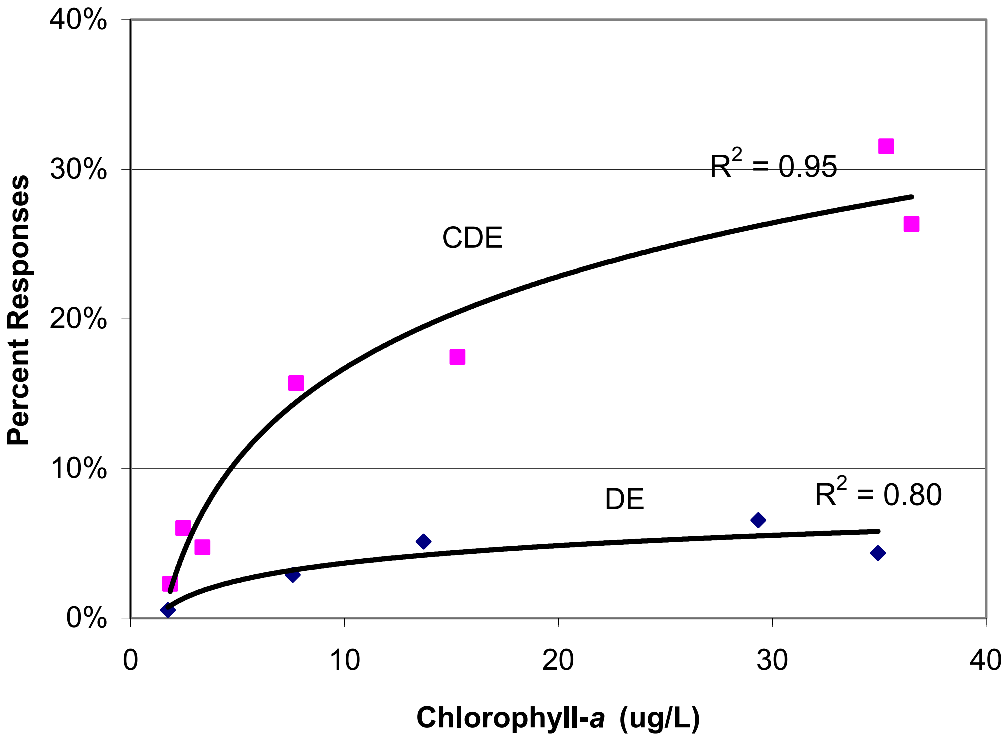


FIGURE IV-7
FREQUENCY OF RESPONSE OF USE IMPAIRMENT
VERSUS CHLOROPHYLL-*A* CONCENTRATION
COMPARISON BETWEEN RESERVOIRS
(Granger Not Included)

Each data point represents a reservoir

For each percentile subset, the following values were computed:

- The average concentration of chlorophyll-*a*
- The percent of the responses that represented the sum of the “c,” “d,” and “e” responses.
- The percent of the responses that represented the sum of the “d” and “e” responses.

The results of this evaluation are presented on Figure IV-8.

The results of this evaluation are very similar to the results of the preceding evaluation. This is not unexpected because the range of chlorophyll concentrations in each reservoir is relatively specific to that reservoir. The cases in which reservoirs exhibit similar concentrations are the three high-clarity reservoirs and the two low-clarity reservoirs. The grouping of data by reservoir and the grouping of data by concentration intervals produce very similar groupings with respect to the results of the user surveys.

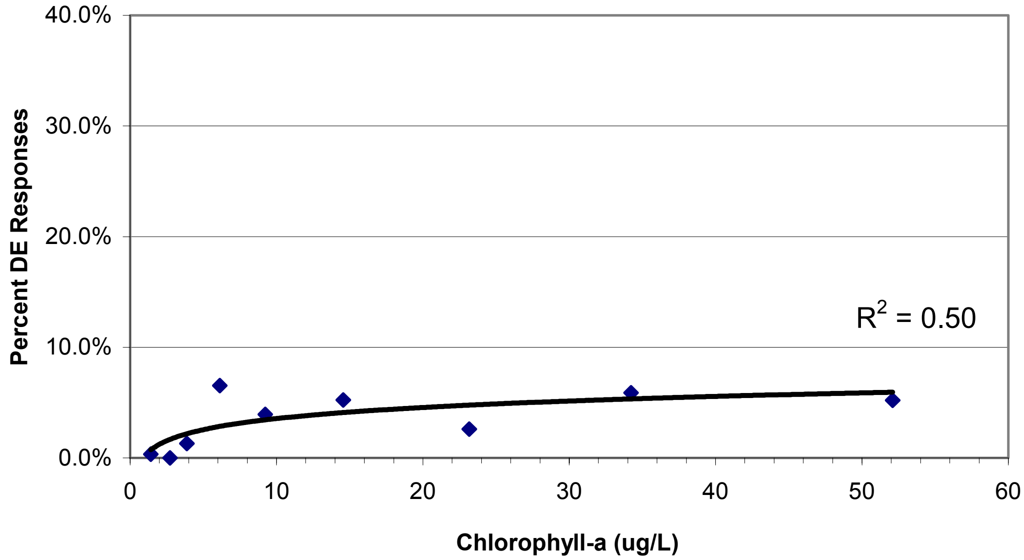
Dr. Walker performed this same evaluation for various subsets of the survey respondents. In addition to all observers at all reservoirs (except Granger), he analyzed the responses of the following groups:

- Sampling crews and contact users
- Non-contact users
- Sampling crews and contact users at high and moderate clarity reservoirs

The results of these evaluations are presented in his report (Appendix D) on Figure 14.

<u>Third Evaluation</u>

For the third evaluation, data subsets were prepared wherein all “a” responses for use suitability were placed in a subset: “b” responses were each placed in a subset; and, similarly, “c,” “d,” and “e” responses were placed in a subset. Then, the average chlorophyll-*a* concentration of each subset was computed. The results are presented on Figure IV-9. As shown on this figure, for the larger dataset representing seven reservoirs, there is a relationship between chlorophyll-*a* concentrations and perceived use impairment. A similar evaluation was performed for the survey question that addressed the amount of greenness perceived. The results of that evaluation are also shown on Figure IV-9. Here, too, there is a relationship between the amount of greenness perceived and chlorophyll-*a* concentrations.



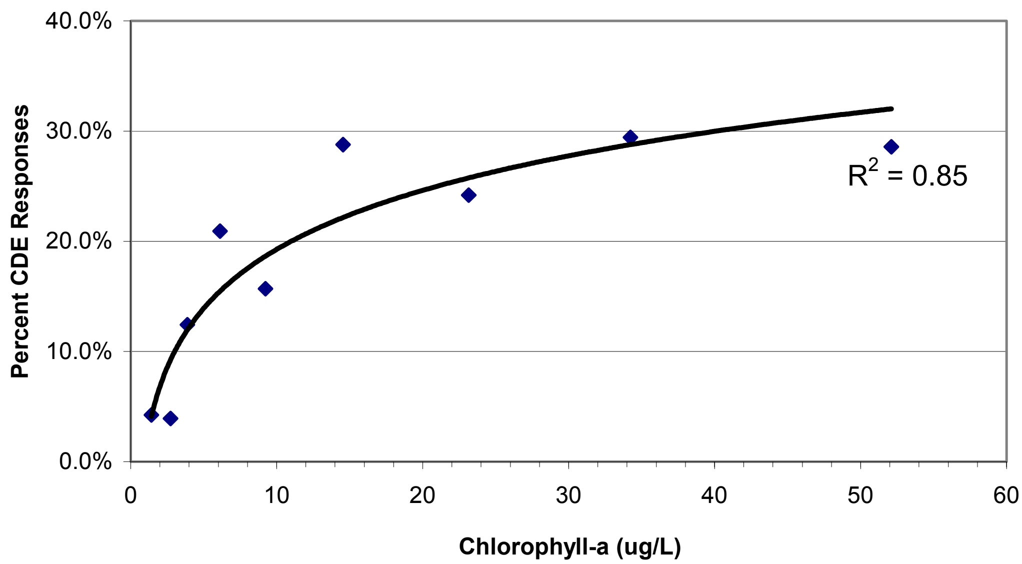
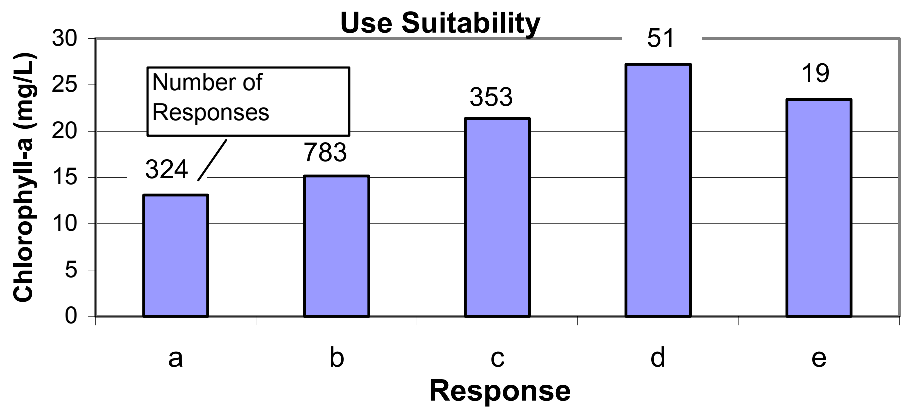


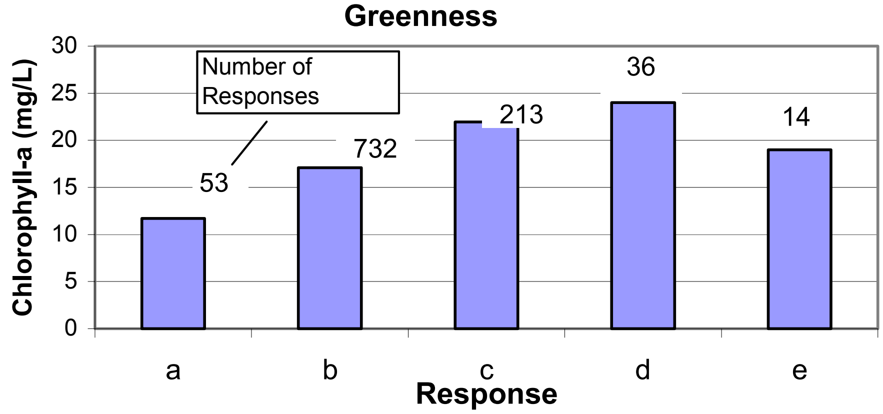
FIGURE IV-8
FREQUENCY OF RESPONSE OF USE IMPAIRMENT VERSUS CHLOROPHYLL-a CONCENTRATION COMPARISON BASED ON CONCENTRATIONS

(Each data point represents a concentration interval)



Use Suitability

a - beautiful, could not be any nicer
b - very minor aesthetic problems
c - swimming and aesthetic enjoyment slightly impaired
d - desire to swim and level of enjoyment of the lake substantially reduced
e - swimming and aesthetic enjoyment of the lake nearly impossible



Greenness

a - no algae, or crystal clear water
b - a little algae visible
c - definite algal visible
d - very green, some scum present and/or mild odor apparent
e - pea-soup green with one or more of the following: massive floating scums on lake or washed up on shore, strong foul oder, or fish kill

FIGURE IV-9

AVERAGE CHLOROPHYLL-*A* CONCENTRATION FOR EACH CATEGORY OF USE SUITABILITY AND GREENNESS ALL DATA POOLED

OTHER FINDINGS

In addition to providing information regarding relationships between users' perceptions of decreased desirability for recreational use and algal density, the study provided information regarding what parameters would be most functional as a water quality standard. The findings of the study in this regard are as follows:

- A standard based on the seasonal mean chlorophyll concentration will also be effective in controlling seasonal maximum chlorophyll concentrations.
- When data for all the reservoirs except Granger Lake are grouped, chlorophyll concentration is a better measure of the potential for recreational use impairment due to nutrients than transparency (measured as Secchi disc depth).

The evaluations on which these findings are based are set forth below:

Relationship Between Chlorophyll Seasonal Maximums and Seasonal Means

In other states where chlorophyll criteria have been established, they are typically expressed as seasonal mean values. Previous research[1,2,3] has shown that a log-normal (ln) distribution model can be used to predict the frequency of algal blooms based on seasonal mean concentrations. In Figure 5 of Appendix D, Dr. Walker presents the relationships for bloom frequency and seasonal mean concentrations for the reservoirs sampled in this study. Figure 5 also includes a plot of the standard deviation versus the seasonal mean chlorophyll concentration. The standard deviation is 0.39 for ln–transformed values, which is in the range found for data for other reservoirs.

Similarly, there is a strong relationship between the seasonal maximum concentration and the seasonal mean concentration of chlorophyll. This relationship for the reservoirs in this study is shown on Figure IV-10. Therefore, although users respond to the frequency of algal blooms rather than an average seasonal concentration, a seasonal mean criterion is a reasonable surrogate for a bloom frequency criterion, and it provides control for extreme conditions. The seasonal mean is a more useful parameter for a standard because the seasonal mean can be measured more precisely than bloom frequencies with a typical monitoring plan.

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[1] Walker, W.W., "Statistical Bases for Mean Chlorophyll-a Criteria," in "Lake and Reservoir Management – Practical Applications," Proc. 4th Annual Conference, North American Lake Management Society, McAfee, New Jersey, pp 57-62, October 1984. http://www.wwwalker.net/pdf/chlacrit85.pdf

[2] Walker,W.W., "Experience in Developing Phosphorus TMDLs for Lakes," presented at "Enhancing States Lake Management Programs," 16th Annual National Conference, North American Lake Management Society, Chicago, April 2003a. http://www.wwwalker.net/pdf/nalms_Chicago_2003.pdf

[3] Walker, W.W., "Consideration of Variability and Uncertainty in Phosphorus TMDLs for Lakes," Journal of Water Resources Planning and Management, American Society of Civil Engineers, Vol. 129, No. 4, July 2003b. http://www.wwwalker.net/index.htm#tmdl_reports

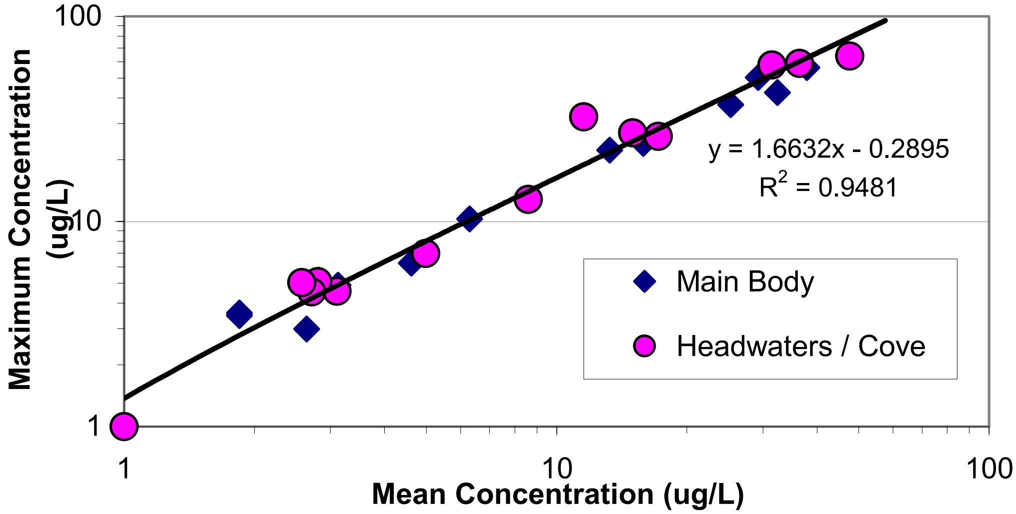

FIGURE IV-10
RELATIONSHIP BETWEEN CHLOROPHYLL-*A* SEASONAL MAXIMUM AND SEASONAL MEAN CONCENTRATIONS

(Each data point represents a reservoir and a specific year)

Selection of Chlorophyll as Parameter for Standard

In EPA guidance documents on developing nutrient criteria, transparency is suggested as a possible water quality standard parameter. The data from this study were evaluated to determine whether Secchi disc depth or chlorophyll would provide the best correlation to impacts on recreational use due to algal growth.

In Figure IV-7, the relationship between the mean chlorophyll-a concentration in each reservoir and the percent of responses represented by the sum of the "c," "d," and "e" responses for that reservoir is presented. A similar analysis was conducted, which compared the average Secchi disc depth for each reservoir to the percent of "c," and "d," and "e" responses for that reservoir. The results of that evaluation are presented on Figure IV-11. The coefficient of determination (R^2) for the relationship with chlorophyll-*a* is 0.90, and the coefficient of determination for the relationship with Secchi disc depth is 0.66. There is a stronger correlation with chlorophyll than with transparency; so, chlorophyll is a better choice for a standard.

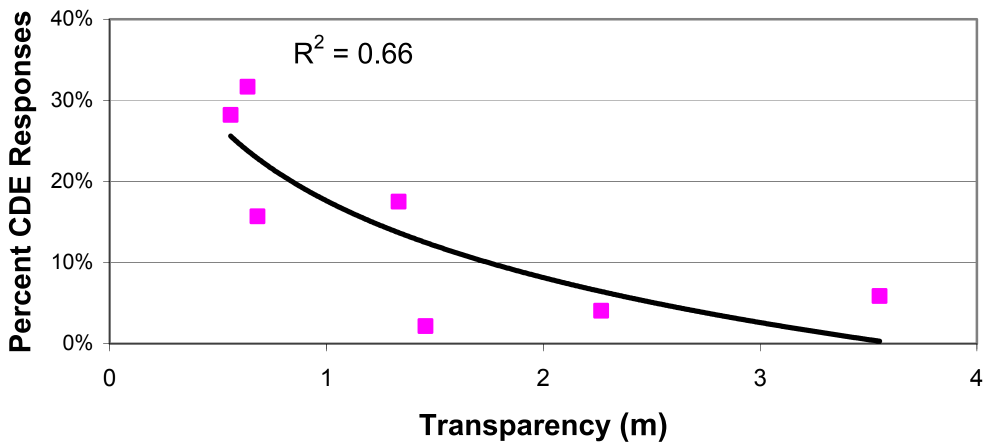

FIGURE IV-11

FREQUENCY OF RESPONSE OF USE IMPAIRMENT VERSUS TRANSPARENCY COMPARISON BETWEEN RESERVOIRS

(Each data point represents a reservoir)

CHAPTER V

STUDY CONCLUSIONS

In association with water quality monitoring, a total of 794 user surveys were conducted in 2003 and 1,010, in 2004 on eight reservoirs across the state. Evaluations of water quality data and user surveys resulted in the following conclusions:

- Lake Granger had high inorganic suspended solids (>10 mg/L), and algal growth was inhibited. Therefore, it was deleted from most data evaluations.
- When all reservoirs but Lake Granger were grouped, a significant relationship ($P<0.05$) was found between Secchi depth and degree of user satisfaction (Figure IV-11) while a significant negative relationship ($P<0.001$) was found between chlorophyll-*a* concentration and degree of user satisfaction (Figure IV-7).
- At all reservoirs the cove sites had higher mean chlorophyll-*a* concentrations than the main body (Figure II-5).
- This study found good agreement with historical chlorophyll-*a* data from the TCEQ database for most of the study reservoirs.
- Pheophytin concentrations were found to be small in relation to chlorophyll-*a* and not necessary for inclusion when doing data analysis.
- Field filtration, freezing and one-day shipping of chlorophyll-*a* samples to a common laboratory produced a dataset with a coefficient of variation of 0.41, which is lower than most other datasets of this nature.
- Reservoir users appear “acclimated” to the conditions of each reservoir, such that use suitability is related to the typical chlorophyll-*a* concentration for that reservoir. This may explain why there is a not a larger disparity in users’ opinions between Lake Travis at 4 µg /L and Cedar Creek at 35 µg/L.
- The mean chlorophyll-a concentration for users selecting “d” (desire to swim and level of enjoyment of the lake is substantially reduced) is 27.2 µg/L (Fig IV-9).
- Seasonal maximum chlorophyll-*a* averages 1.66 times seasonal mean chlorophyll-*a* (R^2=0.95, Fig IV-10).
- The data from the seven reservoirs evaluated (Canyon Lake, Cedar Creek Reservoir, Lake Bridgeport, Lake Fork, Lake Georgetown, Lake Livingston, and Lake Travis) fit the log normal distribution models used elsewhere in the country for relating the summer mean concentration of chlorophyll-*a* to the frequency of a bloom concentration.
- Based upon the bloom-frequency models, a bloom of 30 µg/L is expected more than 25% of the time with a mean growing season concentration of 24 µg/L or greater. If a bloom is defined as 40 µg/L, then the mean reservoir concentration increases to 31 µg/L. (means visually identified on Walker’s Figure 5 in Appendix D).

- Samplers (trained scientists) were more likely to identify use impairment than the public, but the level of chlorophyll-a that defined this impairment differs from reservoir to reservoir.

- Contact users and non-contact users did not show a great difference in opinions on use impairment.

- Little difference was apparent between frequent and infrequent visitors of the reservoir.

