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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by

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

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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_Main	#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

All Reservoirs

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

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

Cove_Ma	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

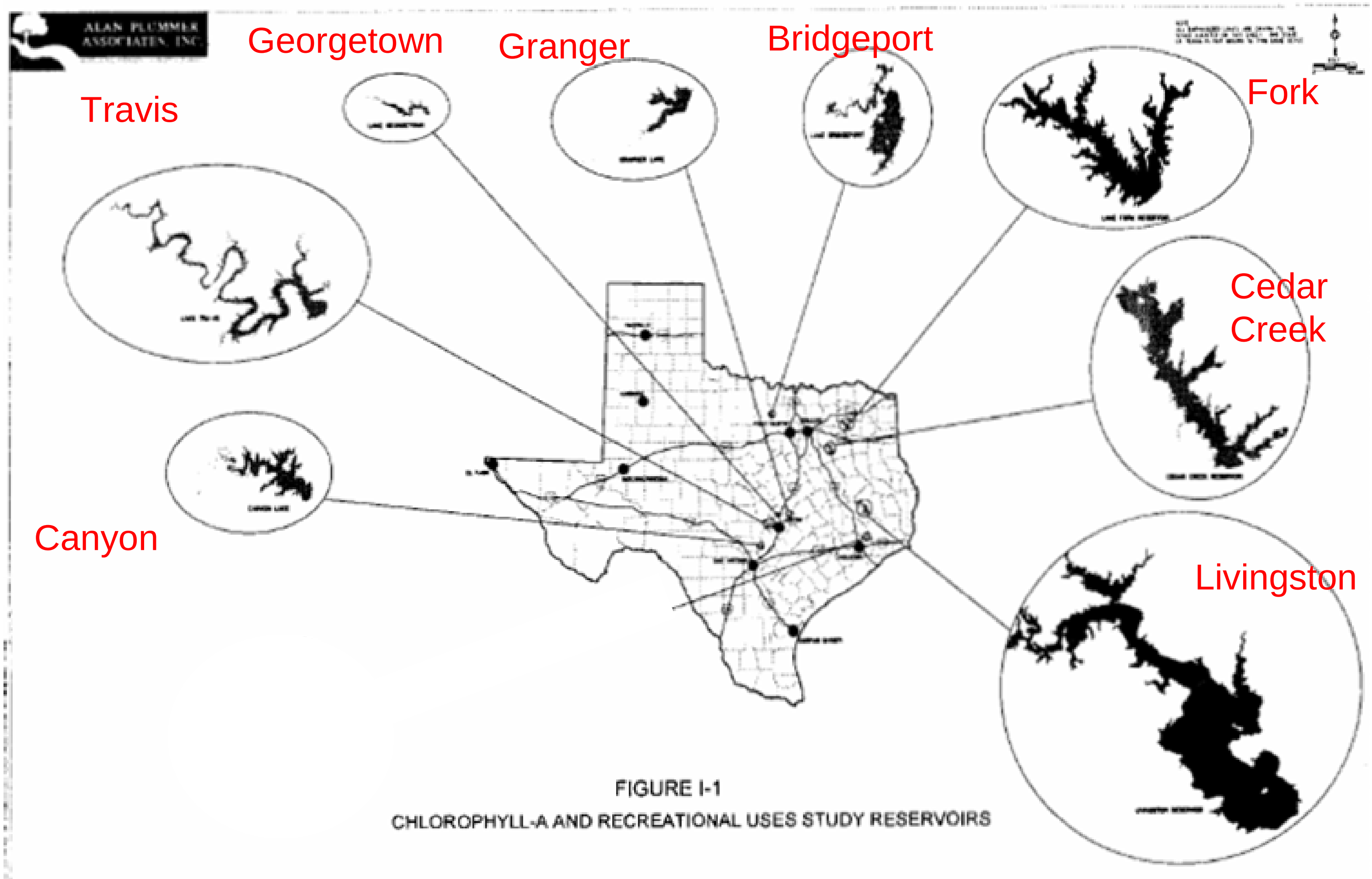


Figure 1. Study Reservoirs.

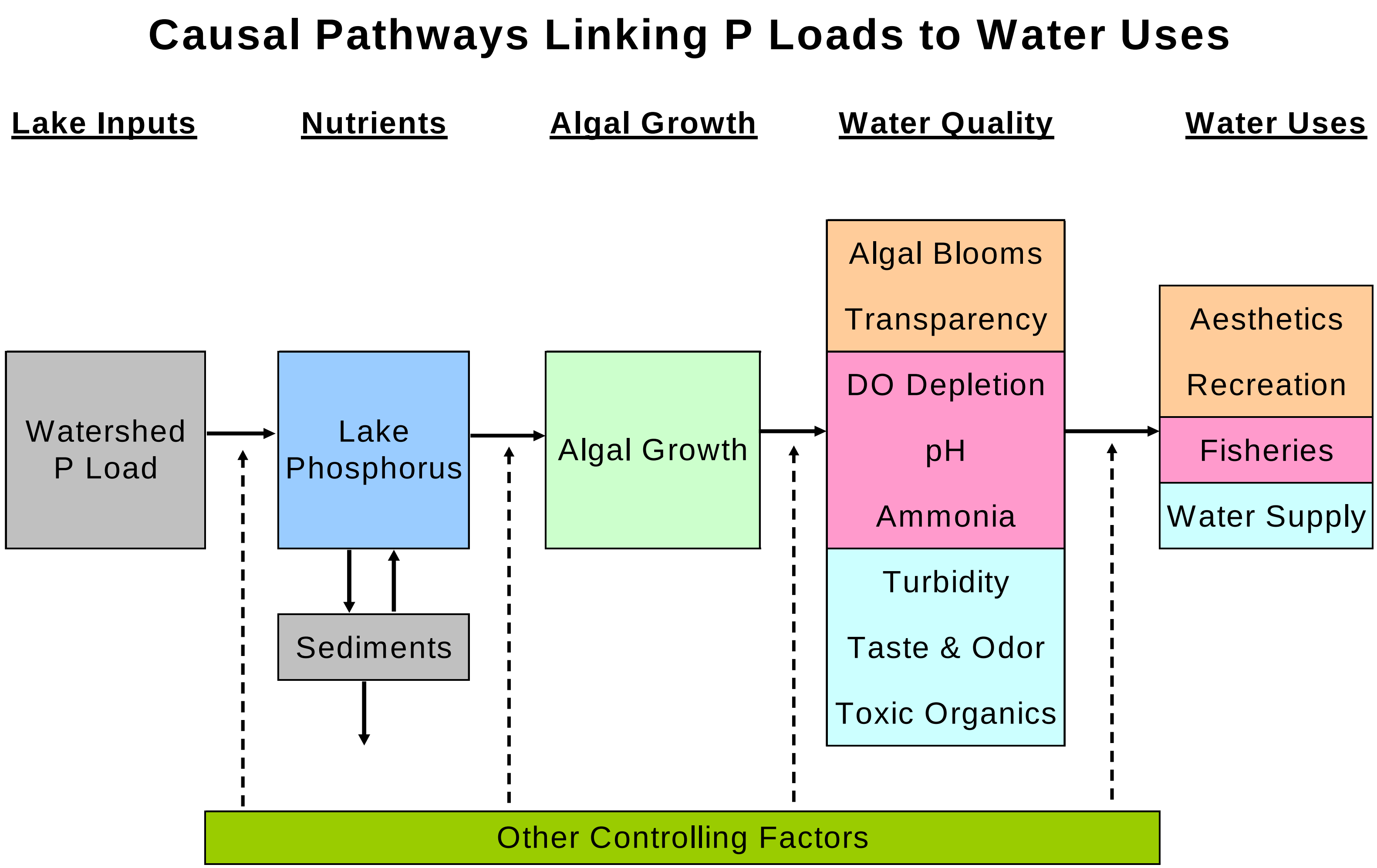


Figure 2. Causal Pathways Linking Phosphorus Loads to Water Uses.

