Chlorophyll Averaging Period

Characterization of water quality in lakes, especially for biological parameters like chlorophyll, has traditionally focused on the "growing season." The term growing season is widely used in limnological literature, and it appears in water quality regulations in many states. In Colorado's control regulations, for example, attainment of standards is defined by average conditions during the growing season. Despite widespread use of the term, there does not seem to be a formal basis for deciding which months should be included in a growing season for lakes.

The meaning of growing season is clear when applied to agriculture, where a formal definition is based on soil temperatures (NRCS 1995). It is the period of time within which a particular crop can be grown at a particular location, and it is a function of climate, meaning temperature, light and rainfall. In Colorado, assuming that water can be made available, the terrestrial growing season extends throughout frost-free months, which are determined largely by elevation. Such a definition is not readily transferred to lakes, however, because ice cover does not prevent algae from growing throughout the winter months.

Most limnologists have an informal sense of what growing season means in a lake, but little attention seems to have been devoted to defining the term for regulatory purposes (but see Hakanson and Boulion 2001 for an approach based on mean temperature). Some regulatory agencies have established growing seasons, albeit without a formal basis. Colorado has used July to September or July to October to define the growing season as it applies in lakes with control regulations. Other states (e.g., AL, AZ, CA, and PA) have defined growing season to begin as early as April or May and end in September or October.

Average chlorophyll during the growing season is now the basis for judging attainment, but it is not clear that the growing season is uniformly appropriate for the protection of all uses. Rather than continuing to be encumbered with the terminological baggage associated with growing season, it might be better to start fresh and characterize time periods within which the average concentration of chlorophyll is most relevant to protection of each use.

Use Protection and Averaging Period

From the standpoint of aquatic life protection, for example, average chlorophyll concentration can be an indicator of potential for habitat impairment. When a lake is stratified, algal biomass produced in the epilimnion settles into the hypolimnion where it decomposes. As long as stratification persists, the oxygen consumed by decomposition is not replaced. The greater the production of algal biomass is in a lake, the greater the demand is for dissolved oxygen in the hypolimnion. When oxygen concentrations fall too low, the habitat is impaired with respect to the aquatic life use. The appropriate averaging period for chlorophyll would thus correspond to the *stratification season*, and defining the duration of stratification becomes important for nutrient criteria development.

The averaging period appropriate for protection of the water supply use is likely to be *annual*. For example, a proposal by the State of Oklahoma calls for assessment of average chlorophyll over a period of at least a year. This makes sense in that water treatment plants typically operate throughout the year. Protection of the water supply use also may depend on avoiding blooms, which may form and disappear on a time scale that is very short with respect to typical averaging periods. Excess algal abundance may be accompanied by formation of cyanotoxins or taste-and-odor problems, both of which are very detrimental to drinking water quality. These problems can occur at any time during the year, although blue-green algae, which are the source of cyanotoxins and some taste-and-odor compounds, tend to be more common during the warmer months.

For primary contact recreation, the chief threat occurs with the formation of algal blooms, when associated with toxin production. Concern about the effect of blooms on primary contact recreation is limited chiefly to those months when swim beaches are open. In Colorado, the principal focus would be on the period from Memorial Day to Labor Day, which is the schedule for monitoring coliforms at swim beaches. The *recreation season* for measuring chlorophyll would thus include June to August.

Describing the averaging period that corresponds best to each use provides a conceptual framework that may or may not be practical to assess in a routine monitoring program. In particular, it is rarely practical to sample throughout the winter months for safety reasons. Also important is the matter of efficiency: Are samples required in all months of the stratification season, for example, or could a shorter time period yield an equivalent result?

The growing seasons defined for control regulations in Colorado must included in the analysis in order to recognize historical precedent and to establish context in the event a change is made in an averaging period definition. Two definitions of growing season appear in the control regulations – Jul-Sep is used for Cherry Creek, Chatfield and Bear Creek reservoirs, and Jul-Oct is used for Dillon Reservoir. Only the more common one (Jul-Sep; *summer season*) is included in this analysis.

Four alternative time periods are evaluated in the context of assessing attainment for the various uses: annual, stratification season, recreation season (Jun-Aug), and summer (Jul-Sep). The ideal assessment of chlorophyll concentrations would involve frequent sampling in all months of the year. With a very comprehensive data set, it would be a simple matter to determine the maximum or compute the average within any time period of interest. At the same time, it would be of great practical value if it could be shown that sampling within a smaller time window would provide the same level of protection at reduced cost and without the safety concerns of sampling through the ice, for example. Is there a single averaging period that will provide effective protection of all uses?

The quest for an efficient and effective approach to finding a single averaging period for algal biomass (chlorophyll) begins with a descriptive characterization of temporal patterns in as many lakes as possible. For the data to be useful in this analysis, a lake must have been the subject of an intensive monitoring program including all, or nearly all, months of the year and extending over a minimum of five years. In addition to chlorophyll data, temperature profiles also must be available in order to determine the period of stratification in each lake.