APPENDIX A

SAMPLING SITE LOCATIONS

RESERVOIR	SURFACE AREA (AREA)	VOLUME (ACRE FEET)	WATERSHED AREA (SQUARE MILES)
CANYON	8230	378781	1432

FIGURE A–1
CANYON LAKE
MONITORING LOCATIONS

A–1

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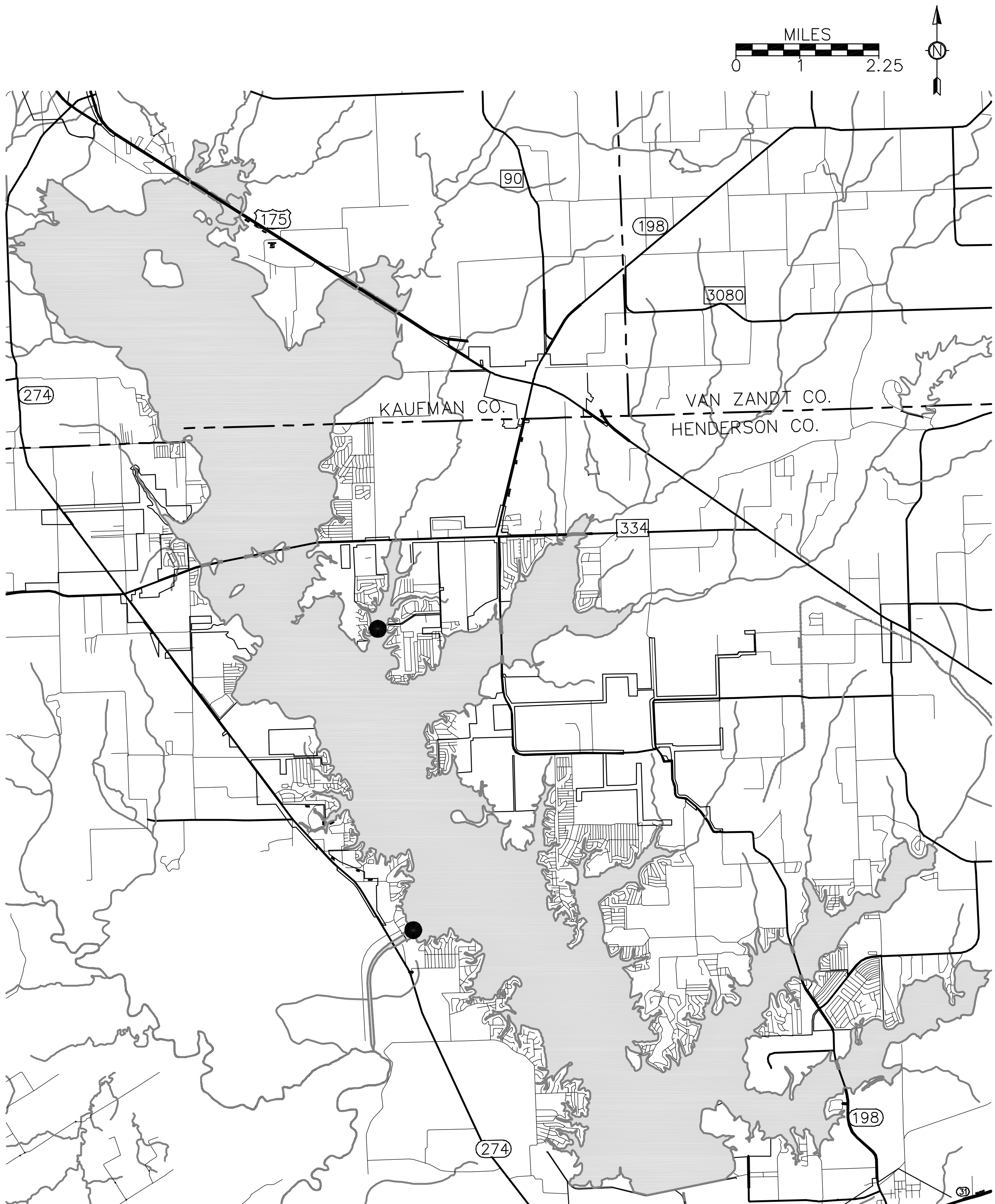


RESERVOIR	SURFACE AREA (AREA)	VOLUME (ACRE FEET)	WATERSHED AREA (SQUARE MILES)
CEDAR CREEK	32623	637180	1007

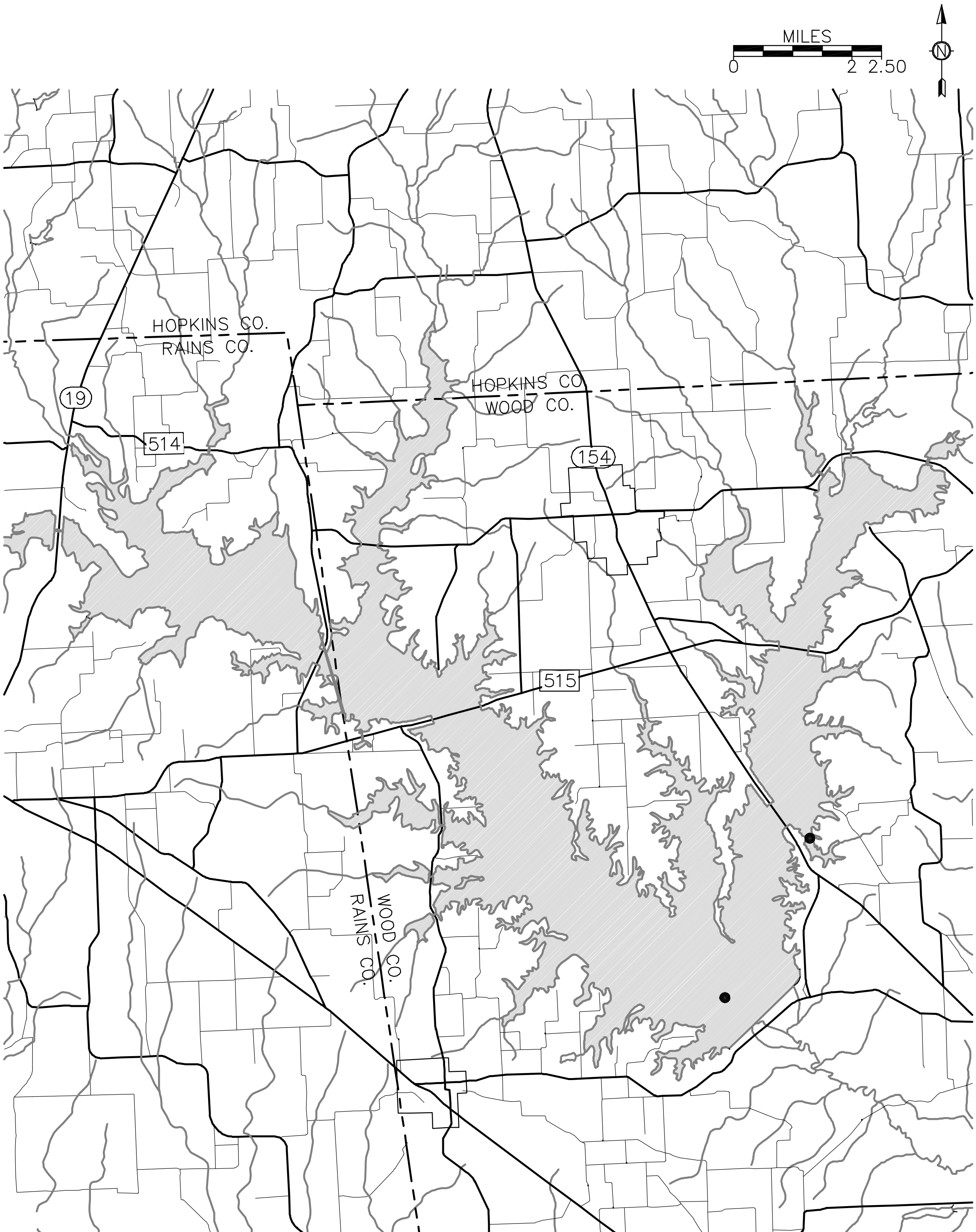
FIGURE A–2
CEDAR CREEK RESERVOIR
MONITORING LOCATIONS

RESERVOIR	SURFACE AREA (AREA)	VOLUME (ACRE FEET)	WATERSHED AREA (SQUARE MILES)
GRANGER	4009	54280	730

FIGURE A–3
GRANGER LAKE
MONITORING LOCATIONS

RESERVOIR	SURFACE AREA (AREA)	VOLUME (ACRE FEET)	WATERSHED AREA (SQUARE MILES)
BRIDGEPORT	11649	366236	1111

FIGURE A–4
LAKE BRIDGEPORT
MONITORING LOCATIONS



RESERVOIR	SURFACE AREA (AREA)	VOLUME (ACRE FEET)	WATERSHED AREA (SQUARE MILES)
FORK	27690	604927	493

FIGURE A-5
LAKE FORK RESERVOIR
MONITORING LOCATIONS

RESERVOIR	SURFACE AREA (AREA)	VOLUME (ACRE FEET)	WATERSHED AREA (SQUARE MILES)
GEORGETOWN	1297	37010	247

FIGURE A–6
LAKE GEORGETOWN
MONITORING LOCATIONS

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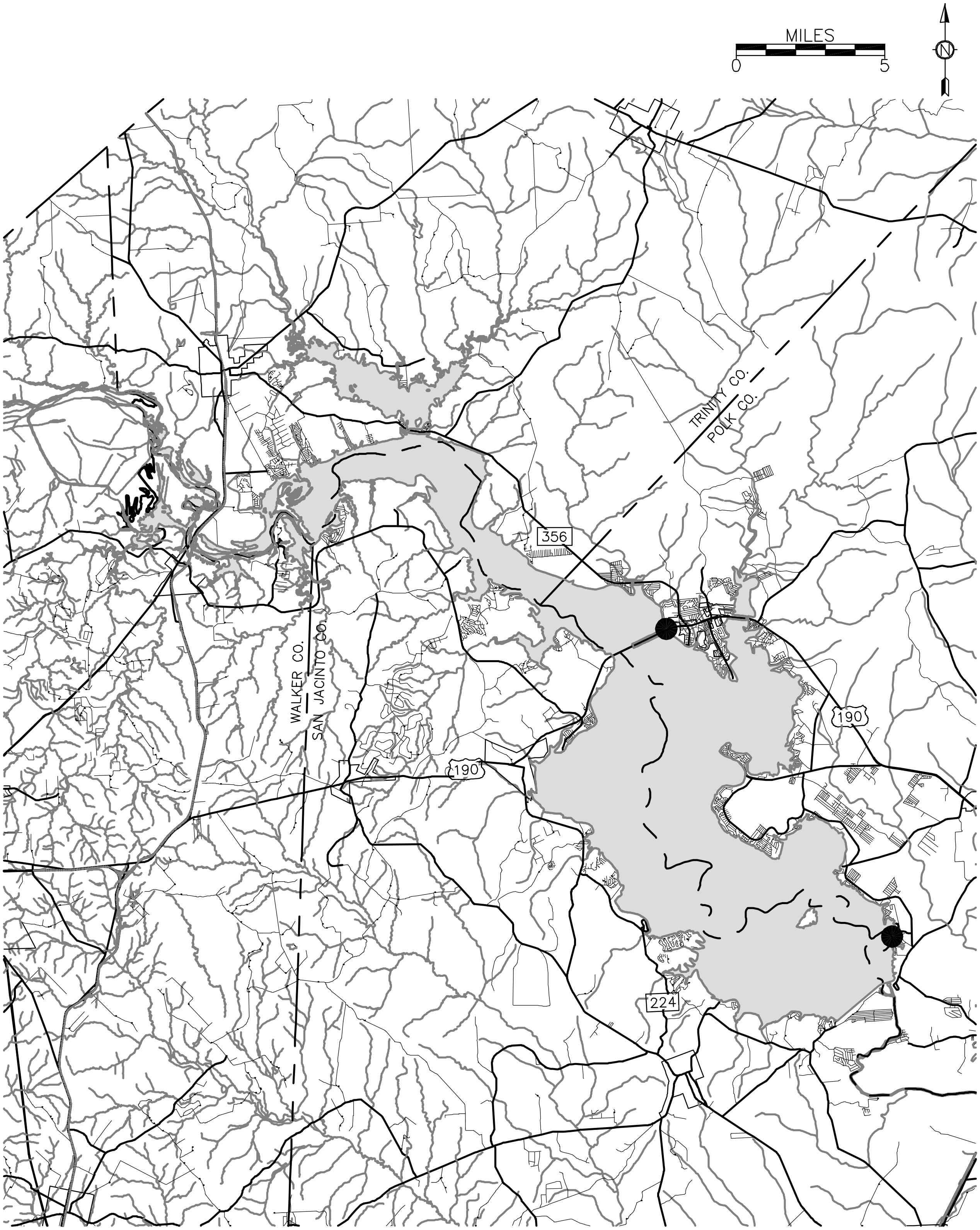

RESERVOIR	SURFACE AREA (AREA)	VOLUME (ACRE FEET)	WATERSHED AREA (SQUARE MILES)
LIVINGSON	83277	1741867	16616

FIGURE A-7
LAKE LIVINGSTON
MONITORING LOCATIONS

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RESERVOIR	SURFACE AREA (AREA)	VOLUME (ACRE FEET)	WATERSHED AREA (SQUARE MILES)
TRAVIS	18622	1131650	26230

FIGURE A–8
LAKE TRAVIS
MONITORING LOCATIONS

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APPENDIX B

RECREATIONAL USER SURVEY FORM

Recreational User Survey

Reservoir ____________________________ **Date** _________________

Site _________________________________ **Time** ________________

Thank you for participating in our survey of lake users. Your answers will help us to determine the impacts of algae at this location on your recreational enjoyment of the lake today.

1) Please circle the **one** response that best describes the **physical condition** of the lake water **today**:

   1) No algae, or crystal clear water
   2) A little algae visible
   3) Definite algal greenness
   4) Very green; some scum present and/or mild odor apparent
   5) Pea-soup green with one or more of the following: massive floating scums on lake or washed up on shore, strong foul odor, or fish kill

2) Please circle the **one** response that best describes your **perception** of how suitable the lake water is for recreation and aesthetic enjoyment **today**:

   1) Beautiful, could not be any nicer
   2) Very minor aesthetic problems; excellent for swimming, boating enjoyment
   3) Swimming and aesthetic enjoyment slightly impaired
   4) Desire to swim and level of enjoyment of the lake substantially reduced
   5) Swimming and aesthetic enjoyment of the lake nearly impossible

3) If you circled c, d, or e in Question No. 2 above, please indicate the factor that most affected your answer:

   1) Muddiness
   2) Algae/greenness
   3) Other (please specify) ____

4) How many times a year do you visit the lake? (Circle one response)

   1) Permanent resident
   2) More than six times per year
   3) Two to six times per year
   4) Typically every year
   5) This is my first visit

5) Please circle the activity that best describes your primary recreational activity **today**:

   1) Swimming
   2) Fishing
   3) Boating
   4) Skiing/Windsurfing
   5) On-Shore Activity (camping, picnicking, etc.)
   6) Other or non-recreational (Please specify)

   ____

Survey Distributed by _______________________ **Survey Code No.** _________

APPENDIX C

WATER QUALITY DATA

Appendix C
Water Quality Data Summary

Chlorophyll

Station	Count	Min	Max	Avg	Median
	Parameter Value				
Canyon Lake, Main Body	15	1.40	5.19	2.96	3.08
Canyon Lake, Cove	16	0.50	6.97	3.76	3.50
Cedar Creek Reservoir, Main Body	20	13.00	56.20	32.70	38.30
Cedar Creek Reservoir, Cove	20	10.20	64.00	37.96	39.20
Granger Lake, Main Body	17	1.00	25.10	8.15	7.45
Granger Lake, Cove	18	1.00	36.30	9.17	6.19
Lake Bridgeport, Main Body	17	2.59	10.30	5.51	5.33
Lake Bridgeport, Cove	17	5.20	32.40	9.98	8.26
Lake Fork Reservoir, Main Body	19	5.00	24.00	14.21	14.00
Lake Fork Reservoir, Cove	19	7.00	27.00	16.37	15.20
Lake Georgetown, Main Body	16	1.00	3.58	1.58	1.00
Lake Georgetown, Cove	17	1.00	4.53	2.11	2.19
Lake Livingston, Main Body	20	7.80	42.60	28.11	28.45
Lake Livingston, Cove	18	20.70	115.00	45.84	38.40
Lake Travis, Main Body	19	1.00	3.48	2.14	2.50
Lake Travis, Cove	20	1.00	5.04	2.79	2.59

Chlorophyll-a + Pheophytin, calculated

Station	Count	Min	Max	Avg	Median
	Parameter Value				
Canyon Lake, Main Body	15	2.81	6.69	4.25	4.37
Canyon Lake, Cove	16	2.00	7.97	5.11	5.07
Cedar Creek Reservoir, Main Body	20	16.21	67.70	40.79	44.72
Cedar Creek Reservoir, Cove	20	17.22	73.52	46.03	48.54
Granger Lake, Main Body	17	2.00	26.10	9.93	8.45
Granger Lake, Cove	18	2.00	37.30	10.89	8.18
Lake Bridgeport, Main Body	17	3.62	12.80	6.82	6.33
Lake Bridgeport, Cove	17	6.20	36.95	11.94	10.10
Lake Fork Reservoir, Main Body	19	6.00	28.00	16.34	16.00
Lake Fork Reservoir, Cove	19	2.00	28.35	17.64	19.00
Lake Georgetown, Main Body	16	2.00	7.15	2.82	2.00
Lake Georgetown, Cove	17	2.00	7.15	3.26	3.19
Lake Livingston, Main Body	20	13.21	62.50	34.06	33.79
Lake Livingston, Cove	18	24.28	130.60	53.68	45.99
Lake Travis, Main Body	19	2.00	5.00	3.38	3.57
Lake Travis, Cove	20	2.00	7.07	4.09	4.54

Appendix C (cont.)
Water Quality Data Summary

Conductivity

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Canyon Lake, Main Body	34	362.00	526.00	407.12	402.00
Canyon Lake, Cove	34	358.00	526.00	404.85	399.00
Cedar Creek Reservoir, Main Body	57	165.80	230.00	202.18	204.00
Cedar Creek Reservoir, Cove	57	166.00	234.00	201.85	203.50
Granger Lake, Main Body	73	242.90	401.90	342.45	344.90
Granger Lake, Cove	73	239.60	633.50	343.07	346.90
Lake Bridgeport, Main Body	60	301.10	363.80	331.93	339.50
Lake Bridgeport, Cove	54	128.00	361.60	298.37	307.00
Lake Fork Reservoir, Main Body	56	151.00	172.00	160.57	160.50
Lake Fork Reservoir, Cove	57	114.00	175.00	161.82	164.00
Lake Georgetown, Main Body	75	246.20	558.00	351.21	357.30
Lake Georgetown, Cove	75	248.50	393.80	356.63	362.80
Lake Livingston, Main Body	57	300.00	507.00	351.19	341.00
Lake Livingston, Cove	57	302.00	541.00	395.54	383.00
Lake Travis, Main Body	60	423.00	476.00	439.15	437.00
Lake Travis, Cove	60	413.00	495.00	441.63	441.50

DO

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Canyon Lake, Main Body	34	6.20	10.50	8.60	8.63
Canyon Lake, Cove	34	6.06	10.30	8.53	8.66
Cedar Creek Reservoir, Main Body	57	4.55	12.73	7.34	7.00
Cedar Creek Reservoir, Cove	57	5.42	10.47	8.18	8.15
Granger Lake, Main Body	73	4.60	8.98	7.04	7.04
Granger Lake, Cove	73	2.04	9.35	6.87	6.83
Lake Bridgeport, Main Body	61	4.60	9.48	7.47	7.24
Lake Bridgeport, Cove	54	4.58	9.19	7.28	7.26
Lake Fork Reservoir, Main Body	56	4.46	9.23	7.39	7.43
Lake Fork Reservoir, Cove	57	3.51	10.11	7.89	8.32
Lake Georgetown, Main Body	75	6.52	10.03	7.41	7.21
Lake Georgetown, Cove	75	6.31	9.54	7.32	7.21
Lake Livingston, Main Body	60	5.05	16.79	10.02	9.87
Lake Livingston, Cove	60	4.90	16.63	8.63	8.01
Lake Travis, Main Body	60	6.86	10.50	8.18	8.06
Lake Travis, Cove	60	6.50	10.80	8.26	8.25

Appendix C (cont.)
Water Quality Data Summary

Nitrate, as Nitrogen

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Granger Lake, Main Body	12	0.01	1.22	0.42	0.44
Granger Lake, Cove	13	0.01	1.13	0.36	0.35
Lake Fork Reservoir, Main Body	18	0.01	0.01	0.01	0.01
Lake Fork Reservoir, Cove	18	0.01	0.01	0.01	0.01
Lake Georgetown, Main Body	13	0.01	0.01	0.01	0.01
Lake Georgetown, Cove	13	0.01	0.01	0.01	0.01

Nitrite, as Nitrogen

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Granger Lake, Main Body	12	0.01	0.01	0.01	0.01
Granger Lake, Cove	13	0.01	0.01	0.01	0.01
Lake Fork Reservoir, Main Body	18	0.01	0.01	0.01	0.01
Lake Fork Reservoir, Cove	18	0.01	0.01	0.01	0.01
Lake Georgetown, Main Body	12	0.01	0.01	0.01	0.01
Lake Georgetown, Cove	13	0.01	0.01	0.01	0.01

NO2/NO3

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Canyon Lake, Main Body	15	0.01	0.39	0.13	0.15
Canyon Lake, Cove	16	0.01	0.29	0.13	0.12
Cedar Creek Reservoir, Main Body	20	0.00	0.14	0.02	0.01
Cedar Creek Reservoir, Cove	20	0.00	0.06	0.01	0.01
Lake Bridgeport, Main Body	17	0.00	0.04	0.01	0.01
Lake Bridgeport, Cove	17	0.00	0.06	0.02	0.01
Lake Fork Reservoir, Main Body	19	0.01	0.02	0.01	0.02
Lake Fork Reservoir, Cove	19	0.01	0.02	0.01	0.02
Lake Livingston, Main Body	19	0.01	0.85	0.17	0.04
Lake Livingston, Cove	18	0.01	2.04	0.37	0.28
Lake Travis, Main Body	19	0.01	0.08	0.02	0.01
Lake Travis, Cove	20	0.01	0.07	0.01	0.01

Appendix C (cont.)
Water Quality Data Summary

pH

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Canyon Lake, Main Body	34	7.41	8.34	8.15	8.17
Canyon Lake, Cove	34	7.48	8.37	8.13	8.14
Cedar Creek Reservoir, Main Body	57	7.68	9.15	8.23	8.13
Cedar Creek Reservoir, Cove	57	7.99	9.34	8.66	8.66
Granger Lake, Main Body	70	7.36	8.44	8.08	8.14
Granger Lake, Cove	70	7.13	8.46	8.06	8.17
Lake Bridgeport, Main Body	60	7.69	8.60	8.09	8.13
Lake Bridgeport, Cove	54	7.26	8.69	8.13	8.14
Lake Fork Reservoir, Main Body	56	6.92	9.00	7.58	7.49
Lake Fork Reservoir, Cove	57	6.84	9.02	7.85	7.78
Lake Georgetown, Main Body	72	7.19	8.39	8.11	8.17
Lake Georgetown, Cove	72	7.47	8.37	8.11	8.15
Lake Livingston, Main Body	60	7.74	9.06	8.49	8.48
Lake Livingston, Cove	60	7.35	9.59	8.37	8.33
Lake Travis, Main Body	60	8.20	8.67	8.41	8.42
Lake Travis, Cove	60	7.90	8.60	8.33	8.37

Pheophytin

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Canyon Lake, Main Body	15	0.73	3.35	1.29	1.00
Canyon Lake, Cove	16	0.73	4.91	1.35	1.00
Cedar Creek Reservoir, Main Body	20	1.00	17.30	8.09	7.62
Cedar Creek Reservoir, Cove	20	3.65	16.60	8.07	8.35
Granger Lake, Main Body	17	1.00	4.81	1.78	1.00
Granger Lake, Cove	18	0.50	5.43	1.72	1.00
Lake Bridgeport, Main Body	17	1.00	2.50	1.31	1.00
Lake Bridgeport, Cove	17	1.00	4.55	1.96	1.71
Lake Fork Reservoir, Main Body	19	1.00	4.00	2.13	2.22
Lake Fork Reservoir, Cove	19	1.00	5.75	2.59	2.37
Lake Georgetown, Main Body	16	1.00	3.58	1.23	1.00
Lake Georgetown, Cove	17	1.00	3.58	1.15	1.00
Lake Livingston, Main Body	20	1.00	29.90	5.95	5.21
Lake Livingston, Cove	18	1.00	17.60	7.84	6.97
Lake Travis, Main Body	19	1.00	2.50	1.24	1.00
Lake Travis, Cove	20	1.00	2.50	1.30	1.00

Appendix C (cont.)
Water Quality Data Summary

TKN

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Canyon Lake, Main Body	14	0.28	1.02	0.55	0.50
Canyon Lake, Cove	15	0.17	2.70	0.60	0.50
Cedar Creek Reservoir, Main Body	20	0.77	1.81	1.13	1.05
Cedar Creek Reservoir, Cove	20	0.87	2.14	1.36	1.35
Granger Lake, Main Body	9	0.10	1.20	0.42	0.26
Granger Lake, Cove	10	0.10	1.38	0.41	0.27
Lake Bridgeport, Main Body	17	0.33	1.25	0.71	0.66
Lake Bridgeport, Cove	17	0.32	1.58	0.80	0.80
Lake Fork Reservoir, Main Body	13	0.29	1.58	0.95	0.86
Lake Fork Reservoir, Cove	13	0.22	1.39	0.91	0.84
Lake Georgetown, Main Body	11	0.10	0.90	0.31	0.24
Lake Georgetown, Cove	10	0.10	0.82	0.37	0.29
Lake Livingston, Main Body	20	0.50	2.50	1.01	0.85
Lake Livingston, Cove	18	0.60	2.10	1.14	0.95
Lake Travis, Main Body	19	0.18	0.95	0.34	0.32
Lake Travis, Cove	20	0.21	0.52	0.34	0.32