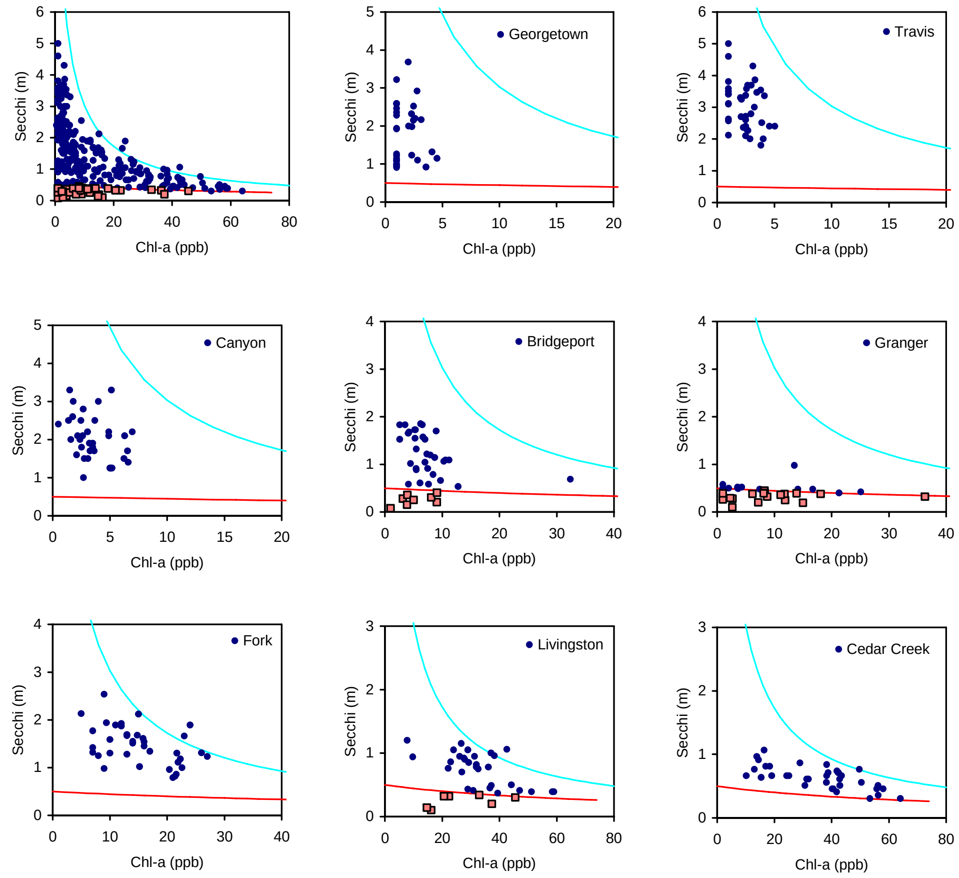


Figure 3. Secchi Depth vs. Chlorophyll-a for Each Reservoir & Sample.
Lines show predicted transparency for different levels of non-algal turbidity (a = 0.08 to 2.0 m^{-1})
using CE reservoir Secchi vs. chl-a model : 1/Secchi = a + b Chl-a, b = 0.025 m^2/mg.
Square symbols are samples with relatively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

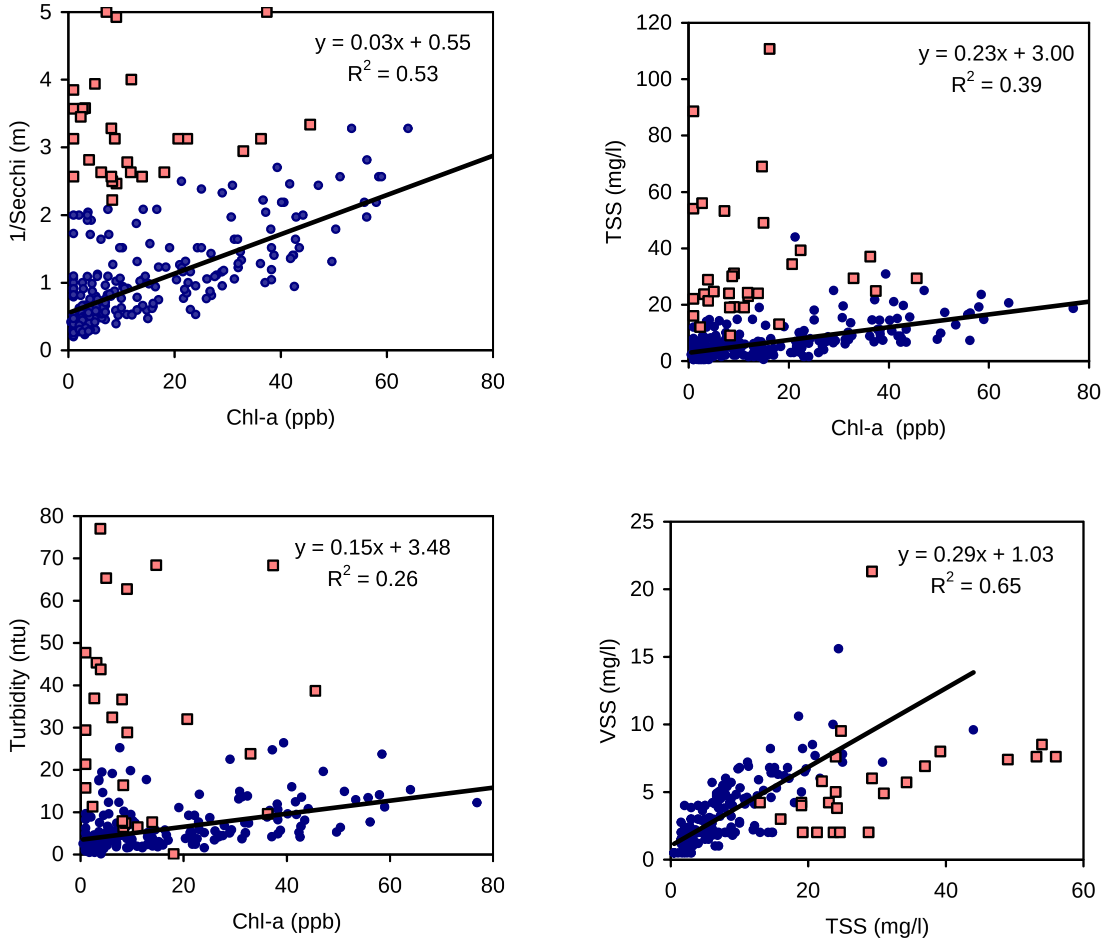
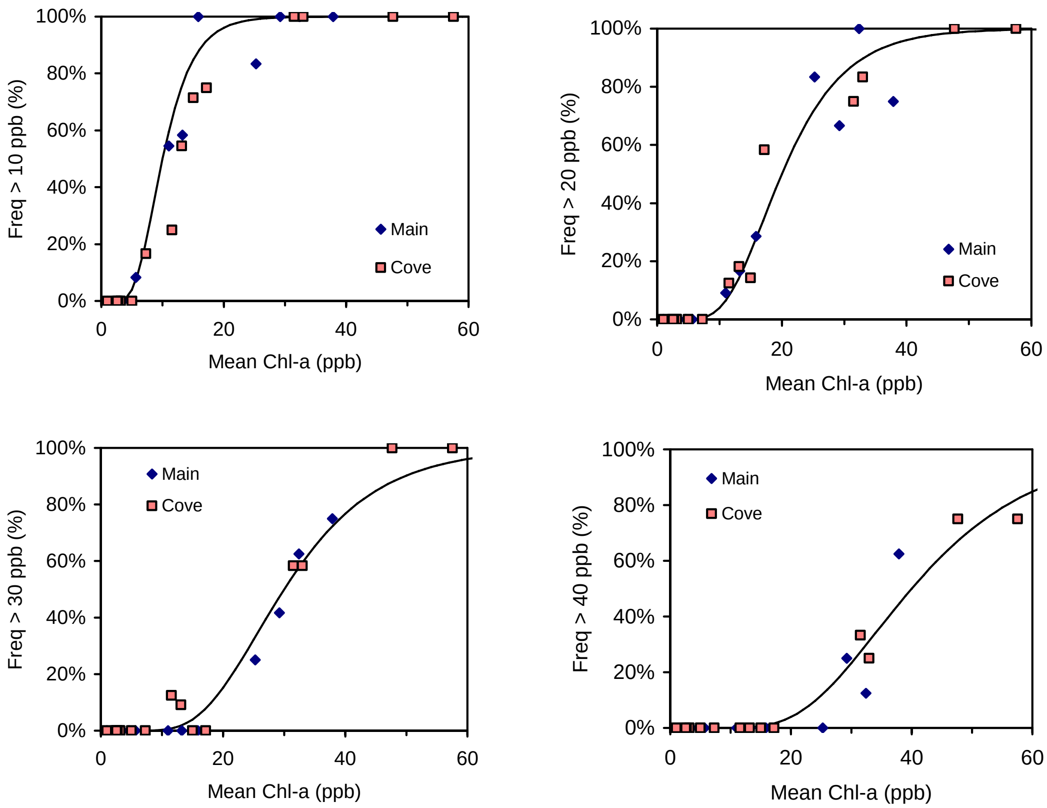