Data Sources
Water quality data have been recorded for many lakes in Colorado, but the frequency and duration of sampling are highly variable. Suitable data records were obtained for 19 lakes, chiefly along the Front Range (Table 1). Many of these lakes have been sampled for at least 10 years, and most have comprehensive coverage of all seasons. In general, comprehensive records are more likely to be available for temperature than for chlorophyll. Temperature profiles are evaluated first (see section on Duration of Stratification) in order to establish the basis for defining the period of stratification in lakes across the state.

Table 1. Lakes with sufficient data to assess temporal patterns for temperature and chlorophyll.

Lake	Elevation, ft	Temperature Record	Chlorophyll Record	Source
Dillon	9000	1981-2001	1981-2005	SWQC
Grand	8367	1997-2005	1996-2006	USGS,USBR
Shadow Mt	8367		1989-2006	USGS,USBR
Granby	8280	1997-2005	1989-2006	USGS,USBR
Barker	8236	2000-2005		Boulder
Green Mountain	7950	1984-1999	1984-1999	SWQC
Wolford Mountain	7490	1995-2005	1995-2005	USGS
Aurora	5930	1998-2006	1998-2006	Aurora
Rampart	5907		1998-2006	Aurora
Arvada	5760	1997-2006	1997-2006	Arvada
Quincy	5710	1998-2006	1998-2006	Aurora
Bear Creek	5558	1990-2005	1990-2005	BC Watershed Assoc
Cherry Creek	5550	1996-2005	1994-2005	CC Basin Authority
Standley	5505	1995-2006	1995-2006	Westminster
Seaman	5478	2000-2005	2000-2005	Greeley
Chatfield	5432	1993-2006	1997-2005	Chatfield Basin Authority
Horsetooth	5430	1979-2005	2000-2006	USGS,USBR
Kenney	5350	1985-1987		USGS
Boulder	5173	1993-2003	1993-2003	Boulder
Pueblo	4881	1985-2004		USGS

Reducing Temporal Bias Associated with Sampling Effort
Sampling programs differ in purpose and scope among lakes or over time within a lake. Resulting variation in the frequency of sampling and the distribution of samples over the year influence the comparison of averages from different time periods in each lake, as well as the confidence that can be placed in averages reported for any lake. Most lakes are sampled more frequently in the summer than in the winter. In some cases, chiefly where safety on the ice is a concern, one or more months may be sampled rarely if at all.

Thus, a simple average of all values within a calendar year is likely to be biased because summer measurements comprise a relatively large portion of the data set.

Especially for the purpose of comparing averages from different time windows, it is necessary to weight values so that each month is given approximately equal representation. It is assumed that the sampling program follows roughly the same schedule from year to year. The weighting factor for each month is the number of samples expected for that month (i.e., the total number of samples in the period of record divided by 12) divided by the actual number of samples collected in that month. The calculation yields a set of 12 factors that are applied to measurements throughout the period of record. A similar rationale is applied to seasonal time windows involving part of the year (e.g., 3 months for the Jul-Sep averaging period used in some control regulations).

For months where the weighting factor exceeds 2 or 3, the data for two adjacent months can be combined. When data are combined to increase the sample size in a particular month, the precision of the median is improved in the "receiving" month, but a gap is left in the "donor" month. The gap creates a problem for estimation of the weighted mean because the basis is now 11 months instead of twelve. To rectify the problem, the calculated weight assigned to the recipient month is doubled and the basis is set to 12 months. Of the eight lakes included, five had a pair of months combined, and two had two pairs of months combined.

A related issue concerns the minimum number of samples used to compute a mean for averaging periods in a single year. For the present analysis, it seems reasonable to require a minimum of one chlorophyll sample per month for the summer and stratification season averages, and something close to that for annual averages. When too few samples were collected, some years may have been excluded from analyses performed on individual lakes where the dataset is otherwise robust.

Equations for the weighted average ($\overline{Y}_w$) and the variance of the weighted variance (s_w^2) are shown below. Weights are represented with a "w" and the unweighted concentration is represented with a "Y". The number of non-zero weights is given by N'; it is equal to the sample number in this weighting scheme.

$$\overline{Y}_w = \frac{\sum w_i Y_i}{\sum w_i}$$

$$s_w^2 = \frac{\sum w_i \left(Y_i - \overline{Y}_w\right)^2}{\frac{(N'-1)\sum w_i}{N'}}$$

Other Statistical Issues

Distributions have been examined for all lakes, and it is clear that the chlorophyll data conform much better to lognormal than to a normal distribution. This conclusion, which is common for water quality constituents, has important ramifications for calculation of means; the geometric mean, rather than the arithmetic mean (or average) is the appropriate representation of central tendency. Statistical comparisons based on parametric procedures (e.g., t-test for comparison of means) would therefore be based on the transformed data, from which the variance also is calculated. Statistical comparisons are performed using Welch's approximate t-test, which is appropriate for populations whose variances are assumed to be unequal (Sokal and Rohlf 1995 Box 13.4).