TP

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Canyon Lake, Main Body	15	0.02	0.19	0.05	0.04
Canyon Lake, Cove	16	0.02	0.07	0.04	0.04
Cedar Creek Reservoir, Main Body	20	0.04	0.14	0.08	0.09
Cedar Creek Reservoir, Cove	20	0.01	0.14	0.11	0.11
Granger Lake, Main Body	8	0.03	1.17	0.23	0.12
Granger Lake, Cove	10	0.03	1.29	0.27	0.16
Lake Bridgeport, Main Body	17	0.02	0.07	0.03	0.03
Lake Bridgeport, Cove	17	0.02	0.12	0.05	0.05
Lake Fork Reservoir, Main Body	13	0.02	0.14	0.04	0.03
Lake Fork Reservoir, Cove	14	0.03	0.13	0.06	0.05
Lake Georgetown, Main Body	11	0.03	0.64	0.19	0.12
Lake Georgetown, Cove	9	0.03	0.56	0.20	0.15
Lake Livingston, Main Body	20	0.10	0.64	0.19	0.16
Lake Livingston, Cove	18	0.18	0.72	0.30	0.24
Lake Travis, Main Body	19	0.01	0.01	0.01	0.01
Lake Travis, Cove	20	0.01	0.02	0.01	0.01

Appendix C (cont.)
Water Quality Data Summary

Transparency

Station	Count	Min	Max	Avg	Median
	Parameter Value				
Canyon Lake, Main Body	12	1.25	3.30	2.42	2.35
Canyon Lake, Cove	13	1.00	2.40	1.74	1.85
Cedar Creek Reservoir, Main Body	18	0.51	1.07	0.76	0.75
Cedar Creek Reservoir, Cove	18	0.30	0.66	0.52	0.51
Granger Lake, Main Body	18	0.25	0.98	0.49	0.48
Granger Lake, Cove	19	0.10	0.50	0.33	0.32
Lake Bridgeport, Main Body	17	0.89	1.85	1.43	1.42
Lake Bridgeport, Cove	17	0.20	1.73	0.90	0.67
Lake Fork Reservoir, Main Body	19	1.18	2.54	1.79	1.68
Lake Fork Reservoir, Cove	19	0.79	1.69	1.19	1.25
Lake Georgetown, Main Body	20	0.34	3.22	2.18	2.34
Lake Georgetown, Cove	19	0.91	3.68	1.52	1.22
Lake Livingston, Main Body	20	0.70	1.20	0.92	0.93
Lake Livingston, Cove	18	0.10	0.50	0.35	0.38
Lake Travis, Main Body	20	2.00	5.00	3.22	3.39
Lake Travis, Cove	20	1.80	4.60	2.83	2.64

TSS

Station	Count	Min	Max	Avg	Median
	Parameter Value				
Canyon Lake, Main Body	15	0.50	5.00	2.39	2.40
Canyon Lake, Cove	16	1.50	6.00	3.43	3.05
Cedar Creek Reservoir, Main Body	20	4.40	11.10	7.45	7.30
Cedar Creek Reservoir, Cove	20	7.60	20.60	13.79	13.60
Granger Lake, Main Body	12	2.00	24.20	14.60	15.00
Granger Lake, Cove	13	12.00	56.00	34.48	30.00
Lake Bridgeport, Main Body	17	2.00	9.00	4.94	5.75
Lake Bridgeport, Cove	17	2.00	31.00	11.19	13.25
Lake Fork Reservoir, Main Body	19	0.50	4.00	2.18	2.00
Lake Fork Reservoir, Cove	19	1.50	7.00	4.14	4.00
Lake Georgetown, Main Body	14	2.00	11.00	3.60	2.00
Lake Georgetown, Cove	13	2.00	12.00	4.86	2.00
Lake Livingston, Main Body	20	5.00	10.00	7.62	7.70
Lake Livingston, Cove	18	14.60	39.20	23.82	24.60
Lake Travis, Main Body	19	0.50	3.00	1.29	0.50
Lake Travis, Cove	20	0.50	4.00	1.78	2.00

Turbidity, field

Station	Count	Min	Max	Avg	Median
	Parameter Value				
Cedar Creek Reservoir, Main Body	15	5.06	10.60	6.81	6.36
Cedar Creek Reservoir, Cove	15	7.48	15.30	11.90	12.90
Lake Bridgeport, Main Body	17	3.10	12.30	6.30	5.82
Lake Bridgeport, Cove	17	2.80	62.70	16.53	15.75

Appendix C (cont.)
Water Quality Data Summary

Turbidity, lab

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Canyon Lake, Main Body	13	0.16	4.74	2.03	2.08
Canyon Lake, Cove	15	0.50	5.22	3.20	3.20
Granger Lake, Main Body	14	0.06	21.30	9.58	8.48
Granger Lake, Cove	15	4.61	47.70	16.31	9.54
Lake Fork Reservoir, Main Body	18	1.57	2.83	2.11	2.19
Lake Fork Reservoir, Cove	18	2.30	9.25	4.28	3.78
Lake Georgetown, Main Body	16	0.69	9.62	1.62	0.91
Lake Georgetown, Cove	15	0.66	6.22	2.48	1.86
Lake Livingston, Main Body	20	3.72	9.40	5.74	5.22
Lake Livingston, Cove	18	10.40	85.70	26.09	23.10
Lake Travis, Main Body	7	1.00	1.60	1.29	1.25
Lake Travis, Cove	8	1.20	2.40	1.55	1.40

VSS

Station	Parameter Value				
	Count	Min	Max	Avg	Median
Canyon Lake, Main Body	15	0.50	2.80	1.31	1.40
Canyon Lake, Cove	16	0.50	3.10	1.67	1.55
Cedar Creek Reservoir, Main Body	20	2.00	6.70	3.87	4.50
Cedar Creek Reservoir, Cove	20	2.00	8.50	6.01	6.30
Granger Lake, Main Body	15	1.20	5.00	3.26	3.60
Granger Lake, Cove	15	1.60	13.50	6.71	6.60
Lake Bridgeport, Main Body	17	2.00	2.00	2.00	2.00
Lake Bridgeport, Cove	17	2.00	7.60	2.68	2.00
Lake Fork Reservoir, Main Body	18	0.50	4.00	2.19	2.00
Lake Fork Reservoir, Cove	14	1.50	5.00	3.03	3.00
Lake Georgetown, Main Body	15	0.25	2.60	1.35	1.20
Lake Georgetown, Cove	15	0.67	4.00	1.75	1.60
Lake Livingston, Main Body	20	1.80	6.80	4.01	3.90
Lake Livingston, Cove	18	4.60	21.30	8.47	7.45
Lake Travis, Main Body	19	0.50	2.00	0.89	0.50
Lake Travis, Cove	20	0.50	4.00	1.35	0.50

APPENDIX D

DRAFT

INVESTIGATION TO SUPPORT THE DEVELOPMENT OF NUTRIENT CRITERIA BASED UPON RECREATIONAL USES OF RESERVOIRS

EXPLORATORY ANALYSIS OF 2003 AND 2004

PREPARED BY
WILLIAM W. WALKER, JR., PH.D.

Investigation to Support the Development of Nutrient Criteria Based upon Recreational Uses of Reservoirs

Exploratory Analysis of 2003 & 2004 Results

prepared for

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April 13, 2005

Introduction

This report analyzes data collected in a two-year study undertaken by Texas regional water agencies to support the development of nutrient criteria for protecting recreational uses of reservoirs (APA, Inc, et al. 2003, 2004). The study was designed to assess relationships among eutrophication-related water quality conditions, water appearance, and suitability for recreational uses in 8 Texas reservoirs (Figure 1), as gauged by simultaneous water quality sampling and user surveys (Table 1). Similar studies have supported development of regional and lake-specific nutrient criteria in Minnesota, Vermont, Florida, and other states (Heiskary & Walker, 1988; Smeltzer & Heiskary, 1990; Hoyer et al., 2004). These results can be factored into a broader framework for developing regional or reservoir-specific criteria that consider a wider range of potential uses (recreation, fishing, water supply), compliance with numerical water quality standards, and anti-degradation concepts (Figure 2). In turn, water quality models linking chlorophyll-a criteria to watershed nutrient loads can be applied to develop reservoir-specific TMDL's (Walker, 2003b).

There are two primary questions in the survey. Question 1 measures the perception of algae, based upon green color, algal particulates, and/or floating mats. Question 2 measures observers' opinions regarding suitability for recreation (swimming, boating, etc.) and aesthetic enjoyment. Information on several factors that may influence these responses has also been collected, including:

- Chlorophyll-a Concentration
- Site Type (Cove vs. Open lake)
- Optical Characteristics (Turbid vs. Clear)
- Trophic State (Reservoirs with Lower vs. Higher Nutrient Levels)
- Observer Category (Lay Public vs. Sampling Crew)
- Type of Water Use (Swimming, Boating, Fishing, etc.)
- Observer Visit Frequency (Seldom vs. Frequent)
- Season (May-Sept)
- Year (2003 vs. 2004)

Variations and correlations in the survey and water quality data are summarized along each of these dimensions using simple cross-tabulation and graphical techniques. The report updates and expands upon the interim report analyzing the 2003 data (Walker, 2004ab).

Data Compilation & Summary

The study has generated approximately 1800 survey forms paired with 310 sampling events at 16 monitoring sites in 8 reservoirs (APA, Inc, 2003; 2004). To investigate correlations between water quality and simultaneous survey responses, water quality measurements at each station have been averaged by date and subsequently paired with surveys. This involved cross-tabulating and linking several tables in the Access database provided by APA and importing the results into an Excel workbook for subsequent analysis. Corrections and enhancements to the database have been made by APA in response to problems identified in linking the tables and analyzing the data. No attempt has been made in this analysis to screen the data for outliers or analytical problems. These aspects have been handled by APA and study agencies under the QA/QC protocols established for the study. In addition, the frequency-based statistics utilized in this analysis are reasonably robust to outliers.

Multiple responses were frequently given to Question 5 (Table 1), despite the fact that it asked the observer to specify the category that ‘best describes’ the water use. These responses were entered as extra records in the database that did not contain results for the other questions and accounted for 6% of the total records. To support statistical analysis, it is desirable that each record contains a single answer to each question. To accommodate these extra records, the Excel table extracted from the Access database has been modified to include separate “sub-questions’ for each of the potential Question 5 answers (i.e., swimming, boating, fishing, etc..), each with a YES or NO answer. In this way, each record in the modified database contains answers to each question, except for infrequent missing values.

Water quality data are summarized by reservoir and site in Table 2. In computing averages, one half of the detection limit has been used for values reported below that limit. Survey results are summarized in Table 3. Approximately 96% of the survey records were paired with chlorophyll-a measurements. The number of surveys per sampling event averaged 6 and ranged from 4 (Georgetown, Travis, Granger) to 8 (Livingston). Generally, survey frequencies were lower in the more remote reservoirs where the use intensity was lower.

In the analysis below, Question 2 responses are ignored when Question 3 responses indicated that impairment was related to factors other than algae (e.g., muddiness, weather, debris, depth, etc). These cases accounted for about 12% of the survey records.

For consistency with previous analyses of user survey and reservoir data (Heiskary & Walker, 1988; Walker, 1999), chlorophyll-a concentration (excluding pheophytin) is utilized as the primary measure of algal density. Because pheophytin levels were frequently below detection limits (1-5 ppb), the precision of computed total pigment concentration is poor in the less productive reservoirs. Pheophytin accounted for18% of the total pigment concentration on average (Table 2). Sensitivity analyses indicate that basic conclusions regarding correlations between algal density and survey responses are independent of whether chlorophyll-a or the sum of chlorophyll-a and pheophytin is utilized as the measure of algal density.

Transparency/Chlorophyll-a Relationships

It is hypothesized that threshold chlorophyll-a levels for perception of algae and impairment of water uses depend upon the level of non-algal turbidity. Turbidity is generally attributed to inorganic suspended solids originating in the watershed and/or to re-suspended bottom sediments. A portion may also be attributed to dissolved color, organic detritus, or calcium carbonate precipitates that are indirectly related to algal productivity in waters with high alkalinity (e.g. Canyon).

Relationships between transparency and chlorophyll-a within each reservoir are shown in Figure 3. Secchi depths are plotted relative to values predicted from chlorophyll-a using a model developed from Corps of Engineer reservoirs (BATHTUB, Walker, 1999) and assuming two levels of non-algal turbidity (α = 1/Secchi - .025 Chl-a = 0.08 and 2.0 m^{-1}). Most of the data are in this range, which is representative of the Corps reservoirs in general. Samples with $\alpha > 2.0$ m^{-1} are identified with different symbols. Secchi depths could not exceed 0.5 m in these cases, even in the absence of algae, and it is likely that algal productivity is limited by light and/or low nutrient bioavailability (Walker, 1999). This subset includes most of the samples from Lake Granger and a few spring/fall samples from Bridgeport, Livingston, and Cedar Creek. It is possible that the latter reflected storm events or shallow water depths. Granger is distinctly different from the others in that transparency levels are consistently below 0.5 meters and independent of chlorophyll-a. Transparency is highly variable but also insensitive to chlorophyll in reservoirs with consistently low chlorophyll-a levels (e.g. Georgetown, Travis, Canyon). Small variations in non-algal particulates and/or algal species can have a relatively large effect on transparency in these reservoirs.

Figure 4 shows correlations among water quality components that reflect the relative importance of algal vs. inorganic turbidity (transparency vs. chl-a, turbidity vs. chl-a, TSS vs. chl-a, and VSS vs. TSS). Samples with $\alpha > 2$ m^{-1} generally have higher turbidity and TSS concentrations at a given chlorophyll-a level and lower ratios of volatile to suspended solids. Non-algal turbidity computed from chlorophyll-a and transparency is highly correlated with inorganic suspended solids and turbidity.

The extent to which significant relationships among chlorophyll, transparency, water appearance (Question 1) and use impairment (Question 2) can be identified within each reservoir is constrained by limited chlorophyll range and variations in non-algal turbidity. As demonstrated below, pooling of data across reservoirs is necessary to identify threshold chlorophyll-a levels for perception of algae and use impairment. In developing nutrient criteria for Minnesota lakes, data were pooled across lakes within the same ecoregion (Heiskary & Walker, 1988). All samples from Lake Granger and samples from other reservoirs with non-algal turbidity levels > 2 m^{-1} have been excluded in evaluating direct correlations between chlorophyll-a and survey responses across the entire dataset. Screening for turbidity and missing chlorophyll-a values leaves 87% of the survey records available for the analysis.

Temporal Variations in Chlorophyll-a

Chlorophyll-a and nutrient criteria for lakes and reservoirs are typically expressed as seasonal mean values. Survey data and statistical models can be used to derive mean criteria to limit the frequency or risk of algal blooms that impair recreational uses. The frequency of extreme values ("blooms") exceeding thresholds for water use impairment identified in user surveys can be predicted from the seasonal means using a log-normal distribution model (Walker, 1984; 2003ab). Figure 5 shows frequencies of chlorophyll-a concentrations exceeding 10, 20, 30, and 40 ppb predicted from mean values for each site and year site using a log-normal distribution with a coefficient of variation (CV = standard deviation / mean) equal to 0.41, which corresponds to a standard deviation of 0.39 for ln-transformed values. The latter is at the lower end of the 0.40-0.60 range calibrated to other datasets, including lakes in Vermont & Minnesota and Corps of Engineers Reservoirs (Smeltzer et al, 1989). The relatively low CV may be related to the special attention paid in this survey to chlorophyll-a analytical procedures. Figure 5 also shows that seasonal maximum concentration averages 1.69 times the seasonal mean.

Results suggest that a criterion expressed as a seasonal mean would be a reasonable surrogate for one expressed as an instantaneous concentration and for the frequencies of nuisance blooms that are be objectionable to water users. One advantage of expressing criteria as seasonal means is that means be measured more precisely, as compared with bloom frequencies or maximum concentrations. Both means and bloom frequencies can be predicted from external nutrient loads using relatively simple empirical mass-balance models linked with the frequency distribution model calibrated in Figure 2 (Walker, 2003b).

Survey Results vs. Reservoir & Monitoring Site

Water quality data and survey responses are plotted by reservoir in Figure 6 and by monitoring site in Figure 7, sorted in order of increasing mean chlorophyll-a concentration. These summaries utilize all surveys and samples (not screened for turbidity). The eight study reservoirs reflect a wide range of reservoir types, water quality, and water uses. Site mean chlorophyll-a levels range from 2 to 43 ppb, transparencies from 0.4 to 3.1 meters, and non-algal turbidities from 0.3 to 2.7 m^{-1}. These levels reflect a range in trophic state from oligotrophic to hyper-eutrophic. Uses vary from predominantly water contact sports and boating (Georgetown, Travis, Canyon) to predominately fishing (Granger, Fork). Variations in Question 1 and 2 responses across reservoirs and sites reflect variations in both water quality and user

communities. The dataset encompasses a wide range of conditions and uses to support criteria development.

Both the perception of algae (Question 1) and the perception of use impairment (Question 2) were generally higher in the more enriched reservoirs. Excluding Granger, the percent of Question 1 responses in the c,d, or e category was <20% in reservoirs with mean chlorophyll-a levels < 10 ppb, as compared with 30-46% in reservoirs with mean chlorophyll-a levels >10 ppb. Percentages of Question 2 responses indicating some degree of use impact (c, d, or e) in these two reservoir groups were <10% and 15-27%, respectively. The percentage for Granger (35%) probably reflects it's relatively high non-algal turbidity. Based upon Question 5 responses, the percentages of observers engaging in contact sports (swimming, water skiing, wind surfing) were generally lower and the percentages engaged in fishing were higher in the more enriched reservoirs. Based upon Question 4 results, year-round residents tend to account for higher percentage of users in the more enriched reservoirs. This may reflect a tendency for higher-quality reservoirs to attract users from greater distances.

Figure 8 plots survey response frequencies vs. reservoir mean chlorophyll-a and transparency. The top panel shows that the combined percentage of c-d-e responses is more strongly correlated with chlorophyll-a ($r^2 = 0.76$ for Q1, 0.81 for Q2) than with transparency ($r^2 = 0.36$ for Q1, 0.69 for Q2). The middle panel indicates that response frequencies are higher at cove sites vs. main reservoir sites at a given chlorophyll-a level. The middle panel shows that both the %cde and %bcde (>a) responses are correlated with chlorophyll-a. The decline in category "a" responses with increasing chlorophyll-a may be particularly relevant to setting criteria for high-quality reservoirs. Similar relationships are derived below from the pooled data set (all reservoirs combined).

Survey Results vs. Reservoir & User Category

There are indications that responses to Questions 1 and 2 at a given site and date vary systematically with observer category. Responses are summarized by site, reservoir, and observer category in Table 4 and Figure 9. For purposes of this analysis, three mutually-exclusive observer categories have been defined: (1) sampling crew; (2) public engaged in water-contact sports (Question 5: "a" or "d"); and (3) public engaged in other activities. Overall, these categories account for 15%, 30%, and 55% of the survey forms, respectively. Survey forms with multiple responses to Question 5 have been assigned to the water-contact category if at least one of the responses was "a" or "d".

Percentages of c-d-e responses were typically higher for sampling crews and water contact users, as compared with non-contact users in most reservoirs. The higher percentages for the sampling crews are consistent with the concept that sampling crews are trained and more likely to distinguish algae from other water quality and physical factors, are routinely exposed to a wider range of reservoir environments, and are presumably less likely to misunderstand the survey questions. The greater sensitivity of the contact vs. non-contact users is not unexpected, given their more direct exposure to the water and given the fact that the survey was not designed to measure impairment of fishing, which accounts for most of the non-contact use. As

demonstrated below, overall correlations between chlorophyll-a and survey responses are also dependent on user category.

Correlations within Reservoirs

Figure 10 plots mean chlorophyll-a for each reservoir and response category in Questions 1 and 2. Figure 11 plots mean transparency in a similar fashion. Category means are compared within each reservoir and across all reservoirs, sorted in order of increasing reservoir-mean chlorophyll-a. Given the relatively low sample sizes in categories c, d, and e, these categories have been combined to improve the precision of the computed mean.

While responses are positively correlated with chlorophyll-a and negatively correlated with transparency within a few reservoirs, the correlations are much stronger in the combined dataset. Measurement of correlations within reservoirs is difficult in most cases because of the limited range of chlorophyll-a, variations in non-algal turbidity, and relatively low numbers of surveys in some categories within each reservoir (vs. combined dataset). It is also evident that the observers are to some degree "acclimated" to the conditions in each reservoir, so that responses in each category have higher mean chlorophyll-a levels in the more enriched reservoirs. Similar patterns were identified in Vermont and Minnesota surveys (Smeltzer & Heiskary, 1990).

Survey Results vs. Chlorophyll-a Interval

Despite potential difficulties associated with combining the data across reservoirs (primarily related to variations in user communities and user adaptation to site-specific conditions), it is useful to examine associations among survey responses, chlorophyll-a intervals, and other potentially controlling factors using the entire dataset. The data have been partitioned into five groups based upon chlorophyll-a level (< 5, 5-10, 10-20, 20-40, and > 40 ppb and the frequencies of a-e responses computed in each category. A similar cross-tabulation approach was taken in analyzing the Minnesota survey data (Heiskary & Walker, 1988). Results for Questions 1 and 2 are shown in Figures 12 and 13, respectively.

The upper left corner of each figure shows results for all data combined. Consistent with patterns across reservoirs and sites (Figures 6 & 7), perception of algae and use impairment generally increase with chlorophyll-a level up to about 10 ppb and stabilize at higher concentrations, except in certain data subsets. Other dimensions are explored by further partitioning the data into groups based upon each of the following secondary factors:

1. Sampling Crew vs. Other Observers
2. Water Contact vs. Other Observers (Excluding Sampling Crew)
3. Fisherman vs. Other Observers (Excluding Sampling Crew)
4. Visit Frequency: Often >= 6/yr vs. Seldom <= 2/yr (Excluding Sampling Crew)
5. Main Reservoir vs. Cove Sites
6. Season: May-July vs. August-September
7. Trophic State (Oligo-Mesotrophic vs. Hyper-Eutrophic)
8. Non-Algal Turbidity ($<0.5\ m^{-1}$ vs. $\geq 0.5\ m^{-1}$)
9. Survey Year (2003 vs. 2004)

While tests for statistical significance have not been performed in this exploratory analysis, there are indications of higher response frequencies and/or more distinct correlations with chlorophyll-a in categories underlined above. These factors include observer category, site type, trophic state, and non-algal turbidity. There are no apparent influences of visit frequency, season, or year. The consistency of results between the two years indicates that survey results are robust and that the duration of the study has been sufficient to measure observer responses.

Figure 14 shows direct correlations between chlorophyll-a and survey responses in various subsets of the data, defined based upon observer category and trophic state. Each subset has been divided into 10 chlorophyll-a quantiles with approximately equal sample size and the response frequencies have been computed within each quantile. A similar approach was taken in analyzing survey data from Minnesota (Heiskary & Walker, 1988) and Lake Okeechobee (Walker & Havens, 1995). Four subsets are examined:

1. All Data
2. Sampling Crews & Contact Users
3. Non-Contact Users
4. Sampling Crews & Contact Users, Excluding Cedar Creek & Livingston

An effect observer category (2 vs. 3) is again evident. Excluding the two hyper-eutrophic reservoirs further improves the correlation between chlorophyll-a and Question 1 responses. It is possible that users of the enriched reservoirs are accustomed to high chlorophyll-a levels and are less likely to find blooms objectionable, as compared with users of oligotrophic-mesotrophic reservoirs which have higher water quality expectations. Data from the less enriched reservoirs (Subset 4) exhibit a stronger correlation between chlorophyll-a and survey responses. In this subset, the combined percentage of cde responses to Question 1 increases sharply from ~20% at 7 ppb to ~100% at 20 ppb. The percentage of bcde (or > a) responses increases steadily from 50% at 1 ppb to ~ 100 ppb at 10 ppb. There is also evidence of a ~10 ppb threshold for Question 2 responses, but the correlations are less strong.