Figure 4. Identification of Samples with High Non-Algal Turbidity. Square symbols are samples with non-algal turbidity > 2 m^{-1}, computed from Secchi depth & chl-a data, (Figure 3). Lines are regressions using the remaining data.



Calibration of Log-Normal Model:

Yearly Maximum vs. Mean:

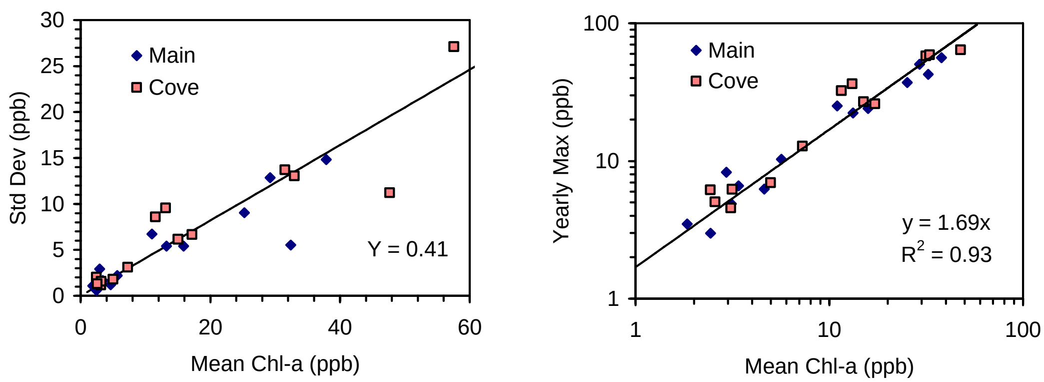


Figure 5. Chlorophyll-a Interval Frequencies vs.Yearly Site Mean Concentration. Log-normal distribution model (Walker, 1985); CV = standard deviation across dates / station mean = 0.41. Std Dev of Ln (Chl-a) = 0.39

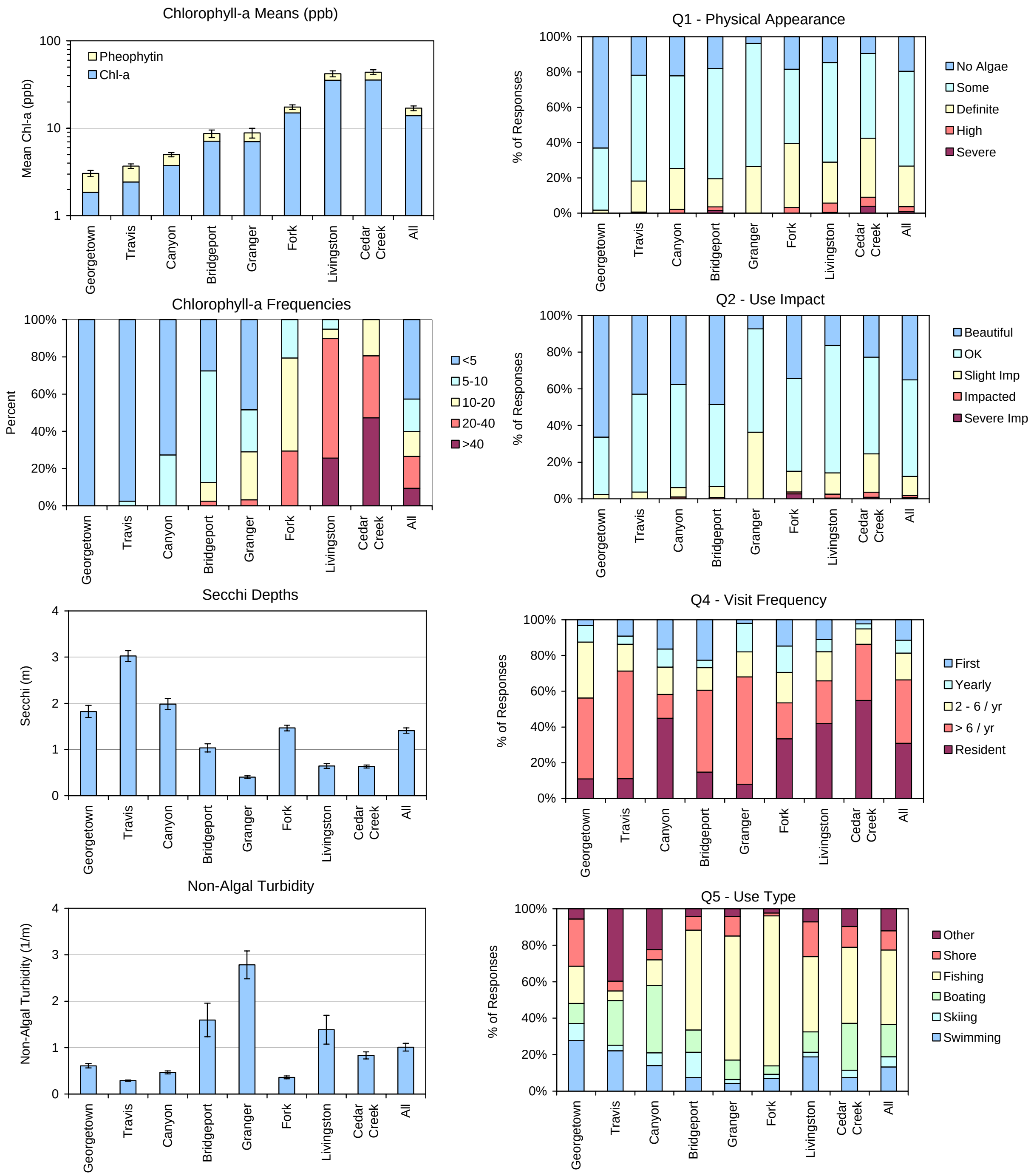


Figure 6. Summary of Water Quality & Survey Responses by Reservoir. Sorted in order of increasing mean chlorophyll-a. Means & standard errors for 2-year survey.