Duration of Stratification in Colorado Reservoirs

The duration of stratification is a key consideration for delimiting the seasons to be compared on the basis of chlorophyll concentrations. As long as stratification persists, the production of biomass by algae contributes organic matter to the hypolimnion where decomposition consumes oxygen. Depletion of oxygen in the hypolimnion is one mechanism whereby excessive abundance of algae can impair conditions for other forms of aquatic life. The analysis is based on examination of temperature data from individual lakes, with a goal of identifying geographical patterns in the timing of stratification.

Comprehensive records of temperature for fourteen Colorado reservoirs are used to establish the timing of stratification (Table 2). The intent is simply to determine the months in which stratification is likely to occur, not to develop a theoretically or mathematically rigorous basis for defining stratification in a conceptual sense. Consequently, a simple metric is used: the difference between the top and bottom temperatures for each profile. The temperature at 1 meter is taken as representative of the mixed layer and the minimum temperature in the profile is taken as representative of the temperature in the hypolimnion. Inverse stratification, which develops under ice cover, is ignored. Plots of temperature difference against ordinal day of the year show clearly when temperatures depart markedly from isothermal; a difference of about $2^{o}C$ is taken as a marker for incipient stratification in the spring and of the last vestige of stratification in the fall.

Table 2. Timing of stratification in a selection of Colorado lakes ordered by elevation. See text for explanation of threshold for stratification.

Lake	Elevation	Start	End	Duration, weeks	Record
Dillon	9000	24 May	31 Oct	23	1981-2001
Grand	8367	14 May	5 Nov	25	1997-2005
Granby	8280	7 May	21 Oct	24	1997-2005
Barker	8236	4 May	12 Oct	23	2000-2005
Green Mountain	7950	18 May	14 Oct	21	1984-1999
Wolford Mountain	7490		21 Oct	ca. 22	1995-2005
Bear Creek	5558	3 Apr	12 Sep	23	1990-2005
Cherry Creek	5550	12 Apr	26 Jul	15	1996-2005
Seaman	5478	5 Apr	26 Sep	25	2000-2005

Lake	Elevation	Start	End	Duration, weeks	Record
Chatfield	5432	30 Mar	2 Sep	22	1993-2006
Horsetooth	5430	19 Apr	26 Oct	27	1979-2005
Kenney	5350		16 Sep	ca. 23	1985-1987
Boulder	5173	15 Apr	30 Sep	24	1993-2003
Pueblo	4881	26 Mar	27 Sep	26	1985-2004

The record from Lake Dillon spans more than 20 years and covers all months of the year (Figure 1). Stratification develops in late May, not long after ice cover breaks up, and it lasts about 23 weeks, until the end of October. The physical dimensions of layering change during the stratification season, especially by late August when cooling of the mixed layer leads to erosion of the thermocline (Lewis et al. 1984). The Dillon data support using a difference of about 2°C as a practical threshold for marking the boundaries of stratification.

Data from other high elevation lakes and reservoirs show a pattern similar to that of Dillon. Stratification forms in late May, after the ice is gone, and it lasts 23-25 weeks (ca. 5.5 months) until overturn occurs in late October or early November. The difference in temperature between the top and bottom layers tends to be relatively large, as demonstrated with the data from Grand Lake (Figure 2).