In subset 4 of Figure 14, the percentage of c,d, or e responses for Question 1 reaches ~80% at a chlorophyll-a level of ~20 ppb, as compared with ~20% for Question 2. The relatively low percentage responses for Question 2 does not necessarily indicate that recreational suitability is in general less sensitive to algae, as compared with perception of algae. That might be true only if the population of potential lake users were randomly sampled in the study. The survey polled actual reservoir users, not random samples of potential users living in the watershed or otherwise nearby. If algal blooms were present, segments of the potential user population that are more discriminating would not have been at the reservoir to begin with. While it would not have been logistically possible to collect true random samples of the potential user population, data limitations resulting from non-random sampling should be considered in interpreting the relatively low percentages of c, d, or e responses for Question 2 in general.

Figure 15 compares survey responses vs. chlorophyll-a interval for two observer categories with results reported by Smeltzer & Heiskary (1990) for Lake Champlain. The chlorophyll-a intervals are identical to those utilized by Smeltzer & Heiskary. Question 1 responses are qualitatively

similar to those observed in Lake Champlain, although the chlorophyll-a thresholds are higher. The %a responses to Question 1 decrease from ~50% to <5% over the 2 to 12 ppb range and the %cde responses increase sharply at 8-12 ppb. While the correlations are less strong, the %a responses to Question 2 decrease from 60% to <5% over the 2 to18 ppb range and the %cde responses increase from <5% to >20% at ~12 ppb.

The apparent threshold chlorophyll-a levels for user response are in the range of values reported in other studies. While these results appear to provide useful information for setting regional criteria, the effects of pooling the data across reservoirs have not been fully determined. Such effects are probably reduced by focusing on data from oligo-mesotrophic reservoirs and more sensitive observer categories (sampling crews, contact water users). Further analysis of the data is recommended, including statistical modeling to test hypotheses regarding the significance of the apparent differences in response across reservoirs and user categories.

References

Alan Plummer Associates, Inc. and Texas Regional Water Authorities, "Investigation to Support the Development of Nutrient Criteria Based on Recreational Uses of Reservoirs, Study Design", July 2003.

Alan Plummer Associates, Inc and Texas Regional Water Authorities, "Investigation to Support the Development of Nutrient Criteria Based on Recreational Uses of Reservoirs, Interim Report, Year 1 of a Two-Year Study", May 2004.

Hoyer, V.M., C.D. Brown, D.E. Canfield, "Relations Between Water Chemistry and Water Quality as Defined by Lake Users in Florida", Lake & Reservoir Management, Vol, 20, No. 3, p 240-248, 2004.

Heiskary, S.A, & W. W. Walker, "Developing Phosphorus Criteria for Minnesota Lakes", Lake and Reservoir Management, Volume 4, No. 1, pp. 1-10, July 1988. http://www.wwwalker.net/pdf/mpca.pdf

Smeltzer, E., W. Walker, & V. Garrison, "Eleven Years of Lake Eutrophication Monitoring in Vermont: A Critical Evaluation", in "Enhancing States' Lake Management Programs", U.S. Environmental Protection Agency and North American Lake Management Society, pp. 53-62, 1989. http://www.wwwalker.net/pdf/11yrs.pdf

Smeltzer, E. & S.A. Heiskary, "Analysis and Applications of Lake User Survey Data", Lake & Reservoir Management, Volume 6, No. 1, pp 109-118, 1990.

Walker, W.W., "Statistical Bases for Mean Chlorophyll-a Criteria", in "Lake and Reservoir Management - Practical Applications", Proc. 4th Annual Conference, North American Lake Management Society, McAfee, New Jersey, pp. 57-62, October 1984. http://www.wwwalker.net/pdf/chlacrit85.pdf

Walker, W.W. & K.E. Havens, "Relating Algal Bloom Frequencies to Phosphorus Concentrations in Lake Okeechobee", Lake & Reservoir Management, Vol. 11, No. 1, pp 77-85, 1995. http://www.wwwalker.net/pdf/chlaokee.pdf

Walker, W.W., "Simplified Procedures for Eutrophication Assessment and Prediction: User Manual", prepared for Headquarters, U.S. Army Corps of Engineers, Instruction Report W-96-2, Waterways Experiment Station, 1999 (updated 2004). http://www.wwwalker.net/index.htm#bathtub

Walker, W.W., “Experience in Developing Phosphorus TMDL’s for Lakes”, presented at “Enhancing States Lake Management Programs”, 16th Annual National Conference, North American Lake Management Society, Chicago, April 2003a. http://www.wwwalker.net/pdf/nalms_chicago_2003.pdf

Walker, W.W., "Consideration of Variability and Uncertainty in Phosphorus TMDLs for Lakes", Journal of Water Resources Planning and Management, American Society of Civil Engineers, Vol. 129, No. 4, July 2003b. http://www.wwwalker.net/index.htm#tmdl_reports

Walker, W.W, “Investigation to Support the Development of Nutrient Criteria Based upon Recreational Uses of Reservoirs, Exploratory Analysis of First Year of Monitoring Data”, prepared for Alan Plummer Associates, Inc., Austin, Texas, April 2004a.

Walker, W.W., “Development of Chlorophyll-a Criteria to Support Recreational Uses of Texas Reservoirs”, presented at “Lakes: Habitat for Fish, Habitat for People”, North American Lake Management Society Symposium, Victoria, British Columbia November 2004b. http://www.wwwalker.net/pdf/nalms_2004.pdf

List of Tables

Recreational User Survey

Reservoir ___________________________ **Date** _________________

Site ________________________________ **Time** ________________

Thank you for participating in our survey of lake users. Your answers will help us to determine the impacts of algae at this location on your recreational enjoyment of the lake today.

1) Please circle the **one** response that best describes the **physical condition** of the lake water **today**:

   a) No algae, or crystal clear water
   b) A little algae visible
   c) Definite algal greenness
   d) High algae levels and/or mild odor apparent
   e) Severely high algae levels with one or more of the following: massive floating scums on lake or washed up on shore, strong foul odor, or fish kill

2) Please circle the **one** response that best describes your **perception** of how suitable the lake water is for recreation and aesthetic enjoyment **today**:

   a) Beautiful, could not be any nicer
   b) Very minor aesthetic problems; excellent for swimming, boating enjoyment
   c) Swimming and aesthetic enjoyment slightly impaired
   d) Desire to swim and level of enjoyment of the lake substantially reduced
   e) Swimming and aesthetic enjoyment of the lake nearly impossible

3) If you circled c, d, or e in Question No. 2 above, please indicate the factor that most affected your answer:

   a) Muddiness
   b) Algae/greenness
   c) Other (please specify) ____

4) How many times a year do you visit the lake? (Circle one response)

   a) Permanent resident
   b) More than six times per year
   c) Two to six times per year
   d) Typically every year
   e) This is my first visit

5) Please circle the activity that best describes your primary recreational activity **today**:

   a) Swimming
   b) Fishing
   c) Boating
   d) Skiing/Windsurfing
   e) On-Shore Activity (camping, picnicking, etc.)
   f) Other or non-recreational (Please specify) ___________________________________

Survey Distributed by ________________________

Survey Code No. _________

Official Use Only

Table 1. Reservoir User Survey.

Reservoir	Site	Dates	Chlorophyll ppb	Pheophytin ppb	Chloro+ Pheo ppb	Std Dev ppb	Maximum ppb	> 10 ppb %	> 20 ppb %	> 30 ppb %	> 40 ppb %	> 60 ppb %	Secchi m	Temp degC	DO ppm	Conductivity uhos	pH -	TP ppm	TKN ppm	NO2N ppm	NO3N ppm	NO23N ppm	Turb_Field ntu	Turb_Lab ntu	TSS ppm	VSS ppm
Bridgeport	Main	20	5.2	1.3	6.5	2.2	12.8	5%	0%	0%	0%	0%	1.28	25.6	7.5	332	8.09	0.039	0.708			0.026	10.78		7.2	2.0
Bridgeport	Cove	20	9.0	1.9	10.8	6.9	37.0	20%	5%	5%	0%	0%	0.79	26.6	7.3	301	8.12	0.075	0.849			0.038	33.52		16.6	2.8
Bridgeport	All	40	7.1	1.6	8.7	5.5	37.0	13%	3%	3%	0%	0%	1.03	26.1	7.4	316	8.10	0.057	0.779			0.032	22.15		11.9	2.4
Canyon	Main	18	3.3	1.2	4.5	1.4	7.3	0%	0%	0%	0%	0%	2.28	27.0	8.5	399	8.11	0.059	0.535			0.158		2.23	3.2	1.5
Canyon	Cove	18	3.9	1.3	5.1	1.9	8.0	0%	0%	0%	0%	0%	1.73	27.0	8.5	396	8.07	0.042	0.580			0.140		3.32	3.7	1.8
Canyon	All	36	3.6	1.2	4.8	1.7	8.0	0%	0%	0%	0%	0%	2.00	27.0	8.5	397	8.09	0.050	0.557			0.149		2.80	3.4	1.6
Cedar Creek	Main	20	32.7	8.1	40.8	16.9	67.7	100%	70%	55%	40%	0%	0.76	26.6	7.3	202	8.23	0.084	1.128			0.023	6.81		7.5	3.9
Cedar Creek	Cove	20	38.0	8.1	46.0	17.1	73.5	100%	85%	75%	50%	5%	0.52	27.3	8.2	202	8.66	0.105	1.355			0.009	11.90		13.8	6.0
Cedar Creek	All	40	35.3	8.1	43.4	17.0	73.5	100%	78%	65%	45%	3%	0.64	27.0	7.8	202	8.45	0.095	1.241			0.016	9.36		10.6	4.9
Fork	Main	19	14.2	2.1	16.3	5.9	28.0	74%	21%	0%	0%	0%	1.79	25.2	7.4	161	7.58	0.359	0.953	0.010	0.010	0.020		2.11	2.2	2.2
Fork	Cove	19	16.4	2.6	17.6	7.2	28.4	74%	42%	0%	0%	0%	1.19	25.8	7.9	162	7.85	0.247	0.911	0.010	0.010	0.020		4.28	4.1	3.0
Fork	All	38	15.3	2.4	17.0	6.5	28.4	74%	32%	0%	0%	0%	1.49	25.5	7.6	161	7.72	0.303	0.932	0.010	0.010	0.020		3.20	3.2	2.6
Georgetown	Main	16	1.6	1.2	2.8	1.4	7.2	0%	0%	0%	0%	0%	2.23	27.5	7.4	351	8.12	0.196	0.336	0.010	0.010	0.010		1.69	3.4	1.4
Georgetown	Cove	17	2.1	1.2	3.3	1.5	7.2	0%	0%	0%	0%	0%	1.52	27.9	7.3	357	8.11	0.201	0.371	0.010	0.010	0.010		2.60	4.9	1.8
Georgetown	All	33	1.9	1.2	3.0	1.4	7.2	0%	0%	0%	0%	0%	1.87	27.7	7.4	354	8.11	0.199	0.354	0.010	0.010	0.010		2.13	4.1	1.6
Granger	Main	17	8.2	1.8	9.9	7.2	26.1	35%	6%	0%	0%	0%	0.49	27.2	7.0	343	8.05	0.235	0.421	0.648	0.433	0.540		9.65	14.6	3.3
Granger	Cove	17	9.3	1.7	11.1	9.6	37.3	35%	12%	6%	0%	0%	0.33	27.6	6.9	344	8.06	0.267	0.411	0.010	0.362	0.186		17.11	34.5	6.7
Granger	All	34	8.7	1.8	10.5	8.4	37.3	35%	9%	3%	0%	0%	0.41	27.4	7.0	343	8.06	0.253	0.416	0.329	0.398	0.363		13.52	24.9	5.0
Livingston	Main	20	28.1	6.0	34.1	10.4	62.5	90%	90%	40%	5%	0%	0.92	27.8	10.0	351	8.49	0.187	1.005	0.026	0.198	0.174		5.74	7.6	4.0
Livingston	Cove	20	42.8	7.2	50.0	25.0	130.6	100%	90%	75%	45%	10%	0.35	28.2	8.6	396	8.37	0.301	1.100	0.041	0.417	0.397		33.15	30.4	8.9
Livingston	All	40	35.5	6.6	42.0	20.5	130.6	95%	90%	58%	25%	5%	0.65	28.0	9.3	373	8.43	0.244	1.053	0.034	0.307	0.288		19.45	19.0	6.5
Travis	Main	20	2.1	1.2	3.3	1.2	5.0	0%	0%	0%	0%	0%	3.22	27.1	8.2	439	8.41	0.010	0.343			0.016		1.29	1.5	1.1
Travis	Cove	20	2.8	1.3	4.1	1.4	7.1	0%	0%	0%	0%	0%	2.83	27.6	8.3	442	8.33	0.011	0.340			0.013		1.55	1.8	1.4
Travis	All	40	2.4	1.3	3.7	1.4	7.1	0%	0%	0%	0%	0%	3.02	27.4	8.2	440	8.37	0.010	0.342			0.015		1.42	1.6	1.2

Table 2. Summary of Water Quality Data. Computed from depth-averaged values on each date, 2003-2004.

Question 1 - Appearance

ResLabel	ove_Main		a	b	c	d	e	and Total
Bridgeport	Cove		24	76	29	3	3	135
	Main		30	112	18	3	1	164
Bridgeport Total			54	188	47	6	4	299
Canyon	Cove	4	29	49	31	1		114
	Main		23	59	14	3		99
Canyon Total		4	52	108	45	4		213
Cedar Creek	Cove		13	52	57	9	7	138
	Main	3	15	73	34	8	3	136
Cedar Creek Total		3	28	125	91	17	10	274
Fork	Cove		9	34	44	8		95
	Main		33	67	37	3		140
Fork Total			42	101	81	11		235
Georgetown	Cove		43	23	1			67
	Main		46	25	1			72
Georgetown Total			89	48	2			139
Granger	Cove	1	2	35	11			49
	Main		8	59	26			93
Granger Total		1	10	94	37			142
Livingston	Cove		19	89	32	12	4	156
	Main		30	81	41	5	1	158
Livingston Total			49	170	73	17	5	314
Travis	Cove	2	12	44	15		1	74
	Main	1	34	66	15			116
Travis Total		3	46	110	30		1	190
Grand Total		11	370	944	406	55	20	1806

Question 4 - Visit Frequency

ResLabel	Cove_Main		a	b	c	d	e	and Total
Bridgeport	Cove		15	69	22	5	24	135
	Main		18	87	29	5	25	164
Bridgeport Total			33	156	51	10	49	299
Canyon	Cove	4	38	35	17	8	12	114
	Main		24	29	19	10	17	99
Canyon Total		4	62	64	36	18	29	213
Cedar Creek	Cove	1	64	65	8			138
	Main	1	41	63	13	5	13	136
Cedar Creek Total		2	105	128	21	5	13	274
Fork	Cove		58	8	10	11	8	95
	Main		66	28	16	13	17	140
Fork Total			124	36	26	24	25	235
Georgetown	Cove		5	47	9	3	3	67
	Main		2	41	23	4	2	72
Georgetown Total			7	88	32	7	5	139
Granger	Cove	1		37	7	1	3	49
	Main	1	8	52	17	9	6	93
Granger Total		2	8	89	24	10	9	142
Livingston	Cove		103	29	11	5	8	156
	Main		61	39	28	12	18	158
Livingston Total			164	68	39	17	26	314
Travis	Cove	2	7	58	5		2	74
	Main	1	10	64	20	8	13	116
Travis Total		3	17	122	25	8	15	190
Grand Total		11	520	751	254	99	171	1806

Question 2 - Use Impairment

ResLabel	ove_Main		a	b	c	d	e	and Total
Bridgeport	Cove		41	54	26	14		135
	Main		77	59	25	3		164
Bridgeport Total			118	113	51	17		299
Canyon	Cove	4	31	72	7			114
	Main		49	45	3	2		99
Canyon Total		4	80	117	10	2		213
Cedar Creek	Cove		20	60	45	6	7	138
	Main	1	35	72	23	5		136
Cedar Creek Total		1	55	132	68	11	7	274
Fork	Cove		21	45	20	6	3	95
	Main	1	66	61	9		3	140
Fork Total		1	87	106	29	6	6	235
Georgetown	Cove		44	22	1			67
	Main		48	22	2			72
Georgetown Total			92	44	3			139
Granger	Cove		1	12	27	9		49
	Main		9	37	36	11		93
Granger Total			10	49	63	20		142
Livingston	Cove	1	15	89	42	8	1	156
	Main		29	91	32	6		158
Livingston Total		1	44	180	74	14	1	314
Travis	Cove	2	26	40	6			74
	Main	1	55	55	5			116
Travis Total		3	81	95	11			190
Grand Total		10	567	836	309	70	14	1806

Question 5 - Use Type

ResLabel	Cove_Main		a	b	c	d	e	f	rand Tot
Bridgeport	Cove		13	29	13	22	5	53	135
	Main		4	78	12	5	10	55	164
Bridgeport Total			17	107	25	27	15	108	299
Canyon	Cove		10	9	38	6	4	47	114
	Main		21	11	18	4	4	41	99
Canyon Total			31	20	56	10	8	88	213
Cedar Creek	Cove	1	10	42	28	1	11	45	138
	Main	1	5	39	36	6	11	38	136
Cedar Creek Total		2	15	81	64	7	22	83	274
Fork	Cove	1	6	44	2		2	40	95
	Main		3	93	5	2		37	140
Fork Total		1	9	137	7	2	2	77	235
Georgetown	Cove	1	15	8	5	2	1	35	67
	Main		6	6	5	3	14	38	72
Georgetown Total		1	21	14	10	5	15	73	139
Granger	Cove			15	1	1	1	31	49
	Main	1	11	23	9		8	41	93
Granger Total		1	11	38	10	1	9	72	142
Livingston	Cove		31	43	12	4	21	45	156
	Main		14	56	13	1	25	49	158
Livingston Total			45	99	25	5	46	94	314
Travis	Cove		8	3	15	1	1	46	74
	Main	3	38	6	19	4	6	40	116
Travis Total		3	46	9	34	5	7	86	190
Grand Total		8	195	505	231	62	124	681	1806

Question 3 - Reason for Question 2 Response

ResLabel	ove_Main		a	b	c	and Total
Bridgeport	Cove	96	33	5	1	135
	Main	131	18	14	1	164
Bridgeport Total		227	51	19	2	299
Canyon	Cove	107		6	1	114
	Main	94		4	1	99
Canyon Total		201		10	2	213
Cedar Creek	Cove	77	12	40	9	138
	Main	107	2	23	4	136
Cedar Creek Total		184	14	63	13	274
Fork	Cove	68	10	17		95
	Main	129		9	2	140
Fork Total		197	10	26	2	235
Georgetown	Cove	66		1		67
	Main	70		1	1	72
Georgetown Total		136		2	1	139
Granger	Cove	13	25	9	2	49
	Main	43	29	15	6	93
Granger Total		56	54	24	8	142
Livingston	Cove	104	34	11	7	156
	Main	121	14	20	3	158
Livingston Total		225	48	31	10	314
Travis	Cove	70	1	1	2	74
	Main	113		1	2	116
Travis Total		183	1	2	4	190
Grand Total		1409	178	177	42	1806

Chlorophyll-a Intervals

ResLabel	Cove_Mair	#N/A	<5	10-20	5-10	20-40	>40	and Total
Bridgeport	Cove		15	21	92	7		135
	Main	14	66	7	77			164
Bridgeport Total		14	81	28	169	7		299
Canyon	Cove		70		44			114
	Main		88		11			99
Canyon Total			158		55			213
Cedar Creek	Cove	7		20		45	66	138
	Main	7		42		33	54	136
Cedar Creek Total		14		62		78	120	274
Fork	Cove			31	32	32		95
	Main			77	33	30		140
Fork Total				108	65	62		235
Georgetown	Cove		67					67
	Main	8	64					72
Georgetown Total		8	131					139
Granger	Cove		17	14	12	6		49
	Main	28	38	12	12	3		93
Granger Total		28	55	26	24	9		142
Livingston	Cove			14		73	69	156
	Main				14	135	9	158
Livingston Total				14	14	208	78	314
Travis	Cove		71		3			74
	Main		116					116
Travis Total			187		3			190
Grand Total		64	612	238	330	364	198	1806

Table 3. Summary of Survey Results.

Table: Responses by Site & User Category

Question 1

Each Reservoir

ResLabel	Q_Crew	Q_CONTACT	a	b	c	d	e	and Total
Bridgeport	NO	NO	37	89	27	6	1	160
		YES	2	22	17		3	44
	YES	NO	15	77	3			95
Bridgeport Total			54	188	47	6	4	299
Canyon	NO	NO	27	58	25	2		112
		YES	22	17	1	2		42
	YES	NO	3	33	19			55
Canyon Total			52	108	45	4		209
Cedar Cre	NO	NO	26	84	54	10	9	183
		YES	1	13	6	3		23
	YES	NO		28	31	4	1	64
Cedar Creek Total			27	125	91	17	10	270
Fork	NO	NO	39	79	21	9		148
		YES	3	5	2	2		12
	YES	NO		16	58			74
Fork Total			42	100	81	11		234
Georgetow	NO	NO	28	13				41
		YES	22	5				27
	YES	NO	39	29	2			70
Georgetown Total			89	47	2			138
Granger	NO	NO	5	38	16			59
		YES	3	8	1			12
	YES	NO	2	47	20			69
Granger Total			10	93	37			140
Livingston	NO	NO	44	95	36	7	1	183
		YES	3	24	11	10	4	52
	YES	NO	2	51	26			79
Livingston Total			49	170	73	17	5	314
Travis	NO	NO	22	62	15		1	100
		YES	21	25	5			51
	YES	NO	3	21	10			34
Travis Total			46	108	30		1	185
Grand Total			369	939	406	55	20	1789

Question 2

Each Reservoir

ResLabel	Q_Crew	Q_CONTAC	a	b	c	d	e	Grand
Bridgepor	NO	NO	64	61	28	7		160
		YES	16	23	5			44
	YES	NO	38	29	18	10		95
Bridgeport Total			118	113	51	17		299
Canyon	NO	NO	47	57	7	1		112
		YES	23	17	1	1		42
	YES	NO	10	43	2			55
Canyon Total			80	117	10	2		209
Cedar Cre	NO	NO	46	85	39	7	7	184
		YES	8	11	3	1		23
	YES	NO		36	26	3		65
Cedar Creek Total			54	132	68	11	7	272
Fork	NO	NO	76	50	10	5	6	147
		YES	5	6		1		12
	YES	NO	6	50	18			74
Fork Total			87	106	28	6	6	233
Georgetov	NO	NO	27	13	1			41
		YES	23	4				27
	YES	NO	41	27	2			70
Georgetown Total			91	44	3			138
Granger	NO	NO	5	33	13	9		60
		YES	5	6	1			12
	YES	NO		10	48	11		69
Granger Total			10	49	62	20		141
Livingston	NO	NO	26	108	36	11	1	182
		YES	9	27	13	3		52
	YES	NO	9	45	25			79
Livingston Total			44	180	74	14	1	313
Travis	NO	NO	42	51	7			100
		YES	28	19	4			51
	YES	NO	11	23				34
Travis Total			81	93	11			185
Grand Total			565	834	307	70	14	1790

All Reservoirs (Question 1)

Cove_Mai	Q_Crew	Q_CONTACT	a	b	c	d	e	Grand Tot
Cove	NO	NO	90	209	92	19	8	418
		YES	30	57	26	14	6	133
	YES	NO	30	134	102		1	267
Cove Total			150	400	220	33	15	818
Main	NO	NO	138	309	102	15	4	568
		YES	47	62	17	3	1	130
	YES	NO	34	168	67	4		273
Main Total			219	539	186	22	5	971
Grand Total			369	939	406	55	20	1789

All Reservoirs (Question 2)

Cove_Mai	Q_Crew	Q_CONTAC	a	b	c	d	e	Grand
Cove	NO	NO	110	203	73	21	11	418
		YES	50	61	17	5		133
	YES	NO	37	130	83	17		267
Cove Total			197	394	173	43	11	818
Main	NO	NO	223	255	68	19	3	568
		YES	67	52	10	1		130
	YES	NO	78	133	56	7		274
Main Total			368	440	134	27	3	972
Grand Total			565	834	307	70	14	1790

Table 4. Questions 1 & 2 Responses by User Category.