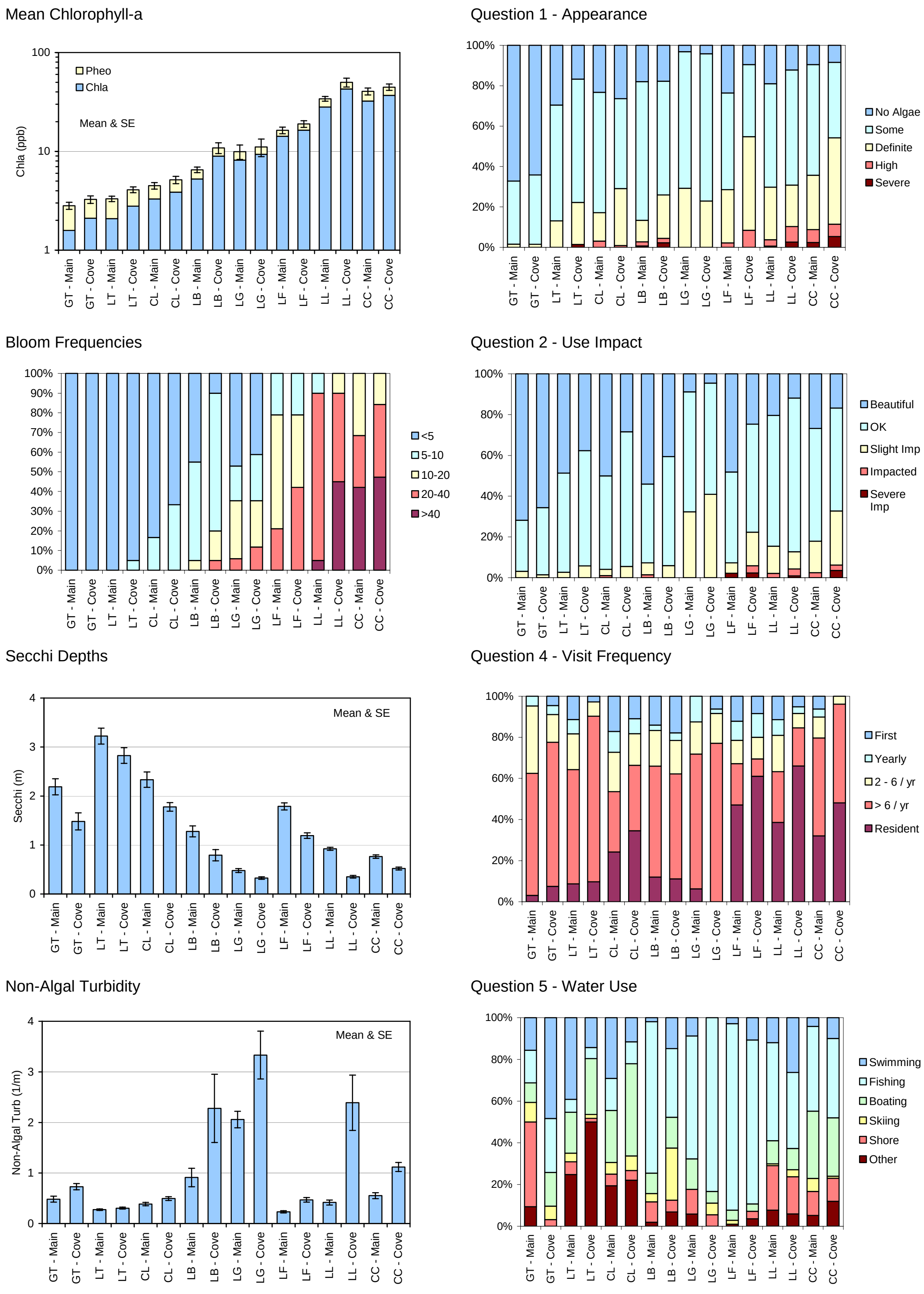
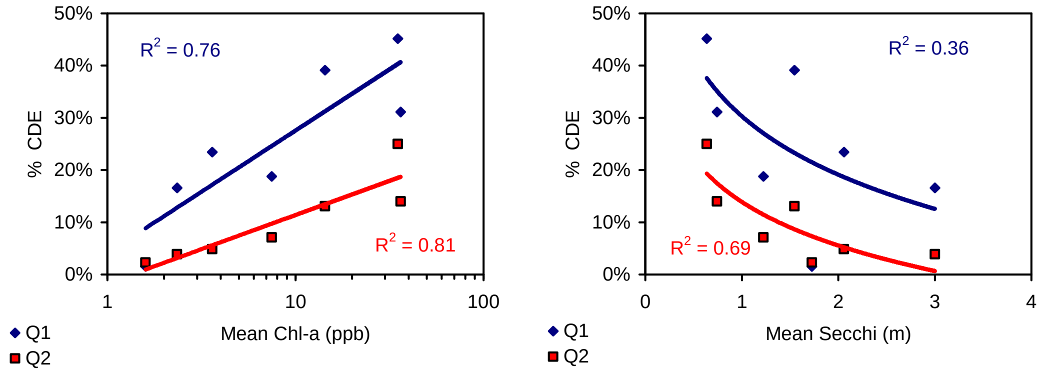
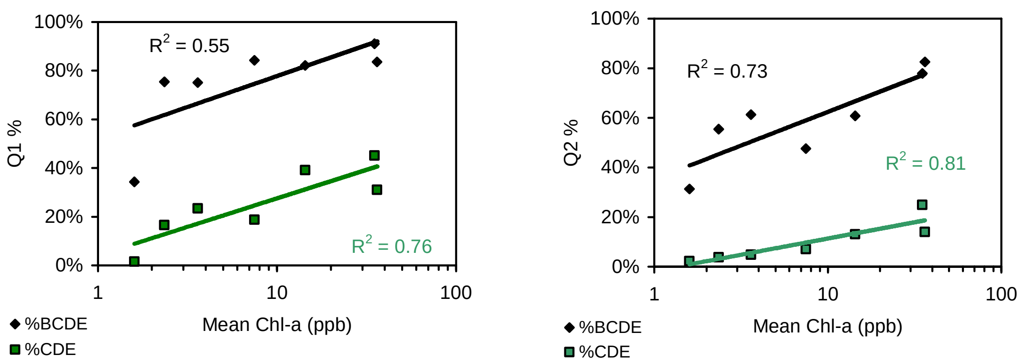


Figure 7. Summary of Water Quality & Survey Responses by Site. Sorted in order of increasing mean chlorophyll-a. Means & standard errors for 2-year survey

Responses vs. Mean Chl-a & Secchi



% BCDE & %BCD vs . Mean Chl-a



Responses vs. Mean Chl-a & Station Type

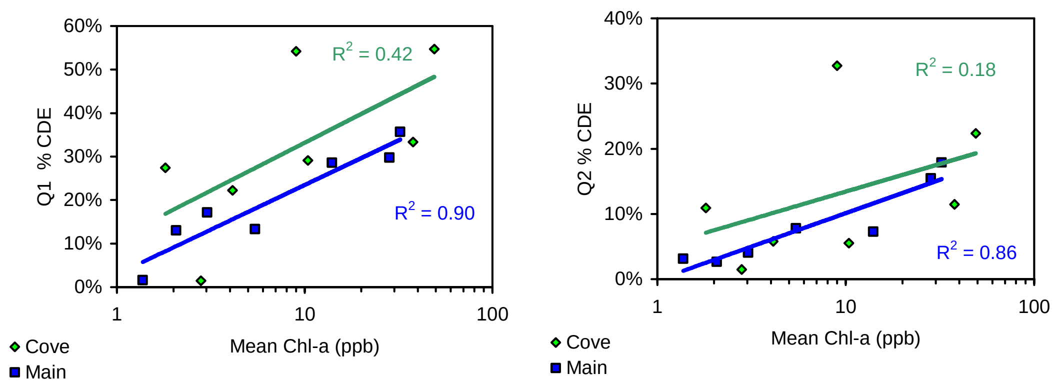


Figure 8. Response Frequencies vs. Reservoir Mean Chlorophyll-a and Secchi Depth. Turbid samples (Figure 3) & Lake Granger excluded.