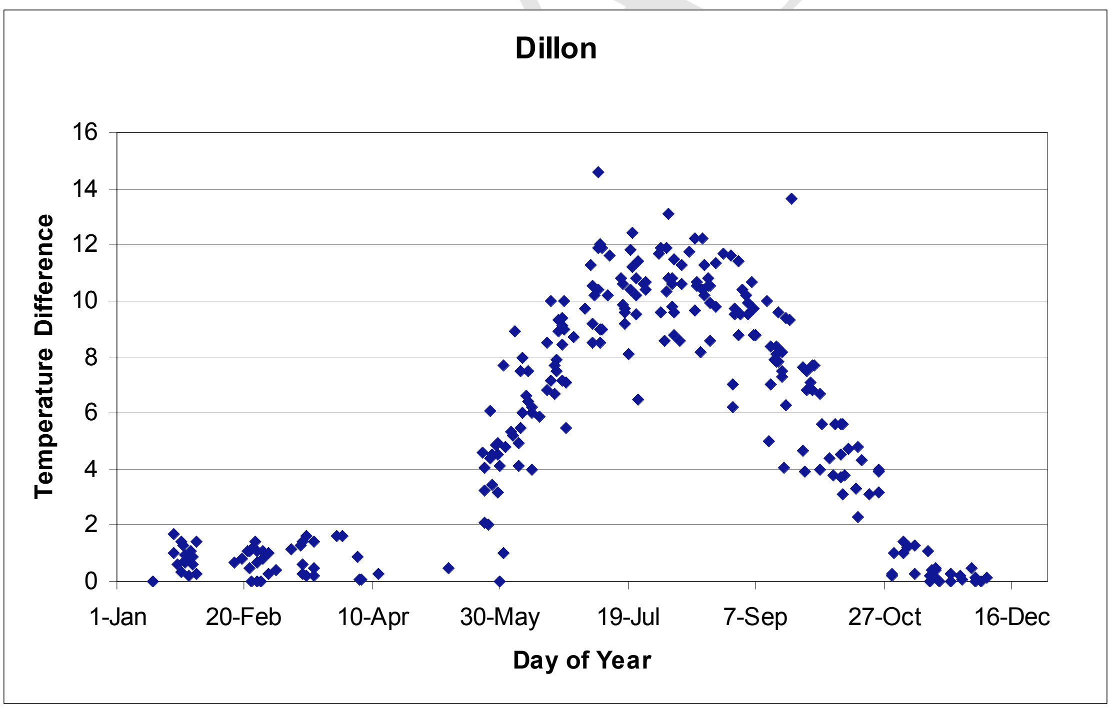

Figure 1. Seasonal pattern of temperature range in Lake Dillon (see text for explanation of calculation). Data have been aggregated from all years of sampling (see Table 2).

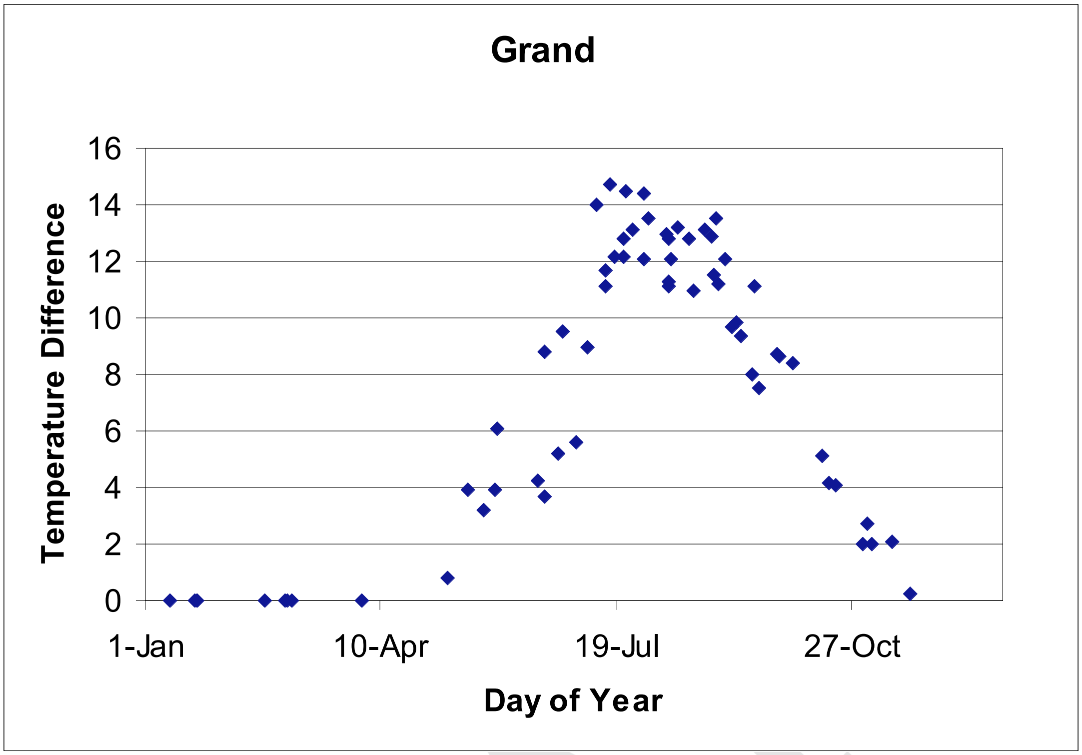

Figure 2. Seasonal pattern of temperature range in Grand Lake (see text for explanation of calculation). Data have been aggregated from all years of sampling (see Table 1).

Similar analyses have been performed for several other reservoirs at different elevations in the state, and some general patterns begin to emerge. Stratification starts first in the low elevation lakes, commonly in early April. In general, stratification lasts 5-6 months, and the duration does not seem to be dependent on elevation (Table 2). The pattern is not always as clear-cut in shallower reservoirs. In Cherry Creek Reservoir, for example, stratification may be intermittent (Figure 4). Also, aeration may prevent stratification, as seen in Bear Creek Reservoir (Figure 5). There is also some indication that at lower elevations, the deeper reservoirs (e.g., Pueblo and Horsetooth) will maintain stratification longer than the shallower reservoirs.