List of Figures

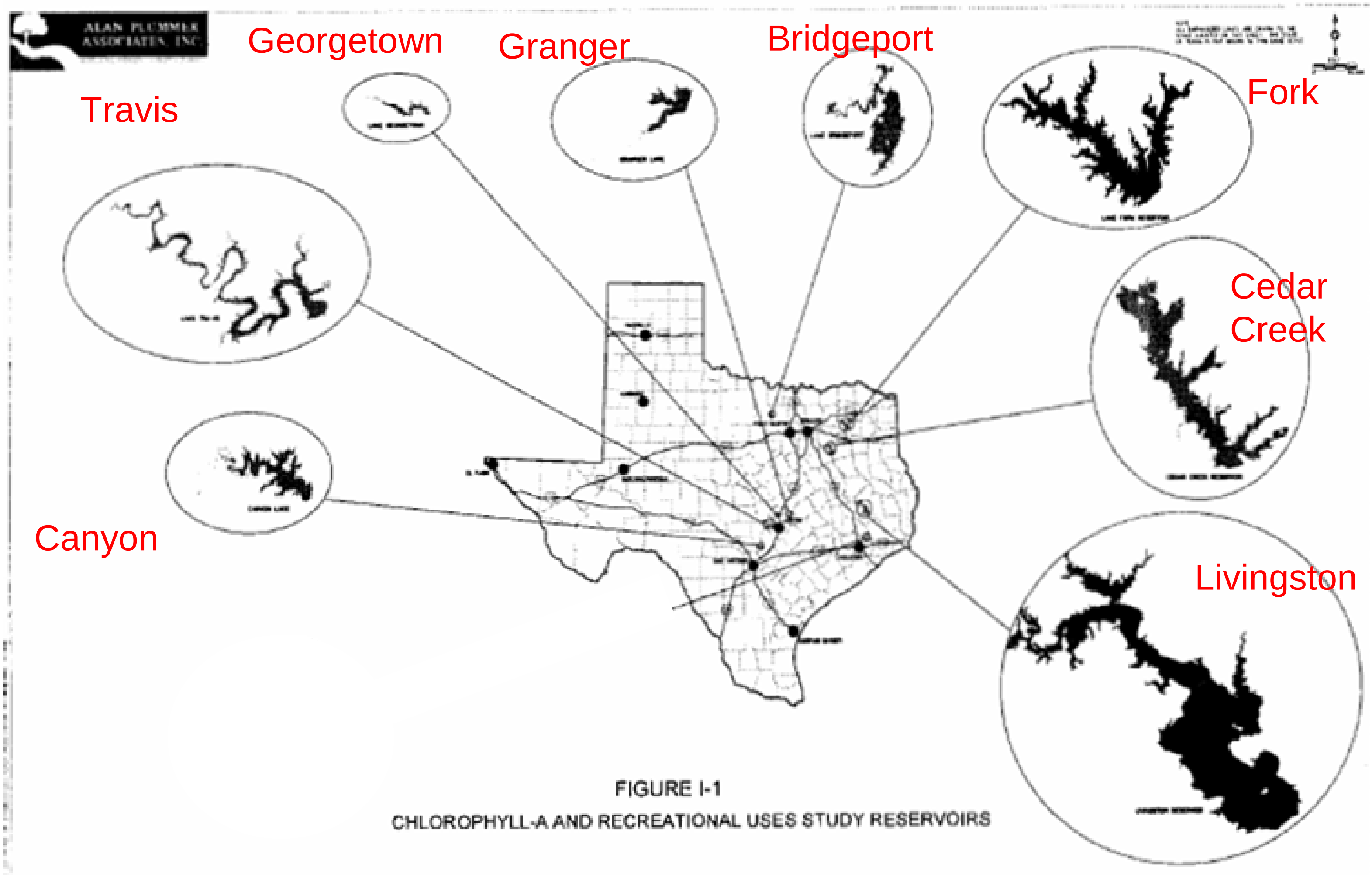


Figure 1. Study Reservoirs.

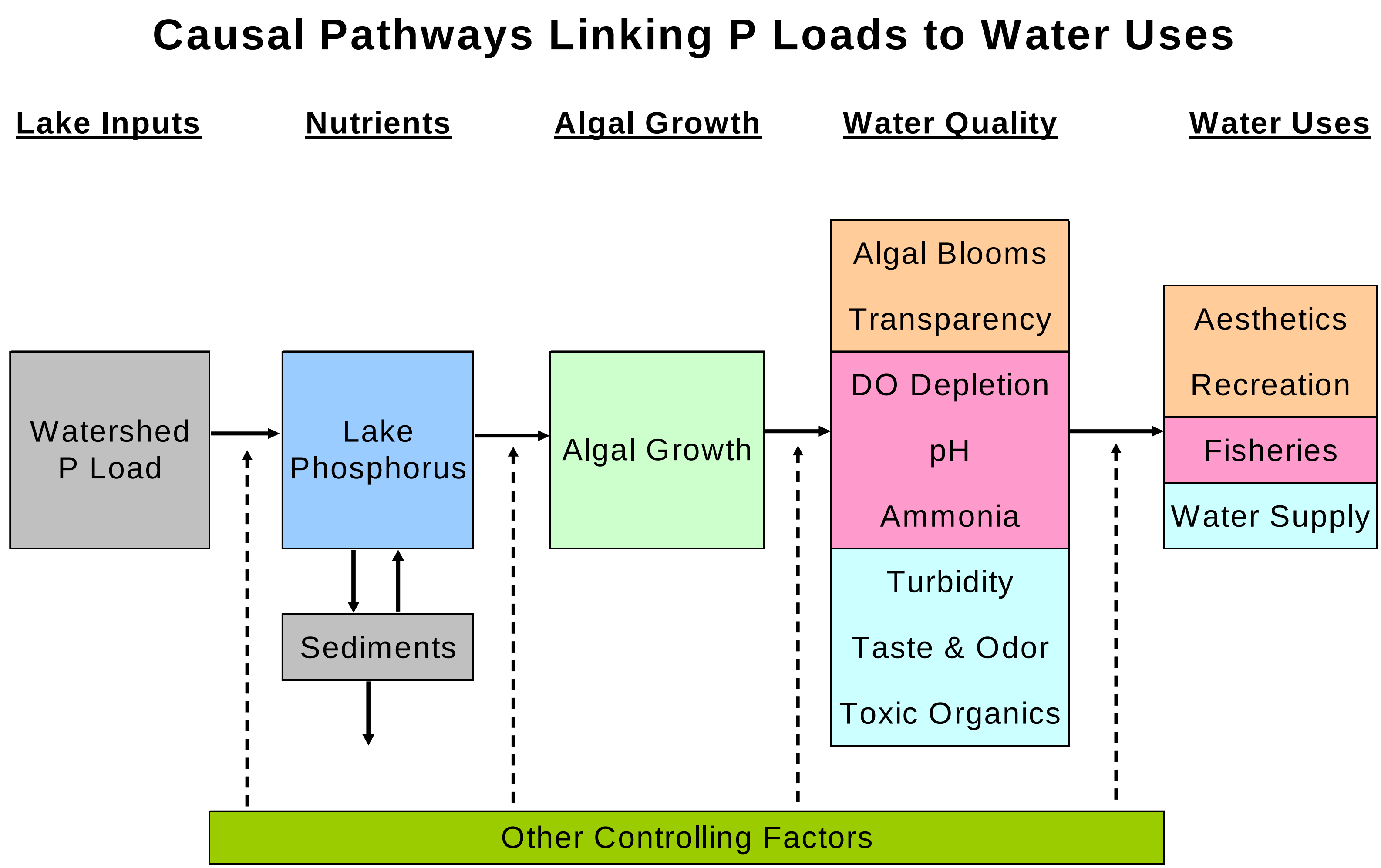


Figure 2. Causal Pathways Linking Phosphorus Loads to Water Uses.

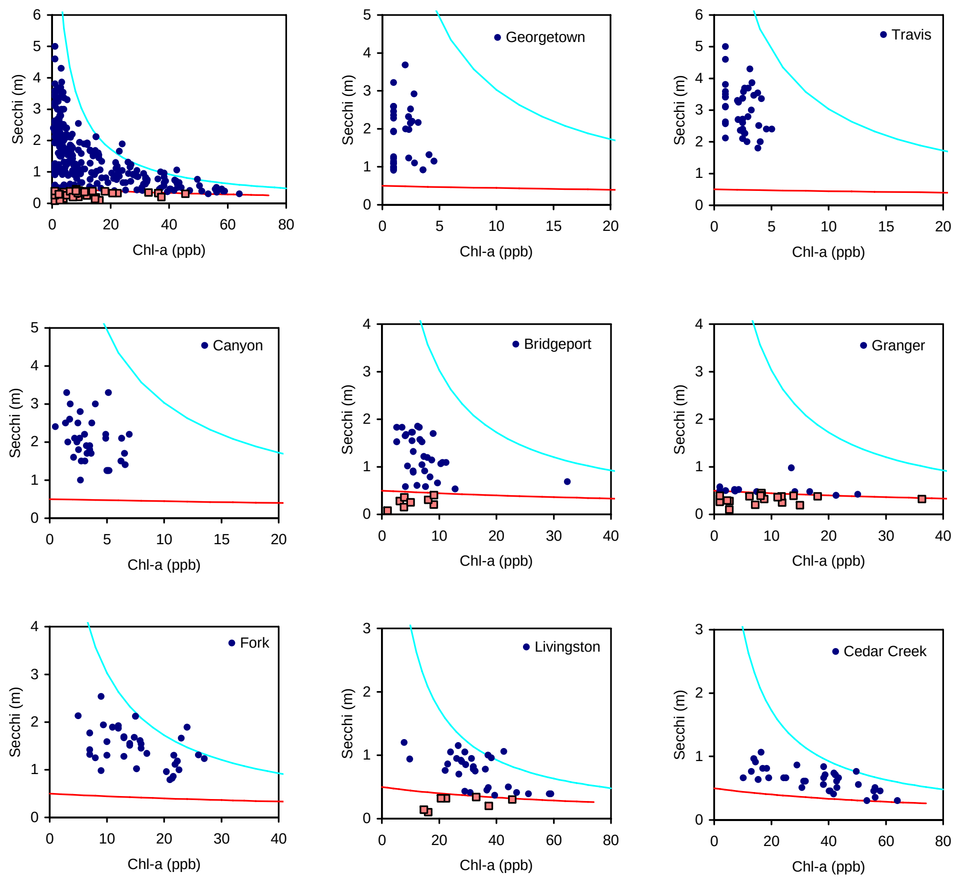


Figure 3. Secchi Depth vs. Chlorophyll-a for Each Reservoir & Sample.
Lines show predicted transparency for different levels of non-algal turbidity ($a = 0.08$ to $2.0\ m^{-1}$)
using CE reservoir Secchi vs. chl-a model : $1/\text{Secchi} = a + b\ \text{Chl-a}$, $b = 0.025\ m^2/\text{mg}$.
Square symbols are samples with relatively high non-algal turbidity levels.

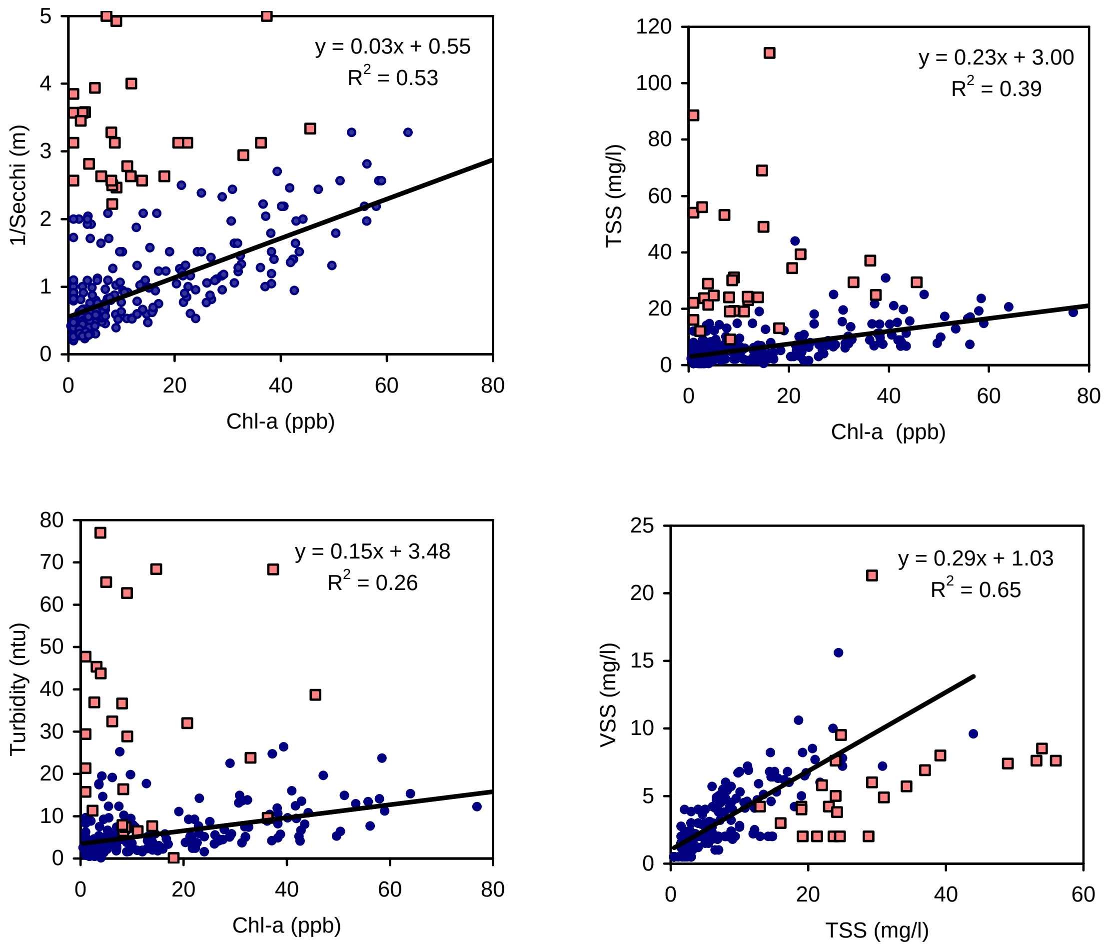
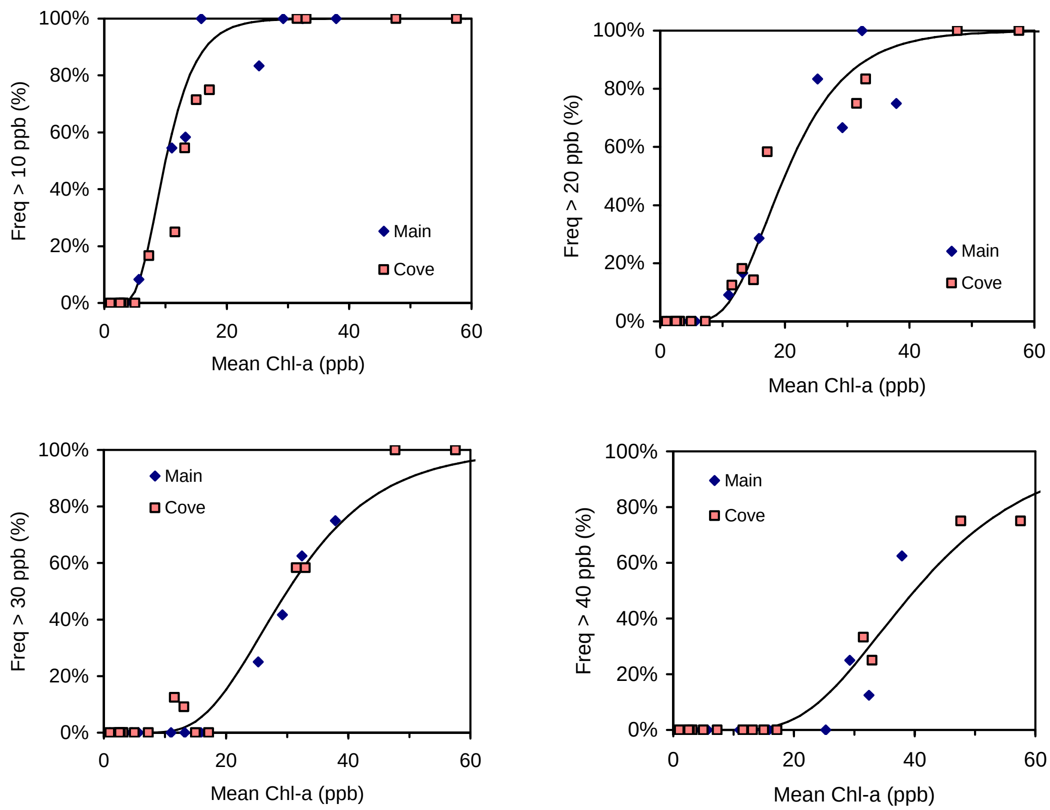
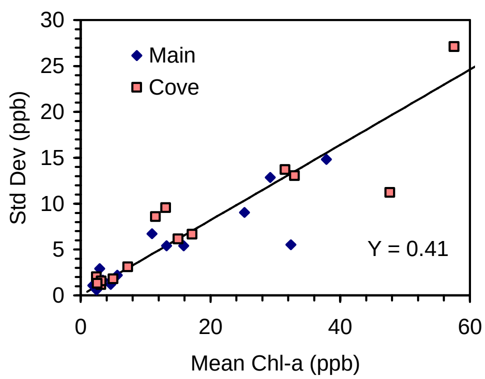


Figure 4. Identification of Samples with High Non-Algal Turbidity. Square symbols are samples with non-algal turbidity > 2 m^{-1}, computed from Secchi depth & chl-a data, (Figure 3). Lines are regressions using the remaining data.



Calibration of Log-Normal Model:



Yearly Maximum vs. Mean:

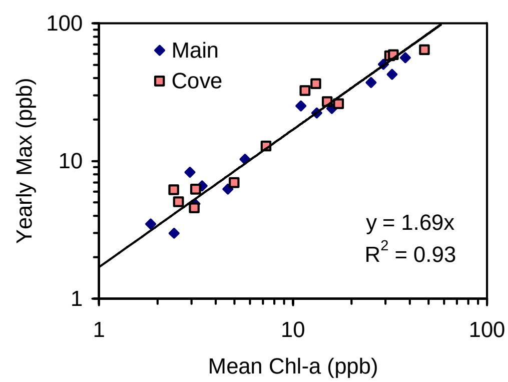


Figure 5. Chlorophyll-a Interval Frequencies vs.Yearly Site Mean Concentration. Log-normal distribution model (Walker, 1985); CV = standard deviation across dates / station mean = 0.41. Std Dev of Ln (Chl-a) = 0.39

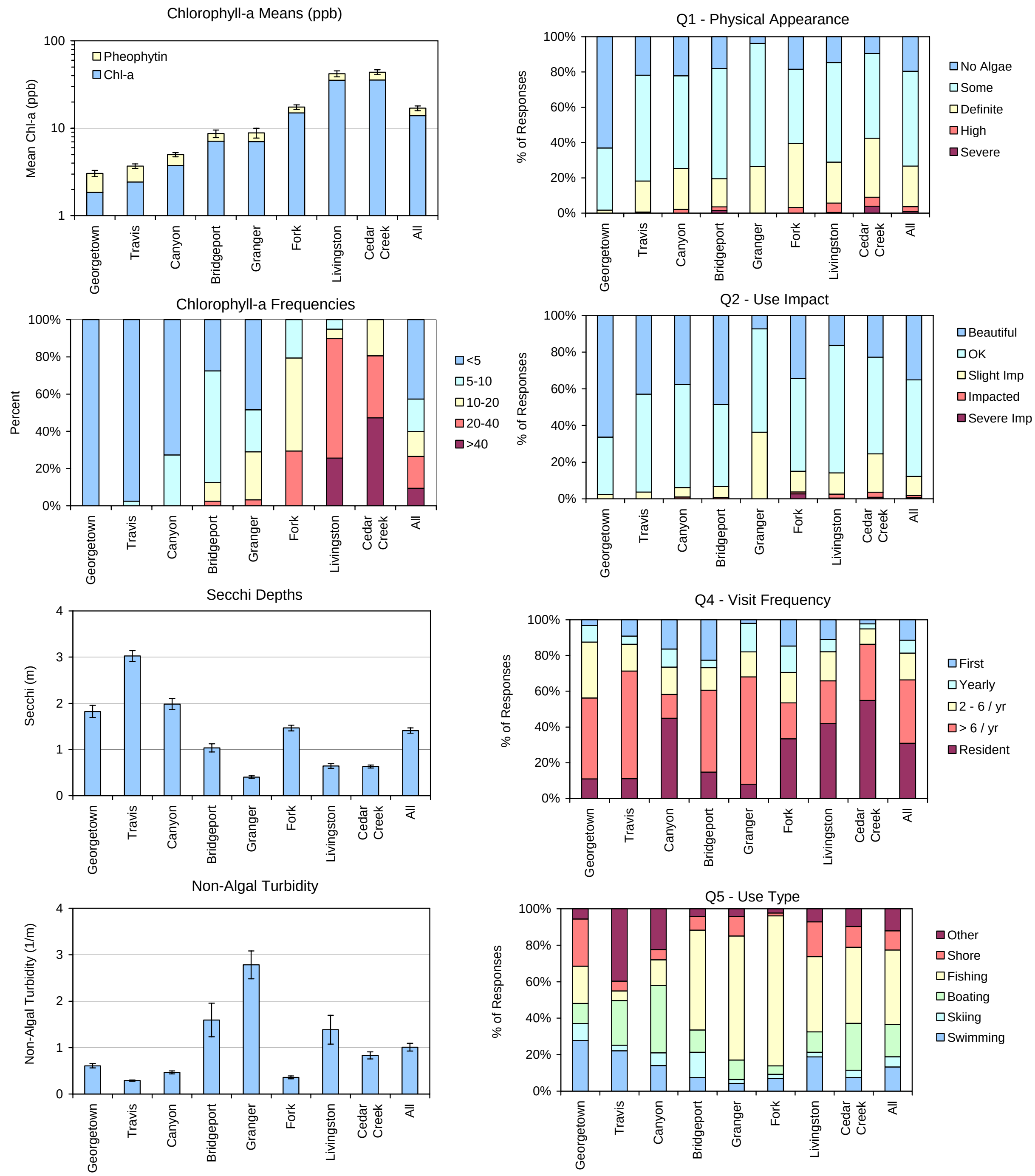
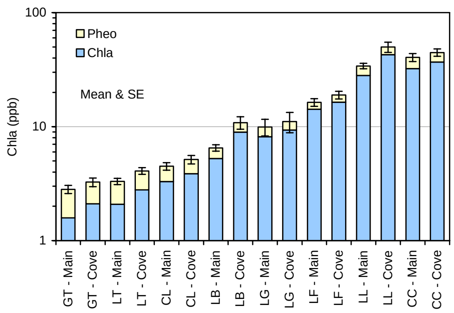
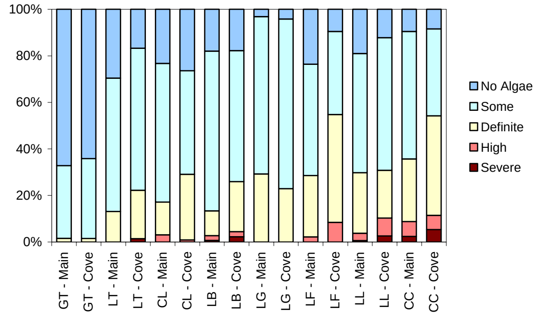


Figure 6. Summary of Water Quality & Survey Responses by Reservoir. Sorted in order of increasing mean chlorophyll-a. Means & standard errors for 2-year survey.