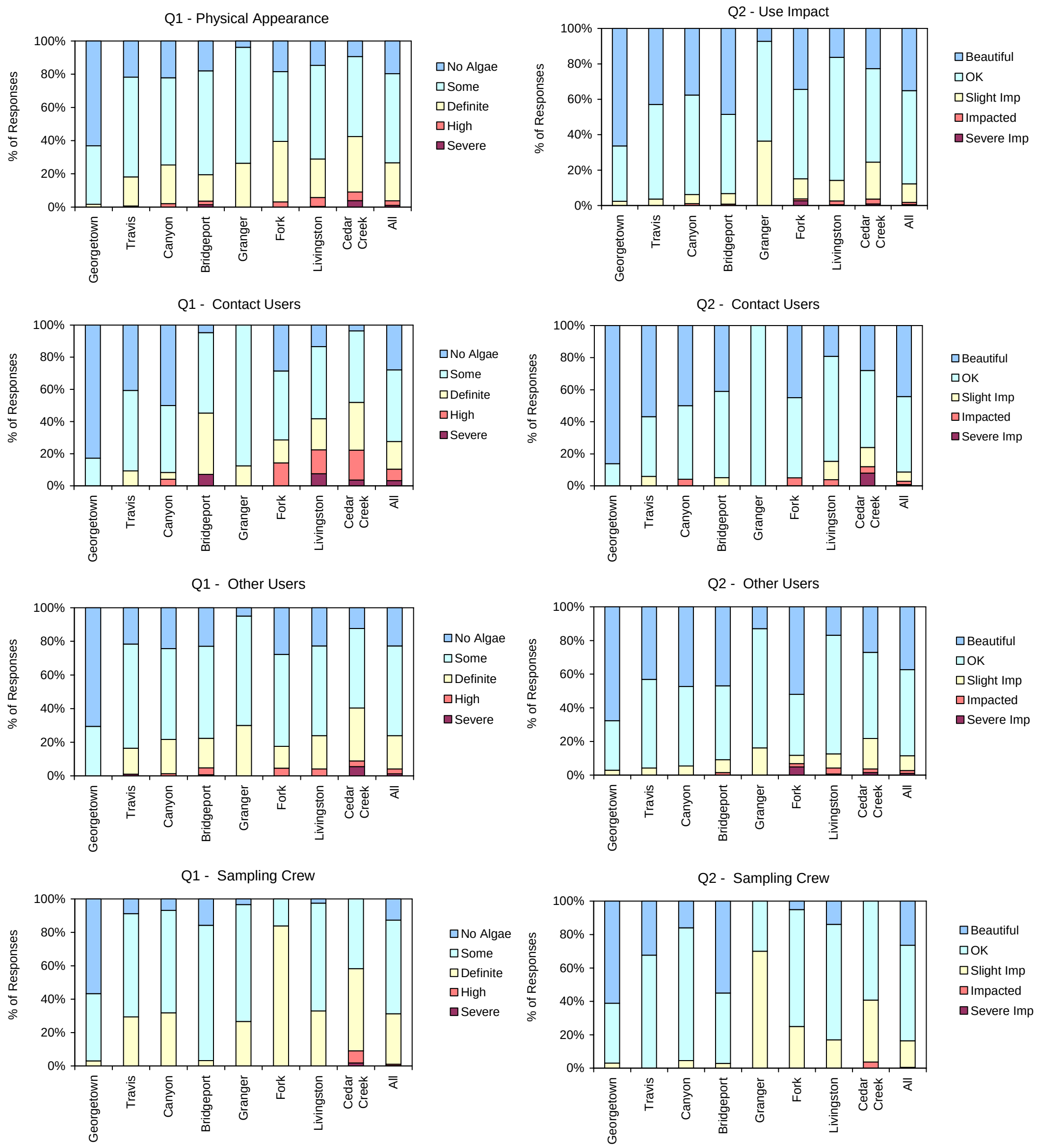
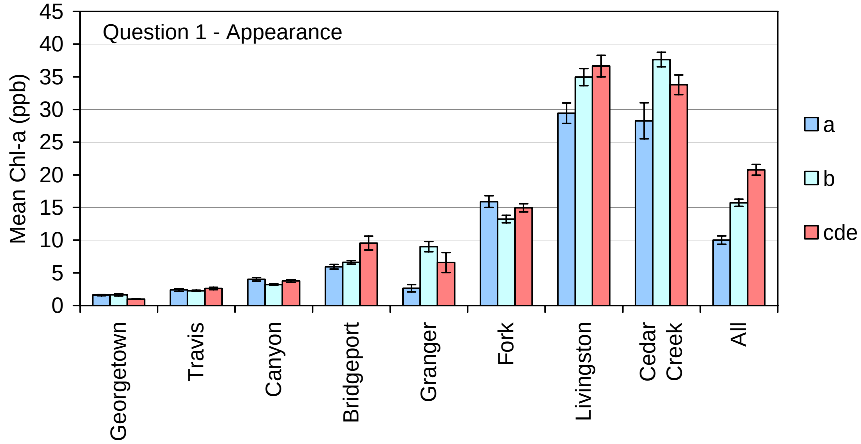
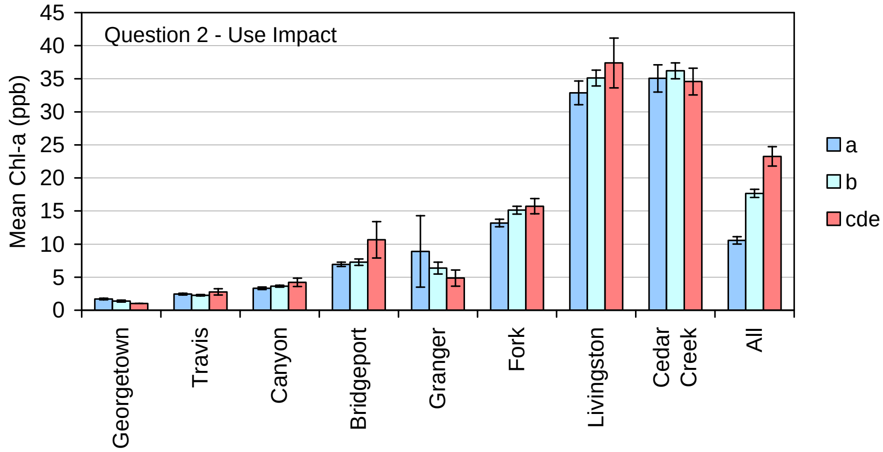


Figure 9. Sensitivity of Survey Responses to Observer Categories. top = all observers; contact users = swimmers, skiers, windsurfers (Question 5 = a or d); bottom = sampling crew; middle = other observers (fisherman, hikers, etc.)