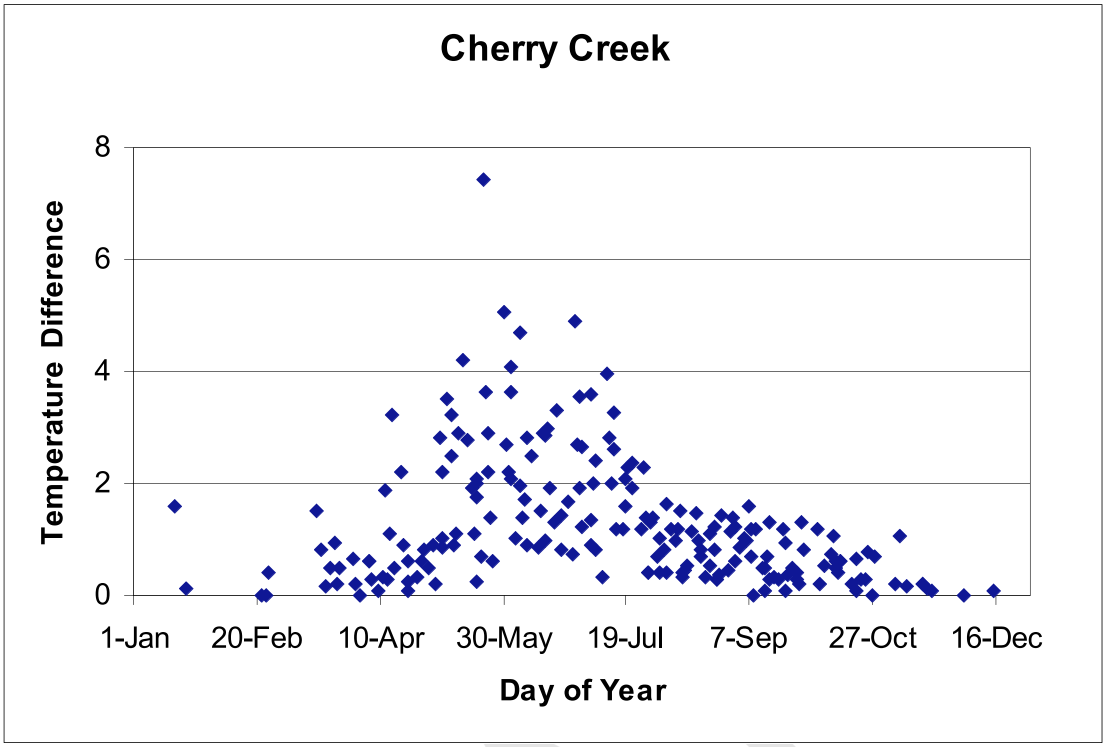

Figure 3. Seasonal pattern of temperature range in Cherry Creek Reservoir, where stratification is intermittent naturally. Data have been aggregated from all years of sampling (see Table 1).

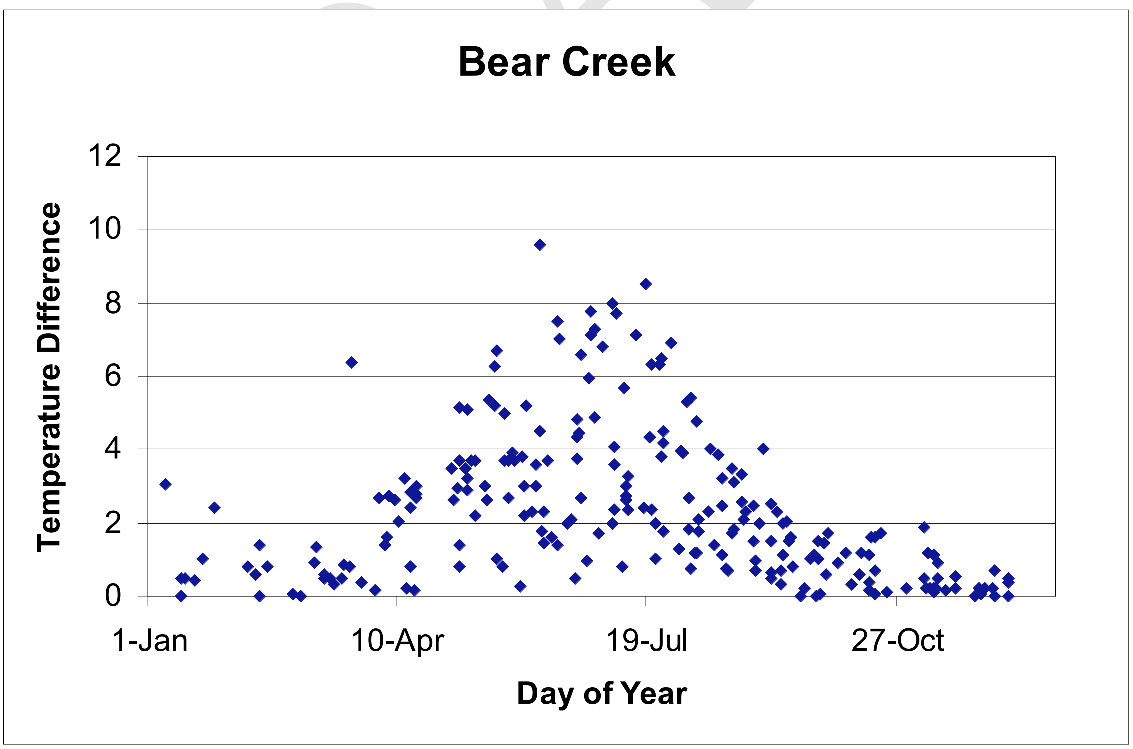

Figure 4. Seasonal pattern of temperature range in Bear Creek Reservoir, where aeration has been used to disrupt stratification in most years. Data have been aggregated from all years of sampling (see Table 1).