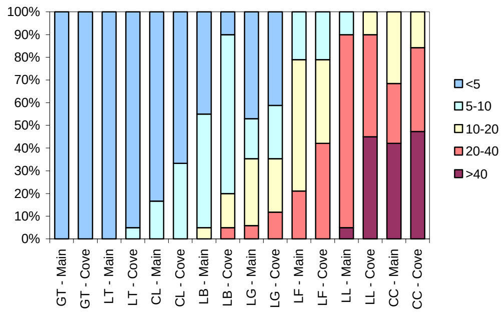
Mean Chlorophyll-a



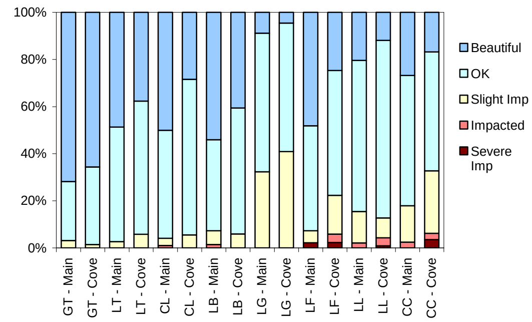
Question 1 - Appearance



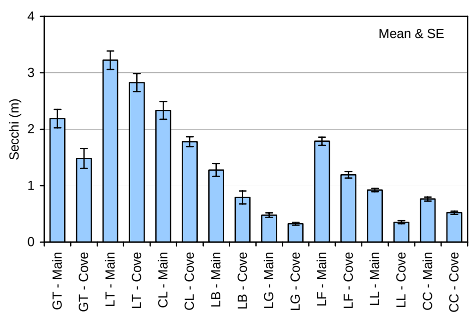
Bloom Frequencies



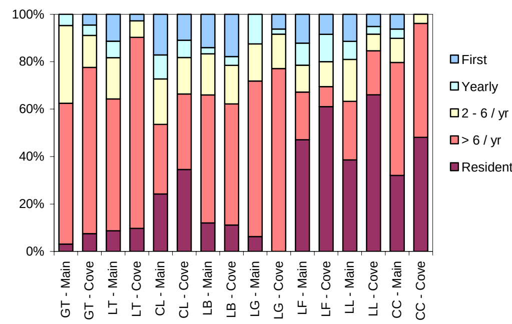
Question 2 - Use Impact



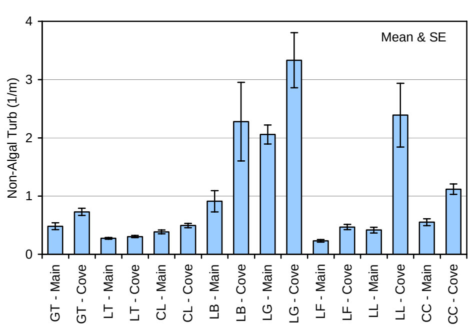
Secchi Depths



Question 4 - Visit Frequency



Non-Algal Turbidity



Question 5 - Water Use

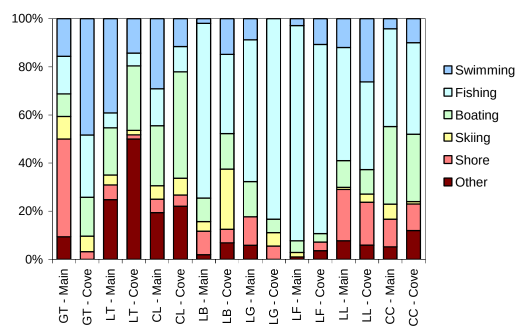
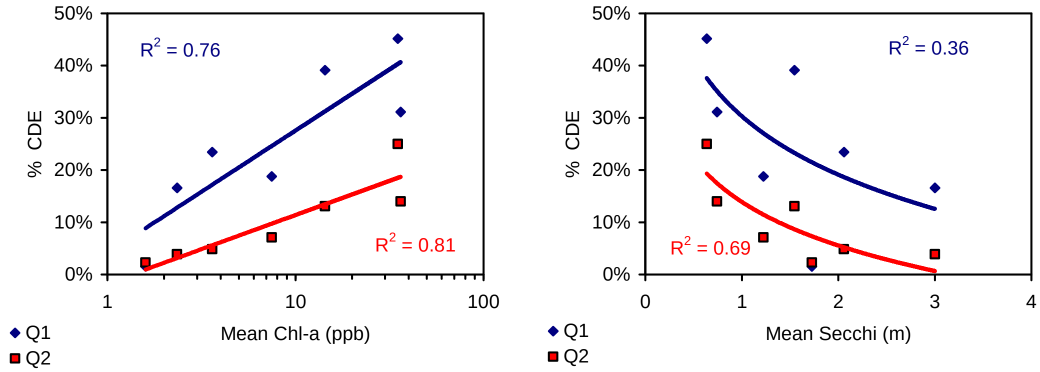
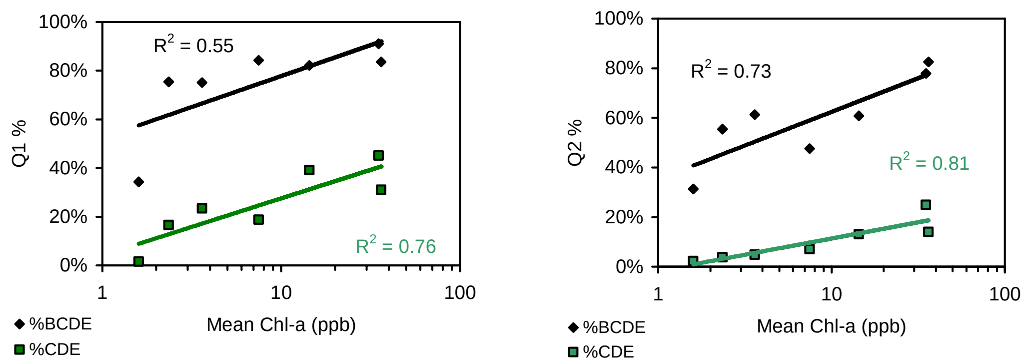


Figure 7. Summary of Water Quality & Survey Responses by Site. Sorted in order of increasing mean chlorophyll-a. Means & standard errors for 2-year survey

Responses vs. Mean Chl-a & Secchi



% BCDE & %BCD vs . Mean Chl-a



Responses vs. Mean Chl-a & Station Type

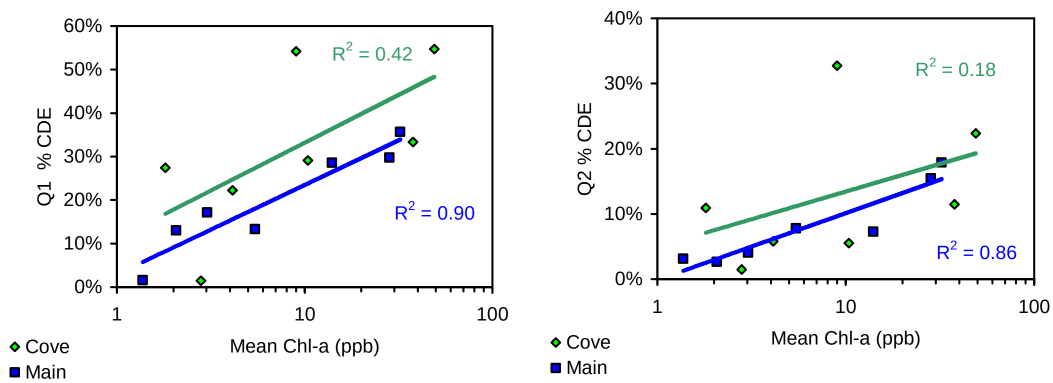


Figure 8. Response Frequencies vs. Reservoir Mean Chlorophyll-a and Secchi Depth. Turbid samples (Figure 3) & Lake Granger excluded.

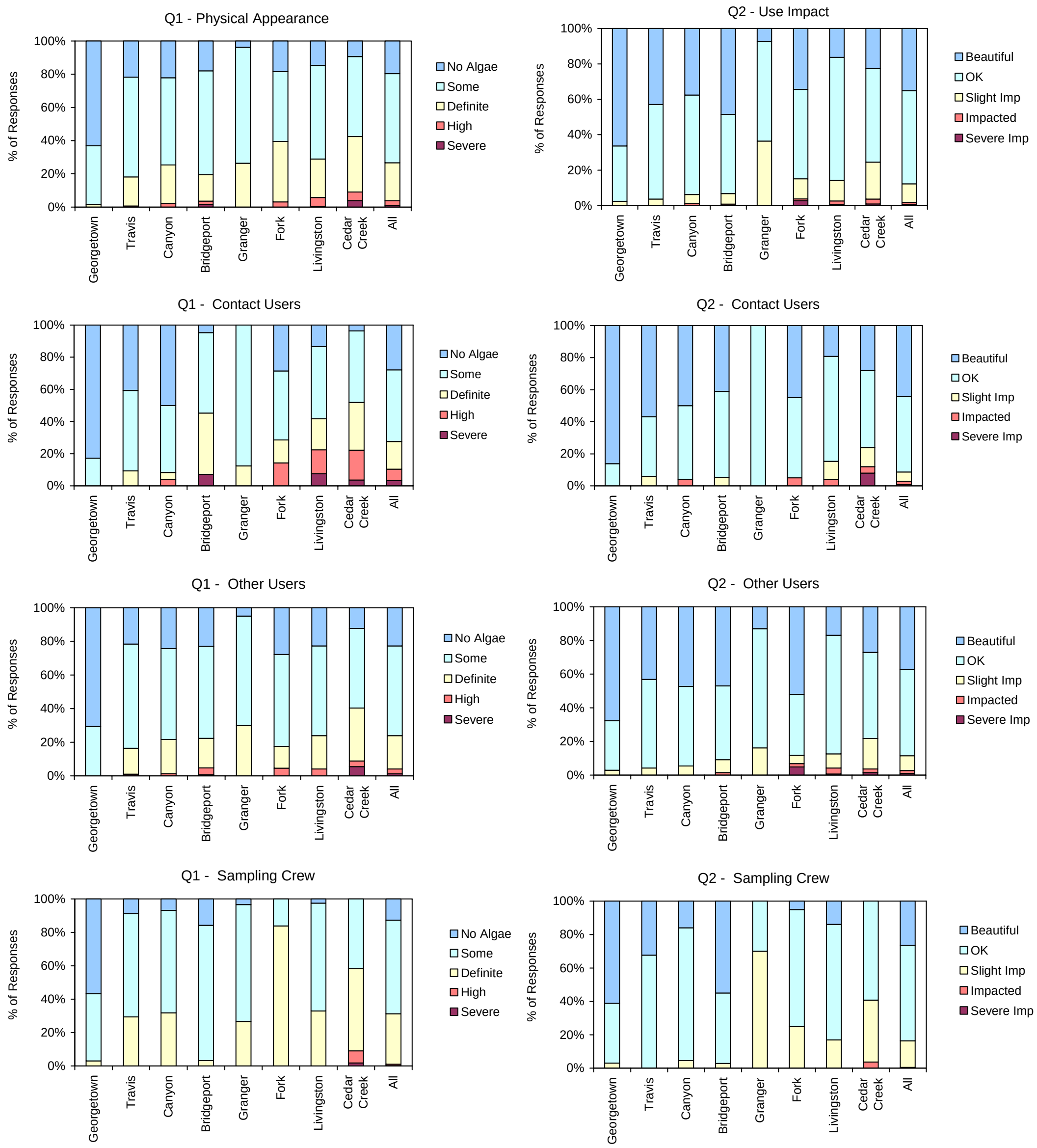
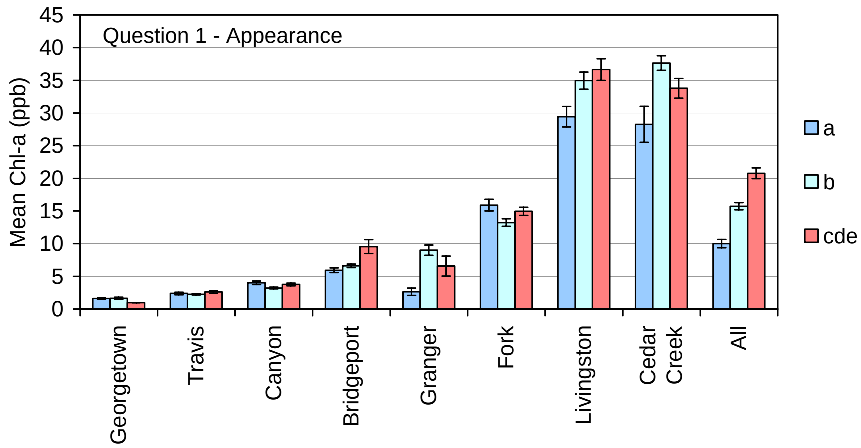
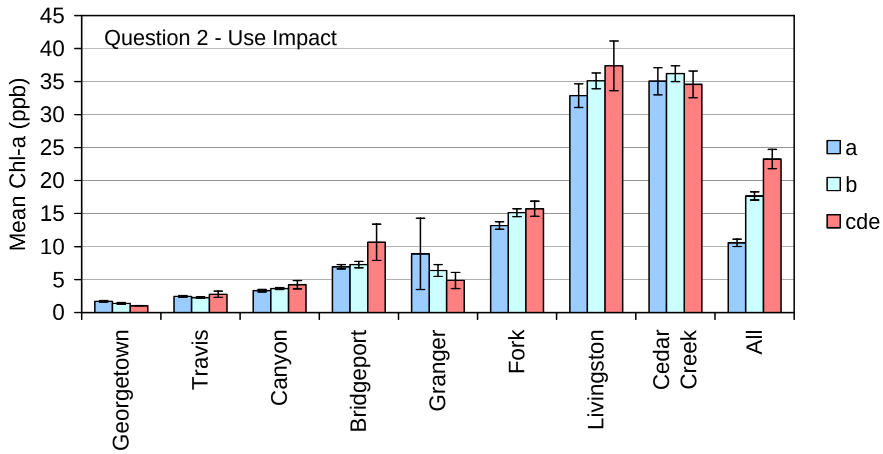


Figure 9. Sensitivity of Survey Responses to Observer Categories. top = all observers; contact users = swimmers, skiers, windsurfers (Question 5 = a or d); bottom = sampling crew; middle = other observers (fisherman, hikers, etc.)





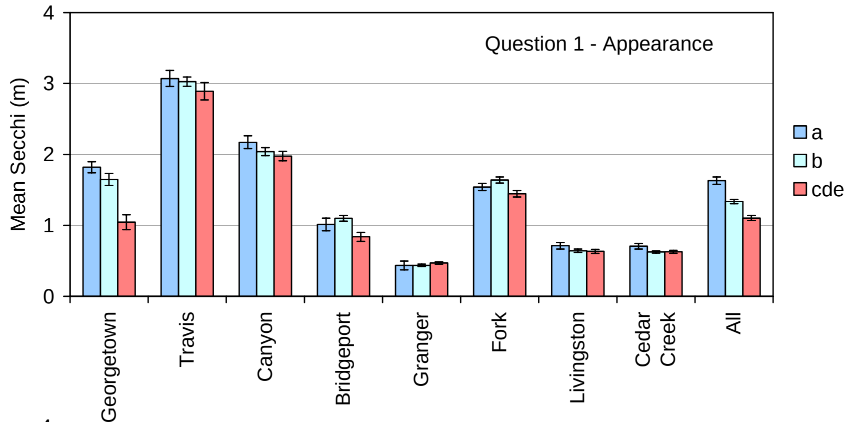
Responses to Question 1 - Appearance

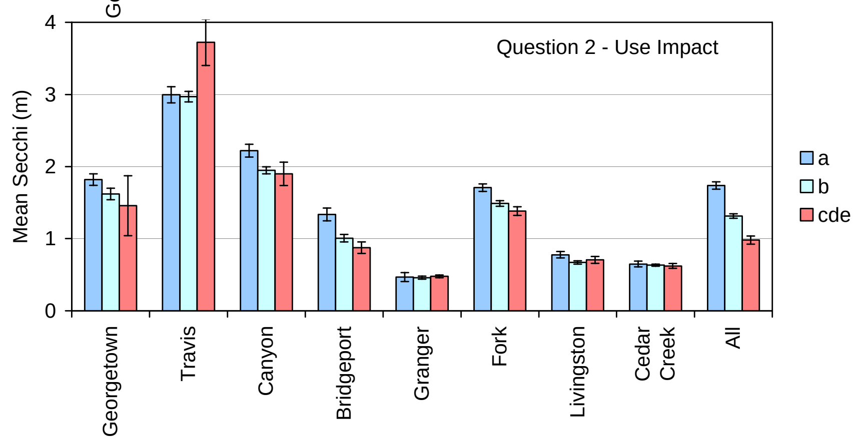
	a	b	cde	All	% cde	Secchi m	Chl-a ppb
Georgetown	86	43	2	131	2%	1.8	1.9
Travis	46	110	31	187	17%	3.0	2.4
Canyon	52	108	49	209	23%	2.0	3.6
Bridgeport	51	179	55	285	19%	1.0	7.1
Granger	4	79	30	113	27%	0.4	8.7
Fork	42	101	92	235	39%	1.5	15.3
Livingston	49	170	95	314	30%	0.7	35.5
Cedar Creek	23	118	116	257	45%	0.6	34.6
All	353	908	470	1731	27%	1.4	14.0

Responses to Question 2 - Use Impairment

	a	b	cde	All	% cde	Secchi m	Chl-a ppb
Georgetown	90	38	3	131	2%	1.8	1.9
Travis	81	94	7	182	4%	3.0	2.4
Canyon	80	117	10	207	5%	2.0	3.6
Bridgeport	115	107	16	238	7%	1.0	7.1
Granger	4	32	20	56	36%	0.4	8.7
Fork	87	106	29	222	13%	1.5	15.3
Livingston	43	180	37	260	14%	0.7	35.5
Cedar Creek	52	125	59	236	25%	0.6	34.6
All	552	799	181	1532	12%	1.4	14.0

Figure 10. Mean Chlorophyll-a vs. Reservoir & Survey Response;
excludes samples with non-algal turbidity > 2 m-1 ; bars = approximate standard errors





Responses to Question 1 - Appearance

	a	b	cde	All	% cde	Secchi m	Chl-a ppb
Georgetown	89	48	2	139	1%	1.7	1.6
Travis	46	110	31	190	16%	3.0	2.4
Canyon	51	108	49	212	23%	2.1	3.6
Bridgeport	51	179	55	285	19%	1.0	7.1
Granger	8	90	36	135	27%	0.4	8.5
Fork	42	101	92	235	39%	1.5	14.4
Livingston	49	160	90	299	30%	0.7	33.3
Cedar Creek	23	103	105	234	45%	0.6	35.4
All	359	899	460	1718	27%	1.3	15.3

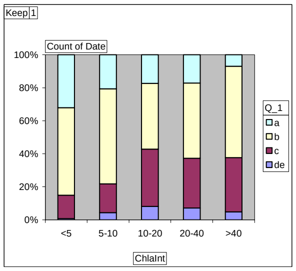
Responses to Question 2 - Use Impairment

	a	b	cde	All	% cde	Secchi m	Chl-a ppb
Georgetown	92	44	3	139	2%	1.7	1.6
Travis	81	94	7	182	4%	3.0	2.4
Canyon	79	117	10	206	5%	2.1	3.6
Bridgeport	115	107	16	238	7%	1.0	7.1
Granger	8	44	25	77	32%	0.4	8.5
Fork	87	106	29	222	13%	1.5	14.4
Livingston	42	171	35	248	14%	0.7	33.3
Cedar Creek	44	119	49	212	23%	0.6	35.4
All	548	802	174	1524	11%	1.3	15.3

Figure 11. Mean Secchi Depth vs. Reservoir & Survey Response.
bars = approximate standard errors ; including turbid samples.