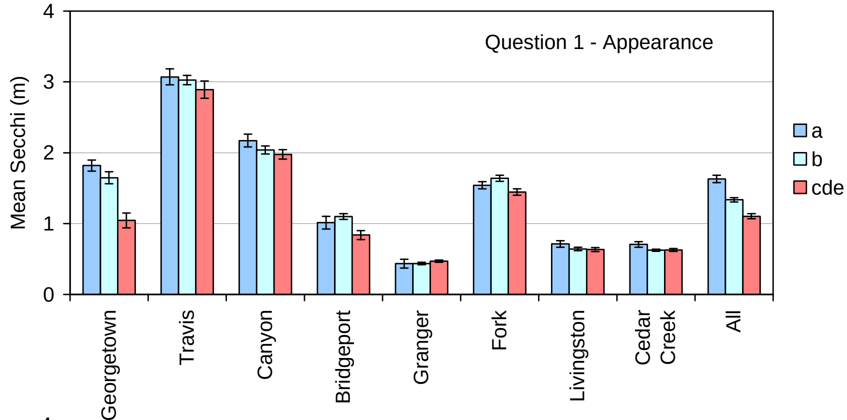
Responses to Question 1 - Appearance

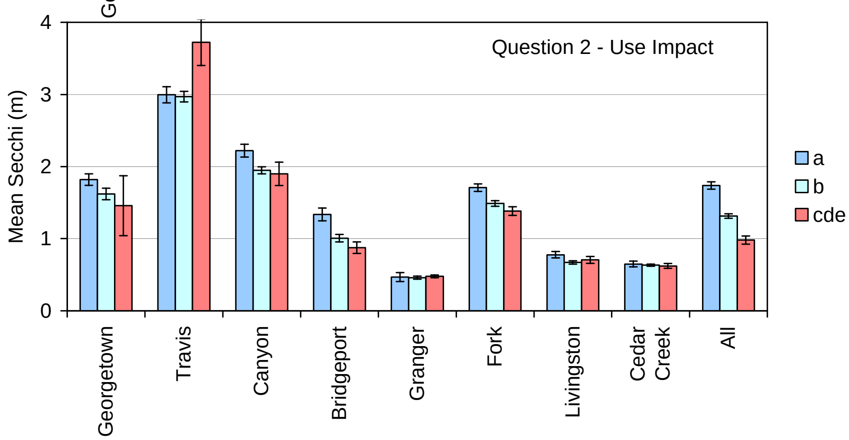
	a	b	cde	All	% cde	Secchi m	Chl-a ppb
Georgetown	86	43	2	131	2%	1.8	1.9
Travis	46	110	31	187	17%	3.0	2.4
Canyon	52	108	49	209	23%	2.0	3.6
Bridgeport	51	179	55	285	19%	1.0	7.1
Granger	4	79	30	113	27%	0.4	8.7
Fork	42	101	92	235	39%	1.5	15.3
Livingston	49	170	95	314	30%	0.7	35.5
Cedar Creek	23	118	116	257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

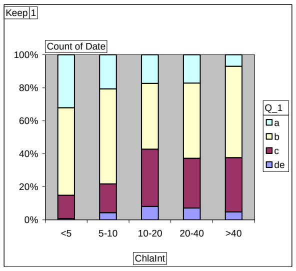
Responses to Question 2 - Use Impairment

	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



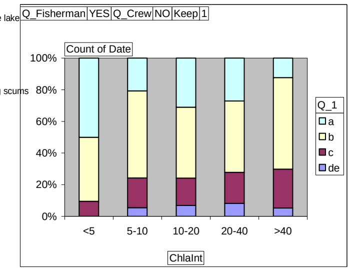
1) Please circle the **one** response that best describes the **physical condition** of the lake water **today**:

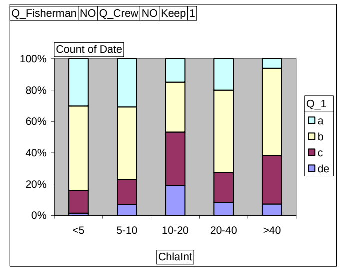
   a) No algae, or crystal clear water
   b) A little algae visible
   c) Definite algal greenness
   d) High algae levels and/or mild odor apparent
   e) Severely high algae levels with one or more of the following: massive floating scums on lake or washed up on shore, strong foul odor, or fish kill

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

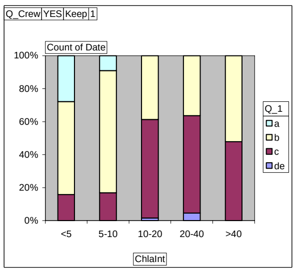
- Excludes Granger & samples with non-algal turbidity > 2 m^{-1}

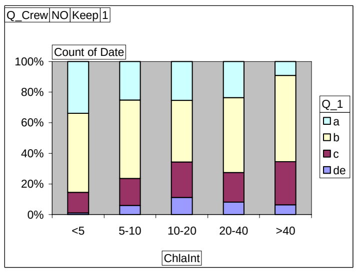
Fishermen vs. Other Observers



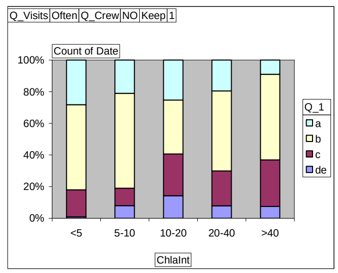


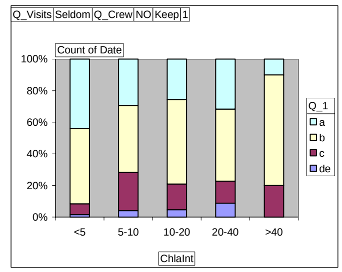
Sampling Crew vs. Other Observer



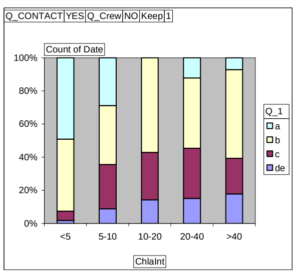


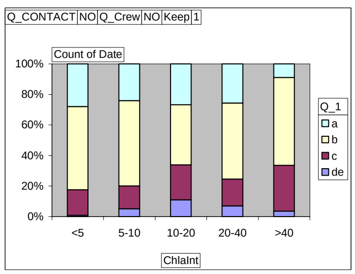
Visit Often vs. Seldom



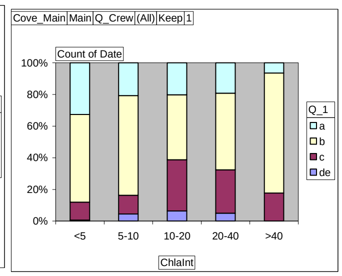


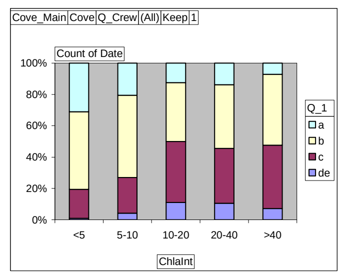
Contact vs. NonContact Recreation



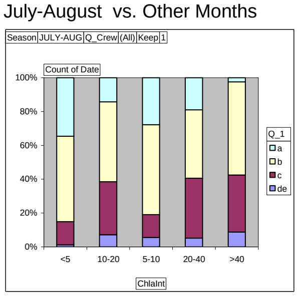


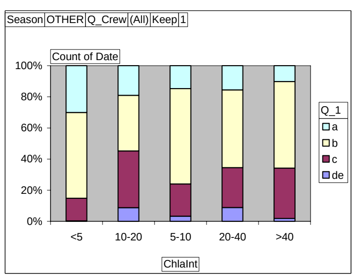
Main Reservoir vs. Cove Sites



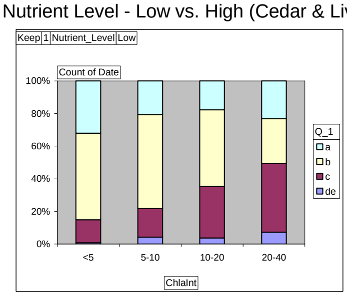


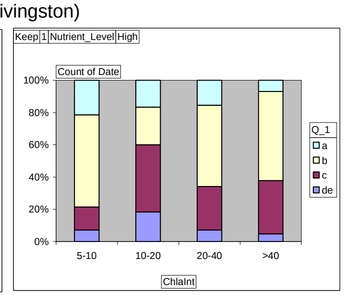
July-August vs. Other Months



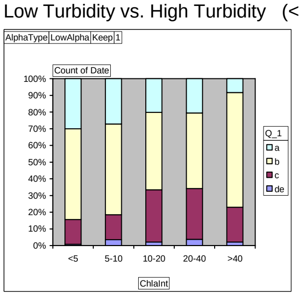


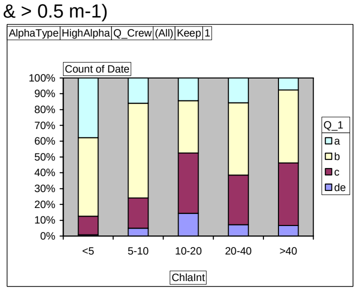
Nutrient Level - Low vs. High (Cedar & Livingston)



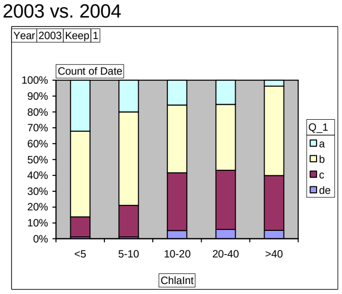


Low Turbidity vs. High Turbidity (< & > 0.5 m-1)