For lakes where the stratification season can be determined directly from the data set (Table 2), the association with elevation is strong enough to support generalizations. Again, the purpose is to specify the months in which stratification is likely to occur. Below about 6000 feet, stratification begins in April and extends into September. Above 6000 ft, stratification begins in May and extends into October. The purpose in setting these approximate time windows is to facilitate calculation of the average algal biomass with potential to contribute to hypolimnetic oxygen demand. It does not preclude a more detailed approach supported by the data for individual lakes, but it does establish a tractable basis for regulation.

The time window for stratification also is used to define the start of annual cycles. The convention used in this analysis is to start each "stratification year" on 1 April (or 1 May for high elevation lakes). The concept is analogous to that used for water years or climate years in that it unifies logical elements on a 12-month cycle. In this case, the months when the lake is not stratified are kept together rather than being split as they would if a calendar year scheme were applied.

Temporal Patterns of Chlorophyll

Extensive data records exist for chlorophyll in several Colorado lakes (Table 1). Of special interest are those lakes with data from all, or nearly all, months of the year (Table 3). They can be used to evaluate seasonal patterns that may be important from a regulatory perspective. Consistent seasonal patterns can provide clues regarding the relationship between observed chlorophyll concentration and the averaging periods proposed for assessment (Figure 5).

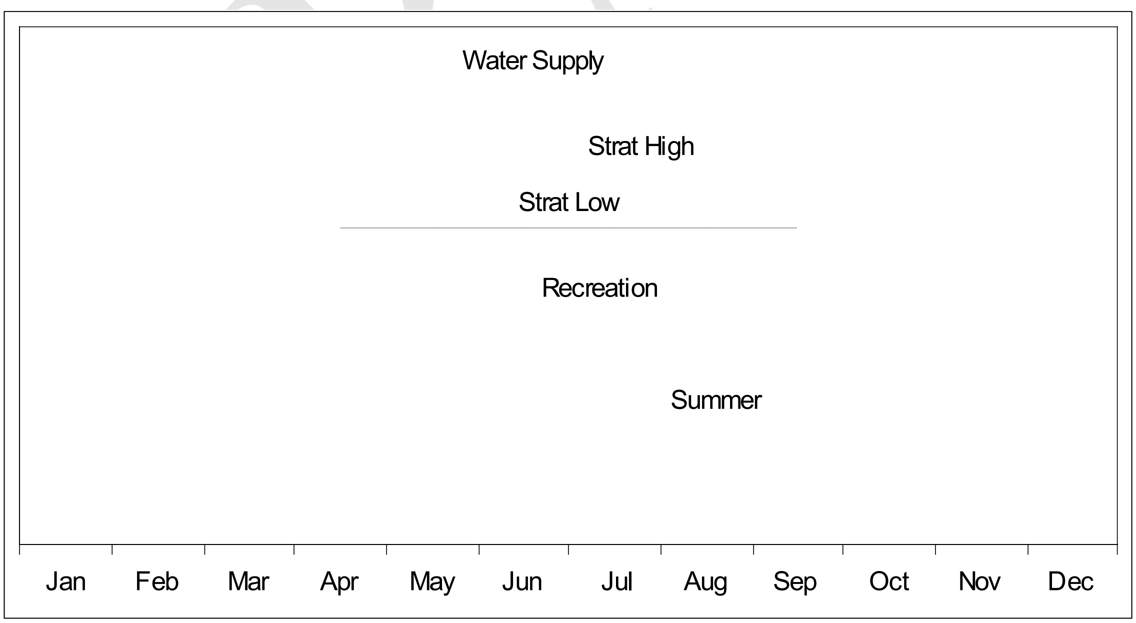

Figure 5. Chlorophyll averaging periods defined on the basis of use protection. "Strat High" is the stratification season that applies to lakes above 6000 ft; "Strat Low" applies to lakes below 6000 ft.

Table 3. List of lakes with best record of chlorophyll data.

Lake	Elevation	Usable Record	N of Values	Comments
Dillon	9000	1984-2005	281	N too small in some years (2000, 2004)
Aurora	5930	1997-2006	275	Trend in pre-1997 data
Arvada	5760	1994-2006	195	Sparse coverage pre-1994
Quincy	5710	1998-2006	232	
Bear Creek	5558	1990-2005	234	
Cherry Creek	5550	1996-2005	192	Sparse coverage pre-1996
Standley	5505	1995-2006	295	
Chatfield	5432	1996-2005	124	Pre-1996 omitted due to sparse coverage and possible trend

It is common to view temporal patterns on a time line spanning the period of record (Figure 6), but seasonal patterns can be highlighted by collapsing all data onto a single "year" based on the ordinal day of the year (1 to 365, or 366; Figure 7). Due to the regulatory interest in averages for specific groups of months, box-and-whisker plots, showing the distribution of values recorded in each month, provide an especially useful perspective (Figure 8).