Question 1 Responses - Physical Appearance

All Categories



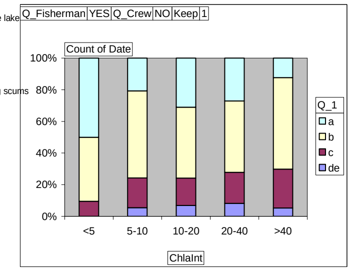
1) Please circle the **one** response that best describes the **physical condition** of the lake water **today**:

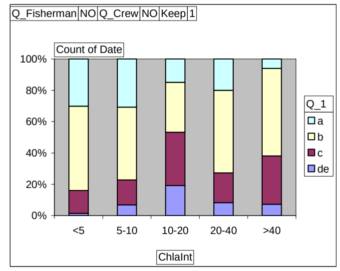
a) No algae, or crystal clear water
b) A little algae visible
c) Definite algal greenness
d) High algae levels and/or mild odor apparent
e) Severely high algae levels with one or more of the following: massive floating scums on lake or washed up on shore, strong foul odor, or fish kill

Chl-a	a	b	c	de	Total
<5	180	328	96	5	609
5-10	64	188	62	12	326
10-20	37	110	71	17	235
20-40	59	173	102	30	364
>40	13	109	65	10	197
Total	353	908	396	74	1731

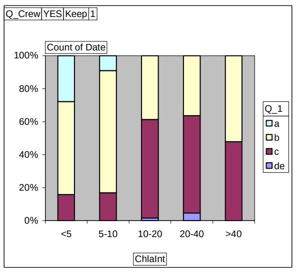
- Excludes Granger & samples with non-algal turbidity > 2 m^{-1}

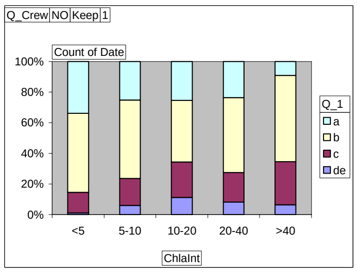
Fishermen vs. Other Observers



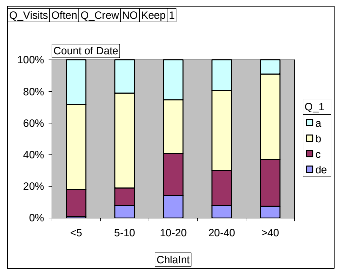


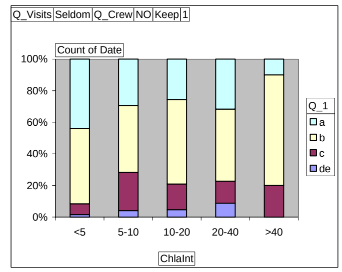
Sampling Crew vs. Other Observer



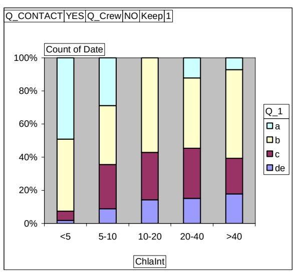


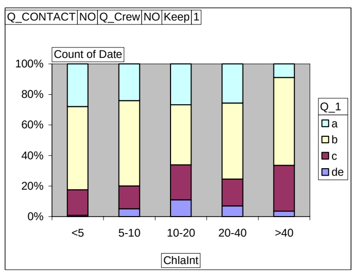
Visit Often vs. Seldom



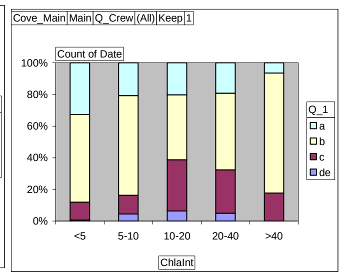


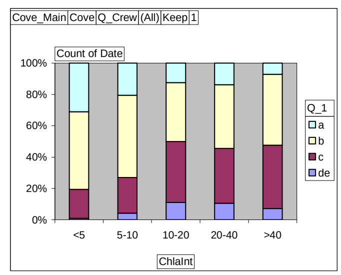
Contact vs. NonContact Recreation



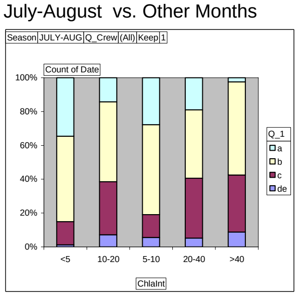


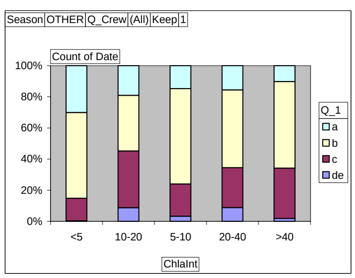
Main Reservoir vs. Cove Sites



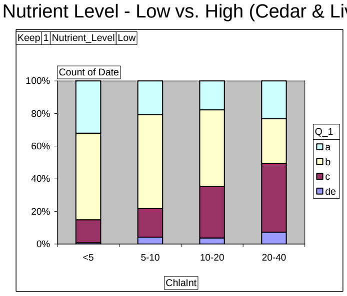


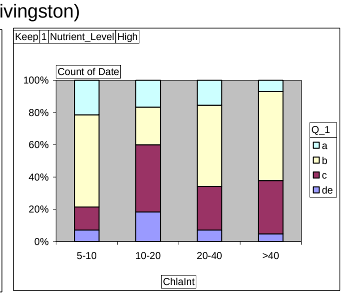
July-August vs. Other Months



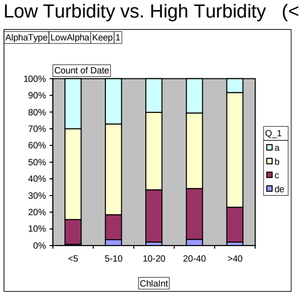


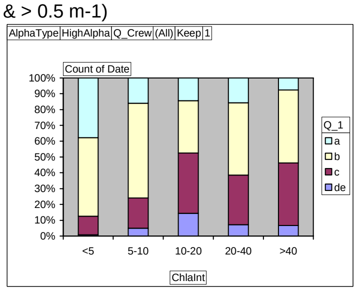
Nutrient Level - Low vs. High (Cedar & Livingston)



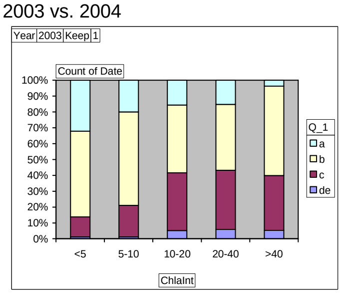


Low Turbidity vs. High Turbidity (< & > 0.5 m-1)





2003 vs. 2004



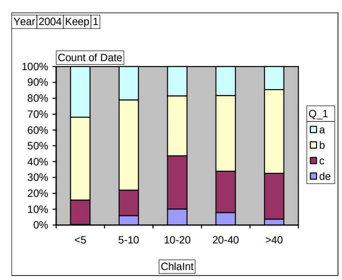
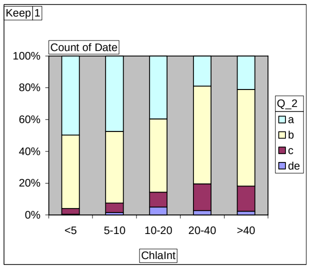


Figure 12. Question 1 Responses vs. Chlorophyll-a Interval & Other Factors. Excludes turbid samples & Lake Granger

Question 2 Responses - Use Impact

All Categories



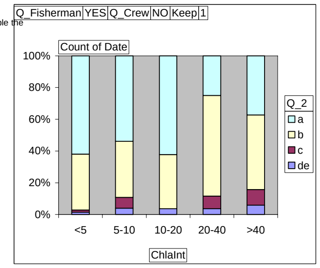
2) Please circle the **one** response that best describes your **perception** of how suitable the lake water is for recreation and aesthetic enjoyment **today**:

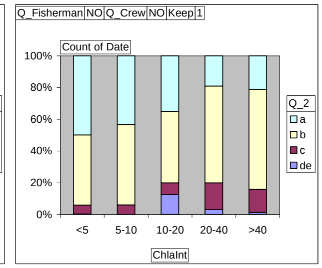
   a) Beautiful, could not be any nicer
   b) Very minor aesthetic problems; excellent for swimming, boating enjoyment
   c) Swimming and aesthetic enjoyment slightly impaired
   d) Desire to swim and level of enjoyment of the lake substantially reduced
   e) Swimming and aesthetic enjoyment of the lake nearly impossible

Chl-a	a	b	c	de	Total
#N/A	14	36	12	2	64
<5	262	268	60	19	609
5-10	122	132	52	20	326
10-20	73	94	54	16	237
20-40	60	198	89	17	364
Total	36	108	42	10	196

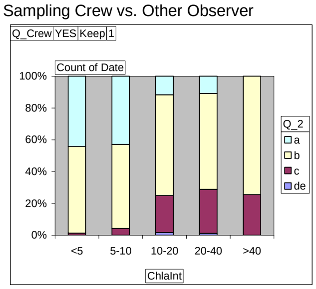
- Excludes Granger & 3 Bridgeport Samples (high non-algal turbidity)
- Excludes responses related to factors other than algae (Question 3)

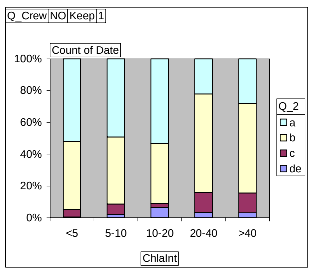
Fisherman vs. Other Observers



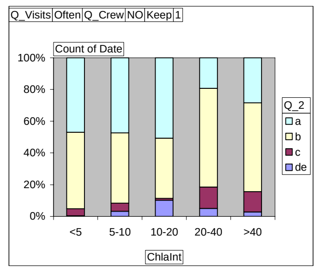


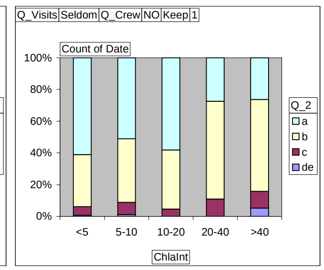
Sampling Crew vs. Other Observer



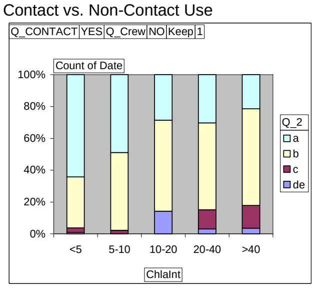


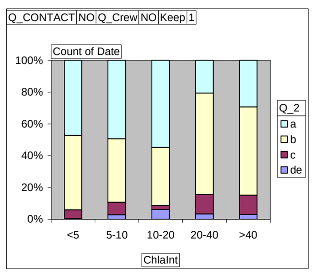
Visit Often vs. Seldom   Question 4: Often = a,b   Seldom = c,d,e



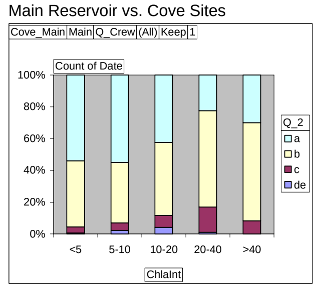


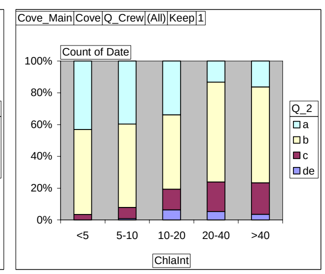
Contact vs. Non-Contact Use



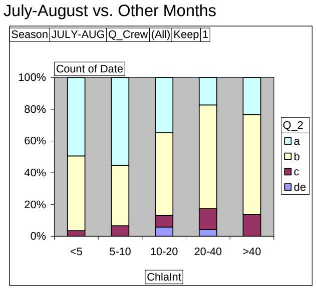


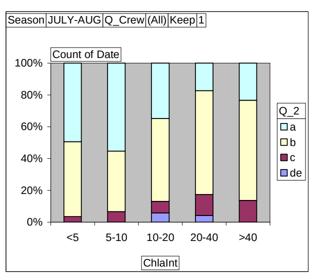
Main Reservoir vs. Cove Sites



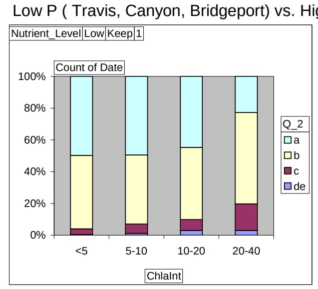


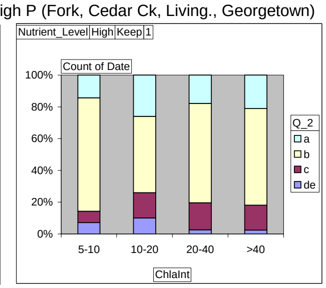
July-August vs. Other Months



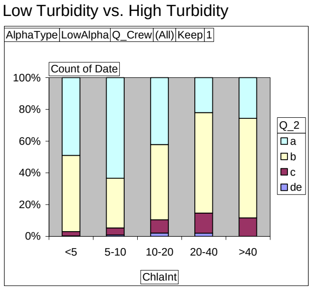


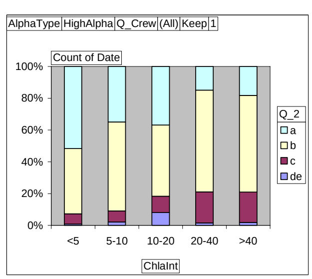
Low P (Travis, Canyon, Bridgeport) vs. High P (Fork, Cedar Ck, Living., Georgetown)



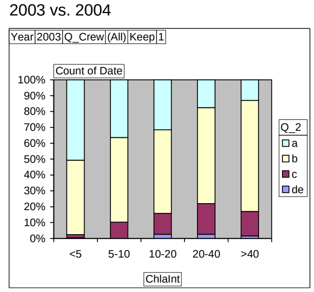


Low Turbidity vs. High Turbidity





2003 vs. 2004



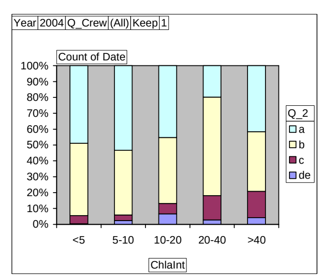


Figure 13. Question 2 Responses vs. Chlorophyll-a Interval & Other Factors. Excludes turbid samples & Lake Granger.

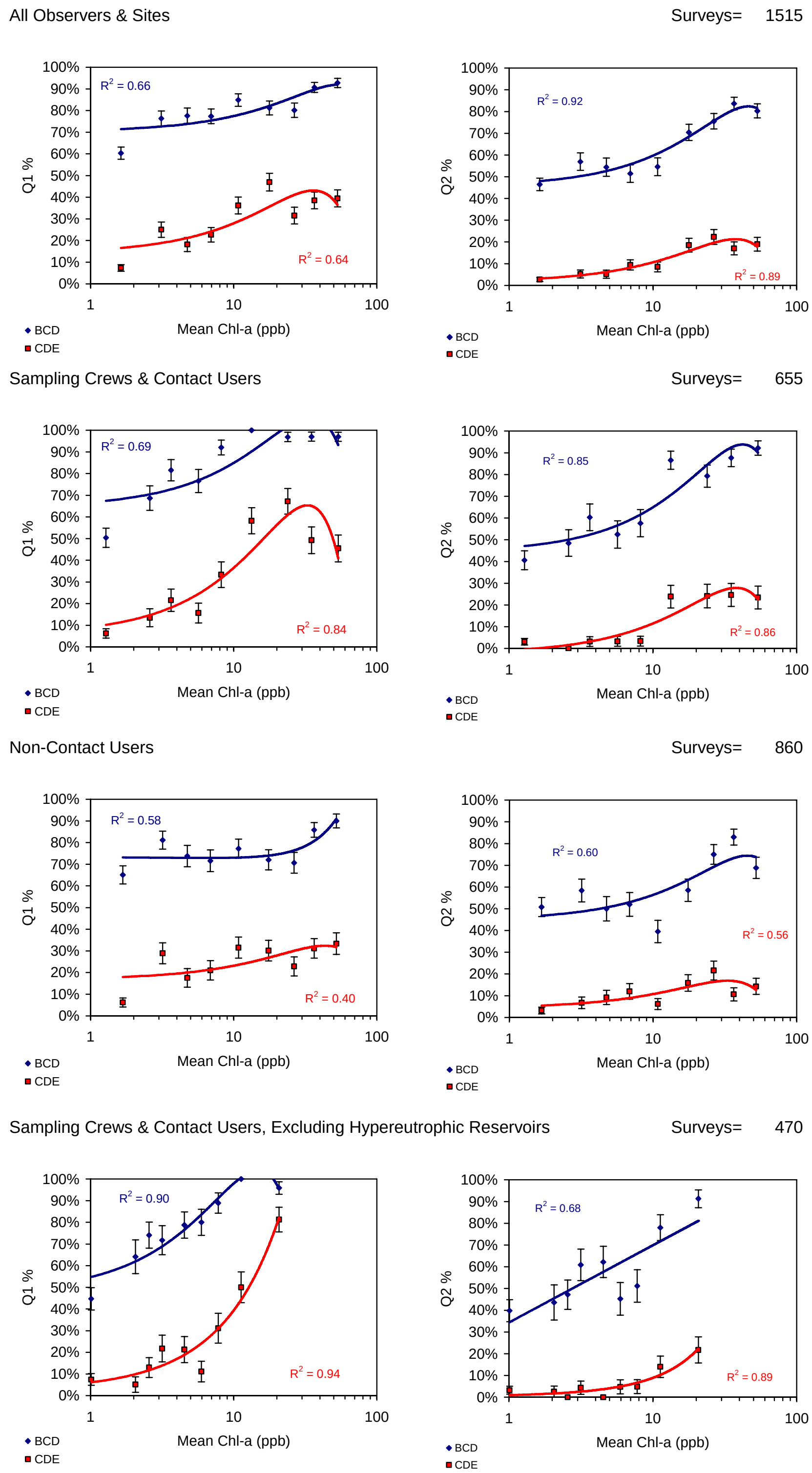
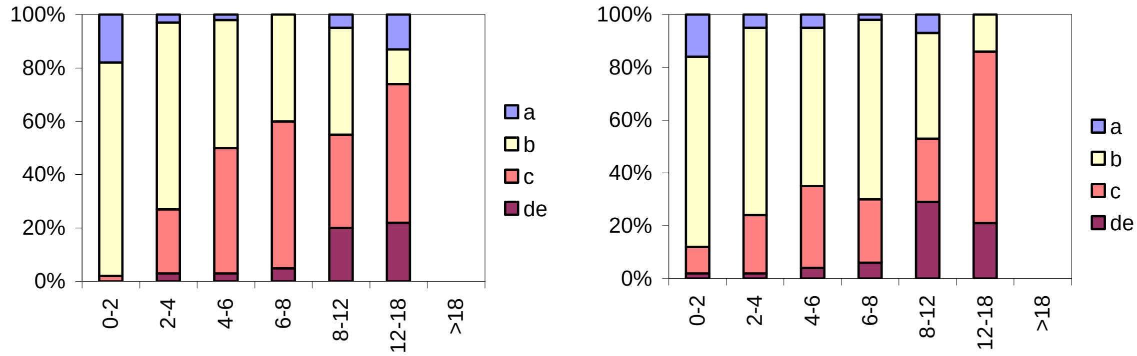


Figure 14. Survey Responses vs. Chlorophyll-a for Pooled Dataset. X= interval-mean Chl-a; Y = % BCDE & % CDE responses (mean +/- 1 standard error); Lines = polynomial regression. Each dataset is divided into 10 chl-a intervals with equal sample size.

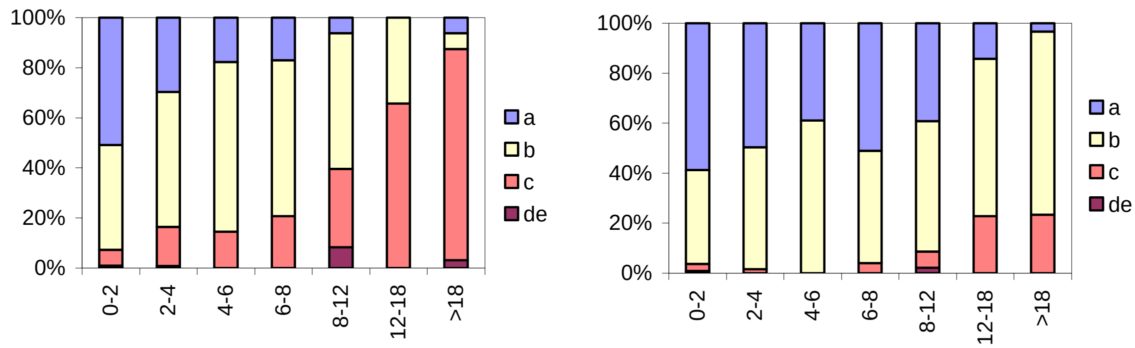
Question 1 - Appearance

Question 2 - Use Impact

Lake Champlain



Texas Reservoir - Sampling Crew or Contact User



Texas Reservoir - Other Observers

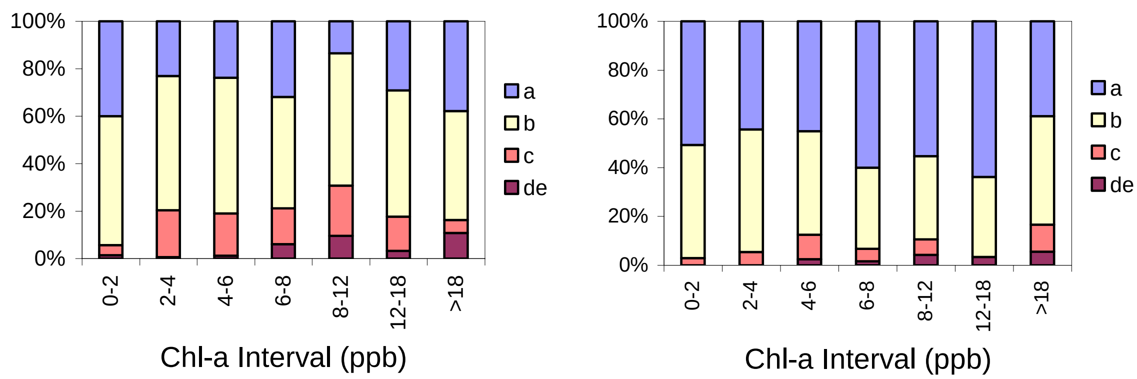


Figure 15. Comparison of Lake Champlain & Texas Reservoir Surveys.
Texas data exclude eutrophic reservoirs (Cedar Creek & Livingston) and turbid reservoirs (Granger)

APPENDIX E

CHLOROPHYLL-*A* STANDARD OPERATING PROCEDURES

APPENDIX E

STANDARD OPERATING PROCEDURE FOR CHLOROPHYLL-A DETERMINATION USED BY SABINE RIVER AUTHORITY

1 SCOPE & APPLICABILITY

1.1 This method is for determining chlorophyll *a* concentration in natural water samples using a spectrophotometer with a 2nm spectral bandwidth.

1.2 This method is prepared in conjunction with guidelines from EPA Method 446.0, Revision 1.2 and Standard Methods for the Examination of Water and Wastewater, 20th Edition, Method 10200H "Chlorophyll".

2 SUMMARY OF METHOD

2.1 A 200mL, or otherwise specified, aliquot of natural water is filtered in a dark room. Pigment is extracted from the filter through maceration, steeping, and centrifugation in 90% acetone. The pigment extract is then analyzed using a spectrophotometer at 664nm and 750nm, and again after acidification at 650nm and 750nm. Addition of acid results in the loss of the magnesium atom, converting chlorophyll *a* to pheophytin *a*. The change in optical density after acidification is used to determine the corrected values for chlorophyll *a*.

2.2 The lower detection limit for this method is approximately 3µg/L, when incorporating a 200mL filtered sample volume and a 20mL extract volume. When other analysis volumes are used, the lower detection limit must be calculated using the absorbance detection limit value for the spectrophotometer. This absorbance detection limit is determined through method detection limit (MDL) studies.

3 DEFINITIONS

The definitions and purposes below are specific to this method, but have been conformed to common usage as much as possible.

3.1 Analyte = the component of interest, in this case, "chlorophyll *a*".

3.2 Chlorophyll *a* = a photosynthetic pigment which is a component of planktonic algae, constituting 1-2% of the dry weight. Chlorophyll *a* is used extensively to estimate phytoplankton biomass.

3.3 Laboratory Pure Water = reagent water meeting purity characteristics of ASTM Type II laboratory distilled water (daily conductivity <1.0umhos/cm).

3.4 Method Blank = a sample containing no target analyte that is taken through the entire sampling and analytical procedure. The analysis of a method blank helps identify any contamination introduced in the analysis process. In this case, the method "blank" consists of 100mL of laboratory pure water that is treated as a natural water sample.

4 HEALTH AND SAFETY WARNINGS

4.1 Lab Safety - Safety glasses are required for all laboratory analysis. Use gloves to avoid skin irritation from contact with acetone; work under a hood when possible. Please refer to the MSDS file for any other information about personal protective equipment and other safety considerations.

4.2 Chemical Hygiene - Hazards of the chemicals used in this method were discussed in the previous section. Please refer to the MSDS file for any further questions concerning a chemical's toxicity and the necessary safety precautions.

4.3 Waste Disposal – Waste is disposed of in an appropriate acetone collection bottle. Dirty 5cm spectrophotometric cells are rinsed with lab pure water and 90% acetone solution.

4.4 Pollution Prevention – If waste is disposed of correctly, no pollution problems should occur from using this method.

5 INTERFERENCES

5.1 Chlorophyll *a* can be significantly under or over-estimated using a spectrophotometer for analysis in part because of the overlap of the absorption bands of co-occurring accessory pigments and chlorophyll *a* degradation products. Using a spectrophotometer with a spectral bandwidth of 2nm or less can help prevent some of these errors.

5.2 Light, changes in temperature, and exposure to air can also interfere with the test, leading to decreases in chlorophyll *a* concentration. Use care in dealing with samples during the analysis process.

5.3 Excess sample turbidity can interfere with proper absorbance readings. 750nm absorbance results represent sample clarity/turbidity; this value should be less than 0.005 absorbance units for optimal chlorophyll *a* results. Samples with a 750nm absorbance of greater than 0.02 must be centrifuged again, except under special circumstances. See management staff if there is a question on sample clarity.