2003 vs. 2004



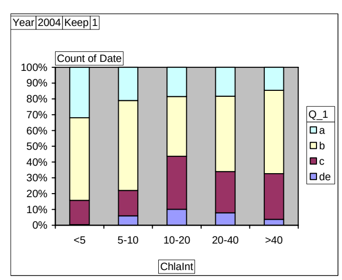
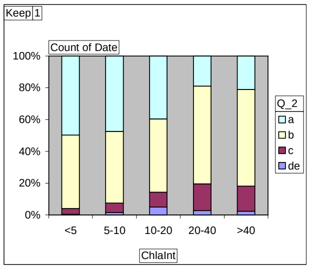


Figure 12. Question 1 Responses vs. Chlorophyll-a Interval & Other Factors. Excludes turbid samples & Lake Granger

Question 2 Responses - Use Impact

All Categories



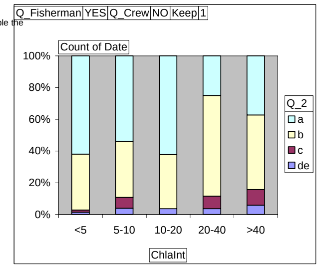
2) Please circle the **one** response that best describes your **perception** of how suitable the lake water is for recreation and aesthetic enjoyment **today**:

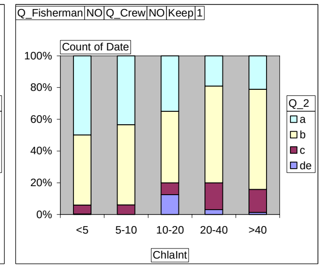
a) Beautiful, could not be any nicer
b) Very minor aesthetic problems; excellent for swimming, boating enjoyment
c) Swimming and aesthetic enjoyment slightly impaired
d) Desire to swim and level of enjoyment of the lake substantially reduced
e) Swimming and aesthetic enjoyment of the lake nearly impossible

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

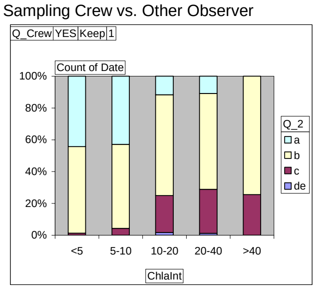
- Excludes Granger & 3 Bridgeport Samples (high non-algal turbidity)
- Excludes responses related to factors other than algae (Question 3)

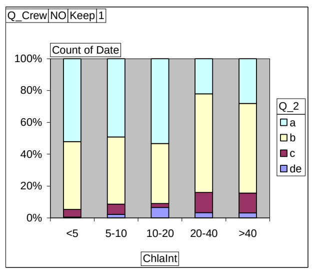
Fisherman vs. Other Observers



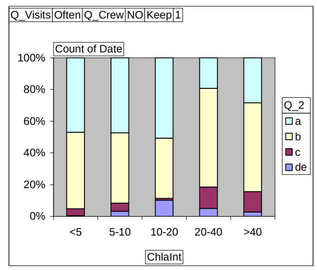


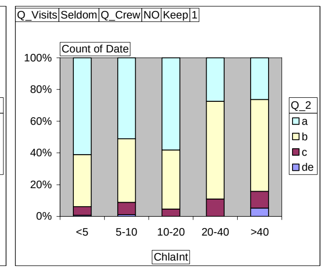
Sampling Crew vs. Other Observer



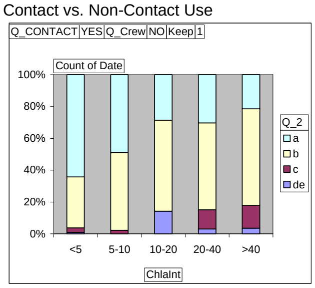


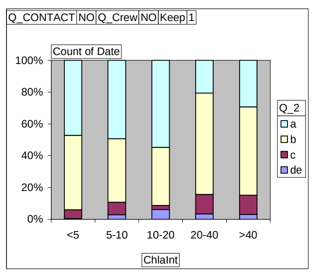
Visit Often vs. Seldom Question 4: Often = a,b Seldom = c,d,e



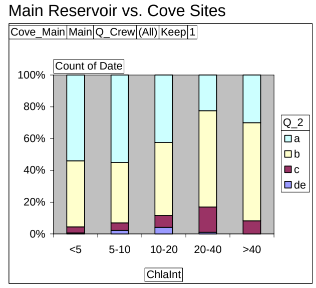


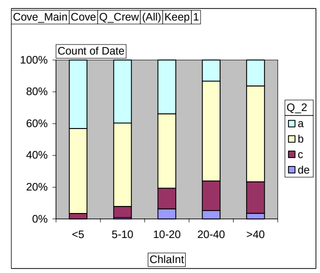
Contact vs. Non-Contact Use



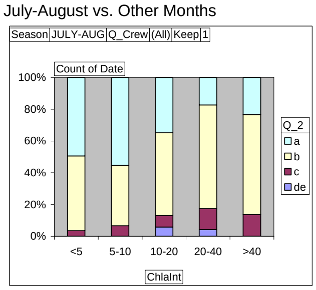


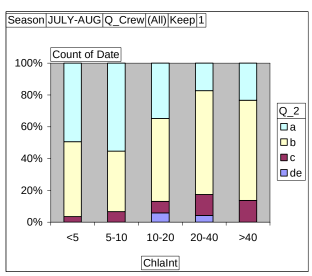
Main Reservoir vs. Cove Sites



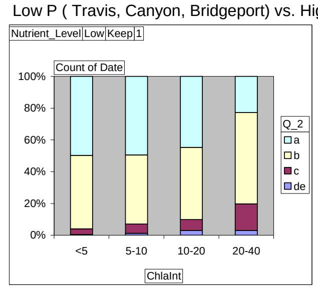


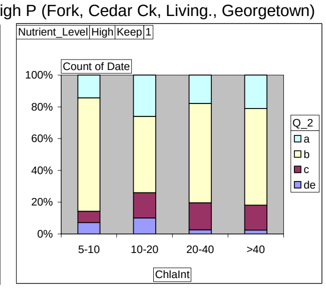
July-August vs. Other Months



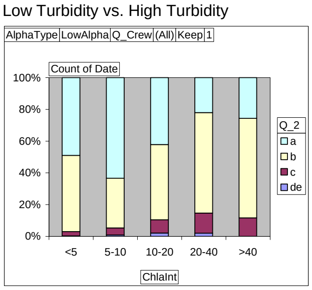


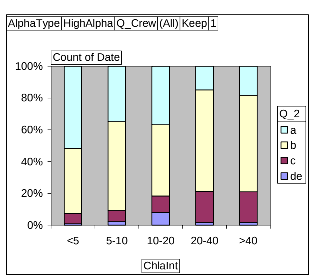
Low P (Travis, Canyon, Bridgeport) vs. High P (Fork, Cedar Ck, Living., Georgetown)



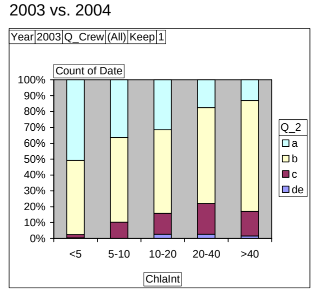


Low Turbidity vs. High Turbidity





2003 vs. 2004



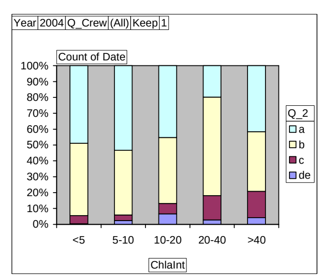


Figure 13. Question 2 Responses vs. Chlorophyll-a Interval & Other Factors. Excludes turbid samples & Lake Granger.