The review begins with data from Lake Dillon, which has one of the most comprehensive sets of chlorophyll data available in Colorado. Chlorophyll has been collected and measured by the same method for most of the period of record. Chlorophyll concentrations were highest during the first two years of study prior to the Control Regulation and improved wastewater treatment (Figure 6). Seasonality is not pronounced although the highest (Jan) and lowest (Mar) medians occur under the ice (Figures 7-8).

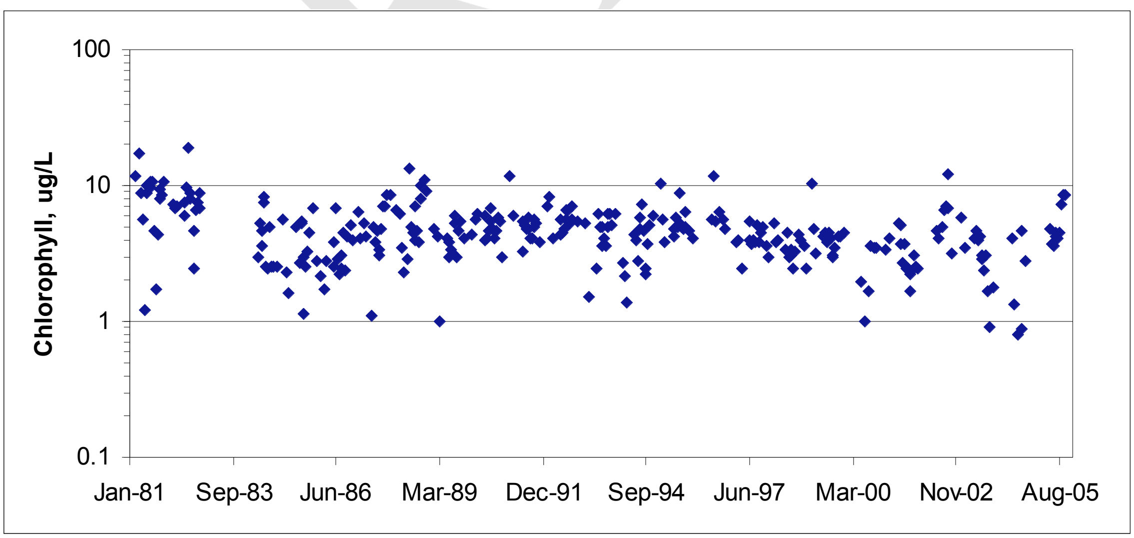

Figure 6. Period of record for chlorophyll measurements in Lake Dillon. There is a gap in the record from Jan-83 through Apr-84. Concentrations are shown on a log scale to highlight trends.

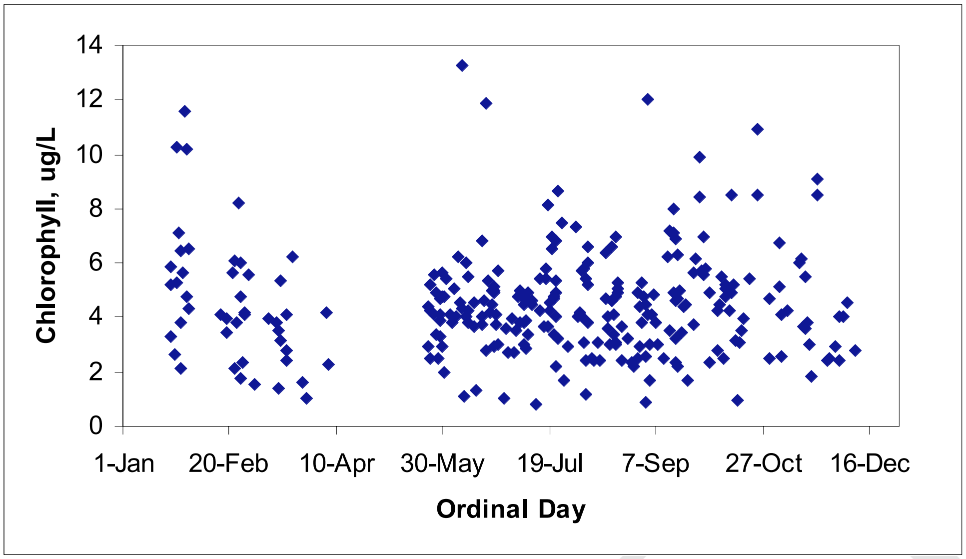

Figure 7. Seasonal distribution of chlorophyll concentrations measured in Lake Dillon, 1984-2005. There are gaps when ice is forming (Dec-Jan) and when it weakens (Apr-May), making it unsafe to sample.