6 PERSONNEL QUALIFICATIONS AND RESPONSIBILITIES

6.1 General Responsibilities – This method is restricted to use by or under the supervision of analysts experienced with the method. Each analyst must be trained and able to read and understand the SOP.

6.2 Laboratory Analysts and Technicians – It is the responsibility of analyst/technicians to:

6.2.1 Read and understand this SOP and follow it as written.

6.2.2 Produce quality data that meets all laboratory and customer requirements.

6.2.3 Complete the required demonstration of proficiency before performing this procedure without supervision.

6.2.4 Enter laboratory sample and QC results into the LIMS data system for laboratory supervisor review.

6.2.5 Repeat the required initial demonstration of laboratory capability each time a modification is made to the method.

6.3 Section Leaders – It is the responsibility of the section leader to:

6.3.1 Ensure that all analysts/technicians have the technical ability and have received adequate training required to perform this procedure.

6.3.2 Ensure analysts/technicians have completed the required demonstration of proficiency before performing this procedure without supervision.

6.3.3 Produce quality data that meets all laboratory and customer requirements.

7 APPARATUS AND MATERIALS

Brand names, suppliers, and part numbers are cited for illustrative purposes only. No endorsement is implied. Equivalent performance can be achieved using equipment and materials other than those specified here, but demonstration of equivalent performance that meets the requirements of this method is the responsibility of the laboratory.

7.1 Milton Roy GENESYS™ 6 spectrophotometer, or equivalent, with an adaptor for cylindrical cells

7.2 5cm cylindrical cells with caps, Fisher Scientific #14-385-930E

7.3 Whatman glass microfiber filters GF/F - 47mm or equivalent

7.4 Vacuum pump

7.5 Gelman magnetic filter funnels

7.6 1000mL side-arm filtering flasks

7.7 Graduated cylinders

7.8 Yamato overhead lab stirrer for grinding filters

7.9 Plastic disposable pipettes

7.10 Kontes glass round-bottom 25mL tubes with grinding pestle attachments

7.11 35mL and 15mL graduated polypropylene centrifuge tubes with caps

7.12 ThermoIEC Centra CL2™ centrifuge or equivalent

7.13 100-1000µL Brinkmann Eppendorf™ micropipette with adjustable dispensing volume feature

7.14 Refrigerator with freezer

8 REAGENTS, GASES, AND STANDARDS

8.1 Lab Pure Water

8.2 90% Acetone Solution: Add 900mL of pure acetone to a 1L volumetric flask, and dilute to the mark with lab pure water. Shake or stir to mix. Use until empty.

8.3 Hydrochloric Acid (HCl), 0.1N: Add 8.5mL of concentrated hydrochloric acid to a 1L flask containing about 500mL of lab pure water. Cool and dilute to the mark with lab pure water. Stir to mix. Use until empty.

8.4 Magnesium Carbonate/90% Acetone Solution: Add 1.0g of solid magnesium carbonate to a 100mL flask, and dilute to the mark with lab pure water. Stir to dissolve as much magnesium carbonate as possible. Filter this mixture using a glass fiber filter and add the filtrate to 900mL of acetone in a 1L flask. Use lab pure water to dilute to the mark, if necessary. Stir to mix. Use until empty.

8.5 Turner Designs Chlorophyll *a* in 90% Acetone Standard Ampoule, concentration varies: This standard is purchased; it is used to find the lower absorbance detection limit of the spectrophotometer (MDL study) and prepare check standards. Use until expiration date, if stored in a freezer.

8.6 Turner Designs Chlorophyll *a* in 90% Acetone, Stock Standard: Transfer 15-17mL from a Turner Designs chlorophyll *a* standard ampoule to a 500mL flask and dilute to the mark with 90% acetone solution. Use chilled pipettes and volumetric flasks when making transfers. Calculate the stock standard concentration using the original concentration of the ampoulized standard. Use until expiration date of original ampoule, if stored in a freezer.

8.7 Turner Designs Check Standard: The concentration of this standard should be close to that of the method estimated detection limit, determined to be 35.4µL. Preparation instructions will vary depending on the concentration of the Turner Designs chlorophyll *a* standard ampoule. Use chilled pipettes and volumetric flasks when making transfers. Prepare fresh with each analysis batch; this check standard should be assigned a standard number.

8.8 Sigma Aldrich 1mg/L Spinach Standard: a purchased ampoulized standard that is used to prepare chlorophyll *a* dilutions for determining upper detection limit data.

9 SAMPLE COLLECTION, HANDLING, AND PRESERVATION

9.1 Aqueous samples are collected in amber jars and stored at 4 ± 2ºC in a dark environment. After samples are obtained, they should be put on ice immediately to avoid degradation.

9.2 Filtration must be completed within 48 hours after samples are collected. The sample filters can be stored frozen for no more than 14 days; filters must be analyzed within this time period.

10 METHOD CALIBRATION

10.1 No method calibration is necessary for this procedure. A spectrophotometer check is conducted quarterly with certified standards to validate instrument performance.

11 SAMPLE PREPARATION AND BATCH ANALYSIS

11.1 Aqueous Sample Preparation:

11.1.1 Conduct filtration in an area with subdued light. Rinse a glass-fiber filter with 100mL of lab pure water. Measure 200mL of well-mixed sample into a graduated cylinder and filter. A smaller sample volume can be used if samples are high in solids (turbidity). NOTE: Notify management staff before using alternate filter volumes; this will affect the reportable detection limit for chlorophyll *a*. Larger volumes can also be used to increase method sensitivity, where applicable. Filter one lab pure water blank and one duplicate for every 10 or fewer samples in a QC filtration batch.

11.1.2 After filtration, fold each filter in half, then two more times (with the residue on the inside) and place inside a plastic 15mL capped centrifuge tube. Make sure that all tubes are numbered and that the numbers and corresponding samples are recorded in the chlorophyll *a* filtration bench book. Record any necessary comments about sample appearance in the bench book.

11.1.3 If sample filters are to be analyzed immediately, go to the next step. Place sample filters in the laboratory freezer for analysis at a later date (store frozen for no more than 14 days).

11.1.4 Transfer an individual filter to a 25mL round bottom grinding test tube and add approximately 5mL of magnesium carbonate/90% acetone solution (NOTE: Maceration is more effective when grinding half of the filter at a time). Tear the filter into pieces to achieve more efficient maceration. (NOTE: Set 15mL labeled plastic tubes aside to use again later).

11.1.5 Securely attach a grinding pestle to an overhead stirring apparatus. Place the grinding pestle slowly into the grinding test tube, submerging it in the 5mL of solution. SLOWLY begin stirring, accelerating the speed to approximately 500 rpm. Stir for several minutes, moving the grinding tube up and down, to macerate the residual filter. Analytical judgment must be used in determining maceration completion. Slowly reduce the stirrer speed while removing the tube from the pestle, avoiding any splashing of tube contents. Rinse residue on pestle with 90% acetone solution into the grinding tube.

11.1.6 Carefully and quantitatively transfer grinding tube contents to a 35mL graduated centrifuge tube with multiple washings and adjust the total volume to 20mL with 90% acetone solution. (NOTE: Extraction volume may vary based on sample appearance. Notify management staff before using an alternate extract volume; this will affect the reportable detection limit for chlorophyll *a*.) Shake each capped tube individually.

11.1.7 Steep samples at a diagonal in a dark refrigerator for AT LEAST 2 hours and no more than 24 hours, shaking each tube several times during this period to allow for maximum filter/acetone contact.

11.1.8 After steeping, centrifuge the samples for 30 minutes at 4000rpm in the 35mL plastic centrifuge tubes. Carefully transfer 13mL of the clarified liquid extract into the ORIGINAL 15mL labeled plastic test tubes with a plastic disposable pipette, leaving the filter residue at the bottom. Centrifuge the 15mL tubes for 30 minutes at 4000rpm. Keep the samples in the dark until analysis.

11.2 QC Batch Analysis:

11.2.1 Turn on the GENESYS 6 spectrophotometer and let it warm up for at least 30 minutes. Use the arrow key on the instrument keypad to highlight the CHLORO #1 program, then press ENTER. Press the RUN TEST key on the screen keypad to display the analysis screen.

11.2.2 Transfer 11mL of sample extract to a 5cm pathlength cylindrical cell using a plastic disposable pipette, avoiding the introduction of solids from the bottom of the test tube. Wipe off the outside of the cell with a Kimwipe™ to remove smudges or excess sample.

11.2.3 Fill a separate 5cm cell with 90% acetone and insert it into the spectrophotometer (Cells have been set aside as "blanks" for this purpose). Press the MEASURE BLANK button. Insert your sample cell, and press MEASURE SAMPLE. The spectrophotometer will print the sample absorbances at 664nm and 750nm on the screen and on paper. The 750nm absorbance should be less than 0.02 for acceptable results; if it is not, the sample can be further centrifuged to remove turbidity.

11.2.4 Add exactly 330µL of 0.1N HCl using an adjustable volume micropipette to the sample cell and slowly rock it back and forth to mix. Be careful not to shake the cell or introduce any air. Wait 90 seconds after acidification before taking absorbance readings. Setting a timer will help.

11.2.5 Using the spectrophotometer keypad, access the "CHLORO 2" program by following the steps below:

11.2.5.1. Hit the ESC key to exit the CHLORO 1 program.

11.2.5.2. Press the STORED TESTS key on the screen keypad, and then LOAD INTERNAL TEST and ENTER.

11.2.5.3. Use the arrow key on the keypad to highlight the CHLORO #2 program and press ENTER.

11.2.5.4. Press the RUN TEST key on the screen keypad to display the analysis screen.

11.2.5.5. Repeat step 11.2.3 to measure the blank and sample at 665nm and 750nm. Save all spectrophotometer printouts.

11.2.6 A Turner Designs check standard (see the REAGENTS, GASES, and STANDARDS section) should be analyzed with each QC batch. This standard is analyzed in the same way as a batch sample, and results should be recorded in the chlorophyll *a* bench book.

11.2.7 Rinse all dirty sample cells with lab pure water and 90% acetone to rinse. Allow them to air dry. Wash all test tubes and plastic ware by hand with laboratory pure water, solid detergent soap, and acetone.

12 DATA ACQUISITION, CALCULATIONS, & DATA REDUCTION

12.1 Filtration batch data is currently recorded in a chlorophyll *a* filtration logbook. Spectrophotometric data from chlorophyll *a* analysis is currently recorded in a chlorophyll *a* analysis bench book and entered into a computer calculation program to obtain final results. Individual LIMS worklists should be pulled for filtration and analysis. Results are manually entered into the laboratory information management system (LIMS). The method lower detection limit should be calculated based on the sample volume and extract volume used, as well as the current lower absorbance detection limit.

12.2 Chlorophyll *a* Calculations:

If a computer program is not available, calculate chlorophyll *a* concentration as follows:

$$\text{Chlorophyll } a\text{, mg/L} = \frac{26.7 * (664 \text{ abs} - 665 \text{ abs}) * EV}{SV * L}$$

$$\text{Pheophytin } a\text{, mg/L} = \frac{26.7 * [1.7(665 \text{ abs}) - 664 \text{ abs}] * EV}{SV * L}$$

Where:

EV = volume of extract, L (0.020 typically)
SV = volume of whole water sample filtered, L (0.2 typically)
L = optical pathlength of cuvette, cm (5)

Note: Multiply by 1000 for results in µg/L.
750nm wavelength results can be subtracted out to correct for any clarity/turbidity issues.

When analyzing standards (ex. Turner Designs), where no filtration or maceration is required, use the following equations:

$$\text{Chlorophyll } a\text{, mg/L} = 26.7 * (664 \text{ abs} - 665 \text{ abs})/L$$

$$\text{Pheophytin } a\text{, mg/L} = 26.7 * [1.7 * ((665 \text{ abs}) - (664 \text{ abs}))]/L$$

12.3 QC Calculations:

Calculate % recovery (%R) for check standards using the following equation:

$$\%R = \frac{\text{Test Result}}{\text{True Result}} * 100$$

Where:

Test Result = the value obtained from the analysis
True Result = the actual value of the standard or LCS

Calculate the %RPD (precision and replication evaluation) for sample duplicates using the following equation.

$$\%RPD = \frac{[SR1 - SR2]}{\frac{1}{2} * (SR1 + SR2)} * 100$$

Where:
SR1 = sample result for replicate 1
SR2 = sample result for replicate 2

13 QUALITY CONTROL, ACCEPTANCE CRITERIA, AND CORRECTIVE ACTION

13.1 Method Blank:

13.1.1 Frequency: A method blank will be analyzed once per QC batch. The method blank consists of 200mL of laboratory pure water treated as a sample. This blank should be less than the calculated method lower detection limit for the analysis.

13.1.2 Acceptance Criteria: If the blank result is greater than the lower detection limit, notify management staff.

13.1.3 Corrective Action: Notify management staff if there is a problem with the laboratory pure water or GENESYS 6 spectrophotometer.

13.2 Matrix Duplicates:

13.2.1 Frequency: Matrix duplicates will be prepared and analyzed on a frequency of at least one per 10 or fewer samples in a filtration batch.

13.2.2 Acceptance Criteria: Refer to the QA book for chlorophyll *a* to obtain the latest control limits for matrix duplicate %RPD values. Limits are recalculated approximately every 40 data points. All duplicate %RPD values are to be recorded and plotted in this book.

13.2.3 Matrix/Standard Spike Recovery and Duplicate RPD Failure Corrective Action: If the duplicate %RPD does not meet the acceptance criteria, the system has to be evaluated for possible errors. All samples must be reanalyzed, or if there is insufficient sample for reanalysis or the sample holding time has expired, the samples must be reported as "No Result." In all cases, the out-of-control result should be recorded in the logbook on the QA officer's desk and the QA officer should be notified.

13.3. Turner Designs Check Standard:

13.3.1. Frequency**:** A Turner Designs check standard should be analyzed with every QC batch

13.3.2 Acceptance Criteria**:** Refer to the QA book for chlorophyll *a* to obtain the latest control limits for check standard %R. Limits are recalculated approximately every 40 data points. All %R data are to be recorded and plotted in this book.

13.3.3 Check Standard and LCS Recovery Failure Corrective Action: If the %R data does not meet the acceptance criteria, the system has to be evaluated for possible errors. In all cases, the out-of-control result should be recorded in the logbook on the QA officer's desk and the QA officer should be notified. Affected samples may be reanalyzed, or if there is insufficient sample for reanalysis or the sample holding time has expired, the samples may be reported as "No Result," or accepted by the QA officer based on other criteria.

14 REFERENCE SECTION

14.1 Standard Methods for the Examination of Water and Wastewater, 20th Edition, 1998, Method 10200H "Chlorophyll"

14.2 EPA Method 446.0, Revision 1.2, September 1997, "In Vitro Determination of Chlorophylls a, b, $c_1 + c_2$ and Pheopigments in Marine and Freshwater Algae by Visible Spectrophotometry."

15 METHOD PERFORMANCE

15.1 See the chlorophyll *a* QA book for details on recent method performance.

Sabine River Authority
Environmental Services Division

Chlorophyll a Standard Operating Procedure Development Special Project

Background

Results from the spectrophotometric analysis of chlorophyll *a* have historically produced variable results, often with less than satisfactory quality assurance; and published analysis methods leave many test parameters open to analyst interpretation. Consequentially, there was a need to study chlorophyll *a* methodology to determine possible areas for improvement and standardization. The purpose of this study was to determine to what extent collection and analytical technique variables affect the results of spectrophotometric analyses of chlorophyll *a* sampled from Texas surface waters.

At the request of the Texas Commission on Environmental Quality, the Sabine River Authority (SRA) conducted a series of chlorophyll *a* analyses using Method 10200-H from *Standard Methods for the Examination of Water and Wastewater, 19th Edition.* The study used the algae *Selenastrum capricornatum* cultured in-house, and the cell count was determined using a hemacytometer. Samples from the culture were analyzed for chlorophyll *a* to determine the typical absorbance range for that known cell concentration. The algae culture was then used to study the precision and accuracy of the acidification techniques, steeping duration, freezing duration, and filtering methods involved in chlorophyll a analysis.

Initial Quality Control

The linear dynamic range (LDR) and instrument detection limit (IDL) were determined for the Spectronic™ GENESYS 6™ UV-Vis Spectrophotometer[1]. An estimated detection limit (EDL) was also calculated using a set of natural phytoplankton samples.

Dilutions were made from standards of known chlorophyll *a* concentration provided by outside vendors. The dilution series was analyzed using the GENESYS 6™ equipped with a 5 cm pathlength cell and instrument absorbance response was recorded. These absorbance results were used to determine the slope and y-intercept of the calibration linear regression and to make capability determinations about the spectrophotometer. Thirteen natural water samples were collected, filtered, macerated, and analyzed according to Method 10200-H; these sample results were then used to calculate an EDL.

The results indicated that a lower detection limit of 0.01 mg/L and an upper analytical limit of 8 mg/L can be achieved for chlorophyll a analysis. A good working range was found to be 0.01 – 1 mg/l.

[1] http://www.thermo.com/com/cda/product/detail/1,1055,17245,00.html, accessed 4/24/05.

Study Procedures

For the procedures using the cultured algae, 100 mL replicate samples were obtained from the stock culture with a known cell concentration. Blank and sample replicates were filtered through Whatman® GF/F glass fiber filters in a darkened room. Samples were filtered for no more than ten minutes per filter and not filtered to dryness. After filtering, forceps were used to remove and fold the filter in half, twice longitudinally, to form a narrow packet. The folded filter was then placed in an opaque plastic 15 mL centrifuge tube. Maceration was performed using a mechanical glass tissue grinder at 400 rpm for two minutes. The filter residue was brought to a volume of 15 mL with magnesium carbonate/90% acetone solution and allowed to steep approximately one hour. Blanks and samples were then analyzed using a 2 nm bandwidth GENESYS 6™ spectrophotometer equipped with a 5 cm pathlength cell at 664, 665, and 750 nm wavelengths. The results from the absorbance readings were printed from the instrument and recorded in the bench book. Final results were calculated using Lorenzen's Pheopigment-Corrected Chlorophyll *a* and Pheophytin *a* equations found in Section 12.2 of EPA Method 446.0 for Chlorophyll *a*.

Acidification Technique

Acidification technique was evaluated using replicate 100 mL samples of cultured algae and filter blanks. The purpose was to determine in the acidification step if pipette mixing or hand mixing results in a significant difference in chlorophyll *a* results. A pipette[2] was used to add the acid to the sample in the cylindrical spectrophotometric cell. Mixing was accomplished by repeatedly withdrawing part of the solution and then slowly replacing it into the cell. The "hand-mixing" technique utilized a slow tilting of the cylindrical cell back and forth to mix the acid and sample after the addition of the acid.

The final results did not show a significant difference between the two methods of acidification, but the hand mixing technique was found to be less likely to introduce error by the addition of air to the sample cell or loss of sample.

[2] Result comparison from inter-laboratory analyses of split samples during the study revealed that delivering an exact volume of acid using a calibrated micro-pipette produced more consistent results than delivering the acid with a "eye-dropper" type pipette.

Steeping Duration

Replicate sets consisting of three 100 mL filter blanks and fifteen 100 mL samples of cultured algae were used to evaluate the effect of steeping duration on the chlorophyll *a* results. The steeping duration test results are shown in Table 1.

Table 1

	Steeping Duration		
Replicate	**2 hrs**	**18.5 hrs**	**23.5 hrs**
1	19.2	34.2	28.8
2	23.8	41.7	32.0
3	31.0	37.4	21.4
4	35.2	39.5	41.7
5	29.9	29.9	47.0
Average	***27.8***	***36.5***	***34.2***
Min	***19.2***	***29.9***	***28.8***
Max	***35.2***	***41.7***	***47.0***
StdDev	***7.6***	***3.0***	***12.9***

No relationship between steeping duration and chlorophyll *a* concentration was observed from the data.

Freezing Duration

The purpose of this analysis was to explore freezing time as a possible contributing factor to chlorophyll *a* result variability. Four 100 mL filter blanks and twenty 100 mL samples of cultured algae were filtered. Each sample filter set was prepared from the same algae culture dilution. The absorbance data and final chlorophyll *a* results obtained from the study are detailed in Table 2.

Table 2

	Freezing Duration			
Replicate	**0 Days**	**5 Days**	**14 Days**	**26 Days**
1	30.4	31.2	36.8	36.0
2	18.4	35.2	30.4	52.1
3	25.6	35.2	31.2	42.5
4	43.3	42.5	20.0	45.7
5	33.6	40.0	*No Result*	*No Result*
Average	***30.3***	***36.8***	***29.6***	***44.1***
Min	***30.4***	***31.2***	***20.0***	***36.0***
Max	***43.3***	***42.5***	***36.8***	***52.1***
StdDev	***2.3***	***6.2***	***11.9***	***6.9***

Filters were more difficult to macerate at this stage due to filter hardening. Problems were also noted with maceration involving the 0 day set, since filters were still very wet. The fewest problems with maceration were observed in the 5 to 14 days sets. No significant losses in chlorophyll *a* concentration over time were observed from the data.

Field vs. Laboratory Filtration

This portion of the study was to determine if a loss of chlorophyll *a* concentration occurs in samples that are transported for laboratory filtration (within 12 hours of collection). Samples of natural water were collected from two different sites and split into two potions for field and laboratory filtrations. The field portions were filtered into five aliquots of 420 mL using a calibrated syringe filtration apparatus. The five laboratory sample portions were divided into 500 mL opaque plastic bottles and stored on ice during transport. When the samples arrived at the laboratory, 420 mL samples were filtered from each bottle using the field syringe filtration apparatus. Results for each sample set are listed in Table 3:

Table 3

	Lab vs. Field Filtration			
Replicate	Lab-Site 6A	Field-Site 6A	Lab-Site 6CN	Field-Site 6CN
1	3.1	2.8	6.1	9.9
2	4.1	5.1	6.6	6.1
3	3.3	3.3	8.6	6.4
4	5.1	4.8	4.8	4.3
5	4.3	4.8	*9.2*	*6.1*
Average	***4.0***	***4.2***	***6.5***	***6.7***
Min	***3.1***	***2.8***	***4.8***	***4.3***
Max	***5.1***	***5.1***	***8.6***	***9.9***
StdDev	***0.8***	***1.4***	***0.9***	***4.0***

No significant chlorophyll *a* loses were observed when field sample were preserved and transported for same-day laboratory filtration; therefore, field filtration offers no quantifiable analytical advantage over laboratory filtration.

Conclusions

The study demonstrated that hand mixing after acidification was sufficient and avoided the addition of air to the sample or the loss of sample, particularly when using a 5 cm pathlength cylindrical cell.

Although each of the freezing duration times studied produced suitable results, a freezing interval of one to fourteen days was found to be optimal for proper filter maceration. Chlorophyll *a* results are highly dependant on adequate maceration of filters. Wet and overly hardened filters can create maceration problems, which affect final sample turbidity and result variability. This is especially true when using glass fiber filters.
Increased extract clarity can also be achieved by varying spectrophotometric cell size. It was also determined that a higher dilution volume prior to steeping improved sample clarity. The filter slurry was increased to 20 mL volume instead of the original 15 mL.

It was found that the use of glass fiber filters for chlorophyll *a* sample filtration improved maceration by assisting in the breaking of algae cell walls. Glass fiber filters are specified in EPA Method 446.0; however, glass fiber and membrane filters are both acceptable in Method 10200H.

No significant difference in chlorophyll a concentration was determined between ambient water samples filtered in the field or filtered in the laboratory.

Although not part of the original study plan, it was discovered that the time between acidification and obtaining final absorbance readings should be standardized. EPA Method 446 specifies a 90-second interval between acidification and final spectrophotometric analysis, but the time interval is not specified in Method 10200H. Test results show optimum results when the final absorbance readings were taken 90 seconds after acidification.