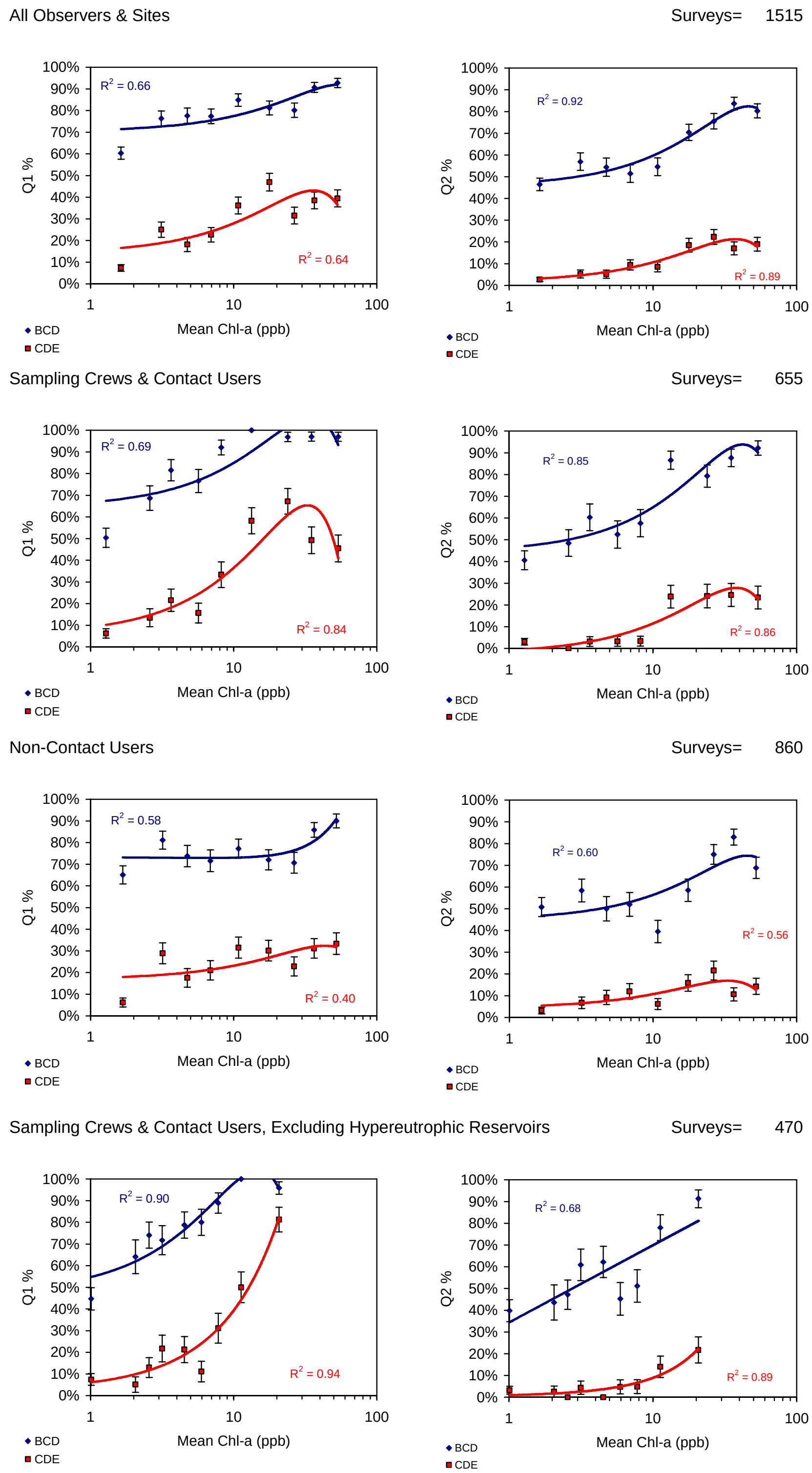


Figure 14. Survey Responses vs. Chlorophyll-a for Pooled Dataset. X= interval-mean Chl-a; Y = % BCDE & % CDE responses (mean +/- 1 standard error); Lines = polynomial regression. Each dataset is divided into 10 chl-a intervals with equal sample size.

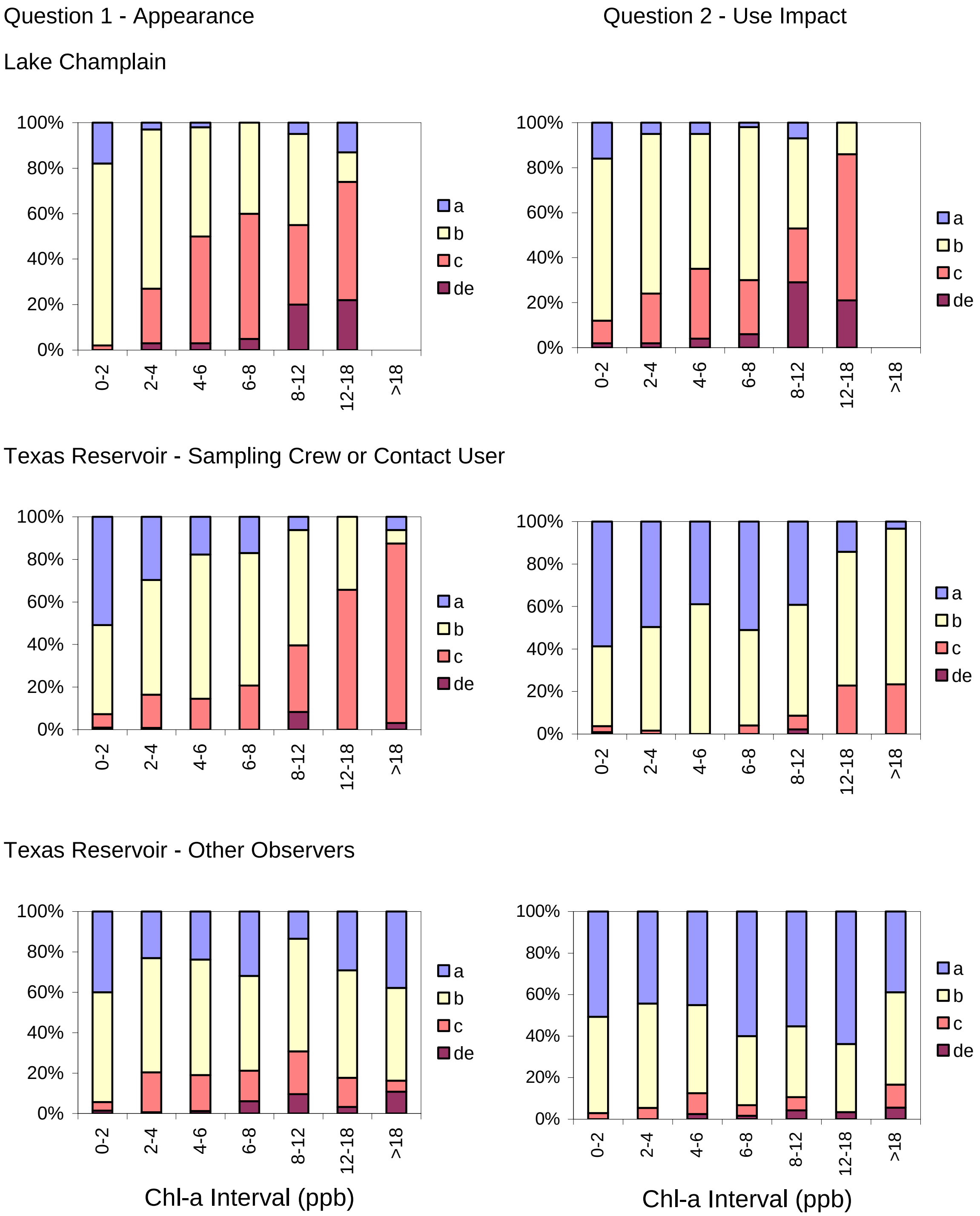


Figure 15. Comparison of Lake Champlain & Texas Reservoir Surveys.
Texas data exclude eutrophic reservoirs (Cedar Creek & Livingston) and turbid reservoirs (Granger)