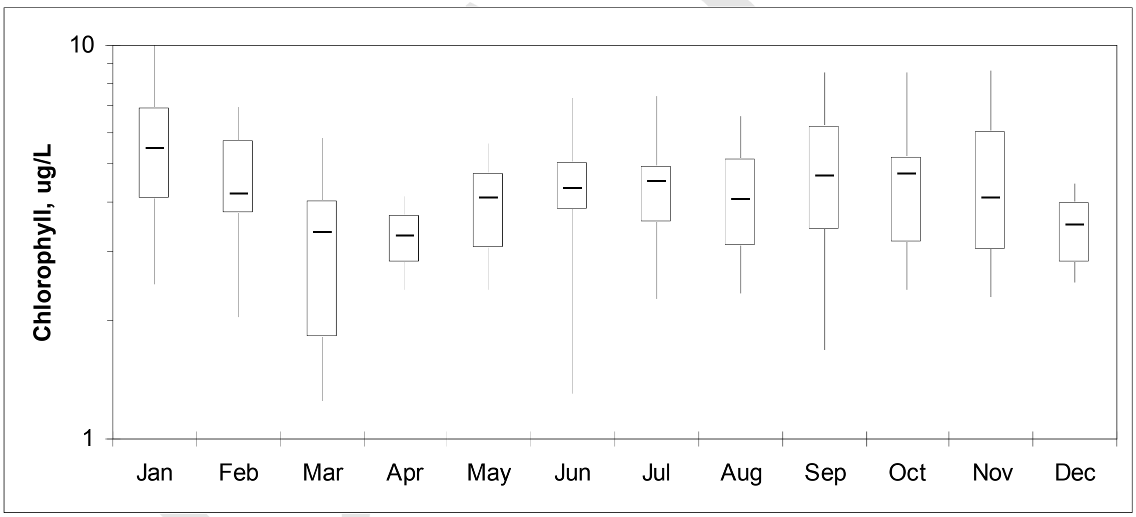

Figure 8. Monthly distributions of chlorophyll concentrations reported for Lake Dillon, 1984-2005. Data points shown in Figure 7 are aggregated by month and the distributions represented with box-and-whisker diagrams that show 5th, 25th, 75th, and 95th percentiles. The median value for each month is shown as a dash within the box. Data sets for December and April are very small (6 or less).

The four lakes with control regulations (Dillon, Chatfield, Cherry Creek, and Bear Creek) have relatively long data records. Although there was little apparent pattern to the data for Lake Dillon, there is more evidence of pattern in the other three lakes. In Chatfield and Cherry Creek, chlorophyll appears to have increased after 1996 or 1997 (Figures 9-10). No such pattern is evident in Bear Creek Reservoir, where variation over time may be influenced by operation of different aeration devices beginning in the mid-1990s (Figure 11).

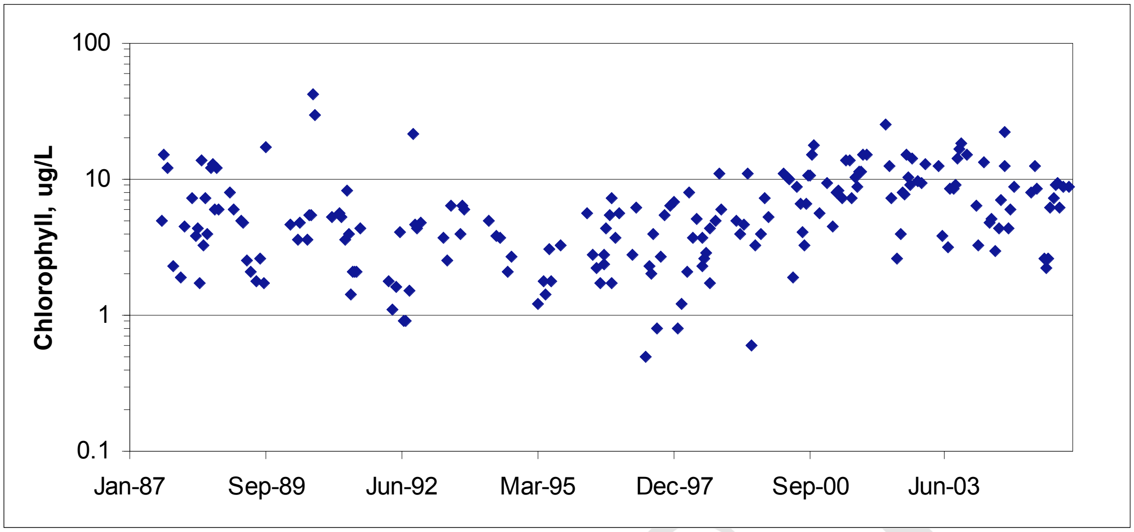

Figure 9. Period of record for chlorophyll measurements (log scale) in Chatfield Reservoir.

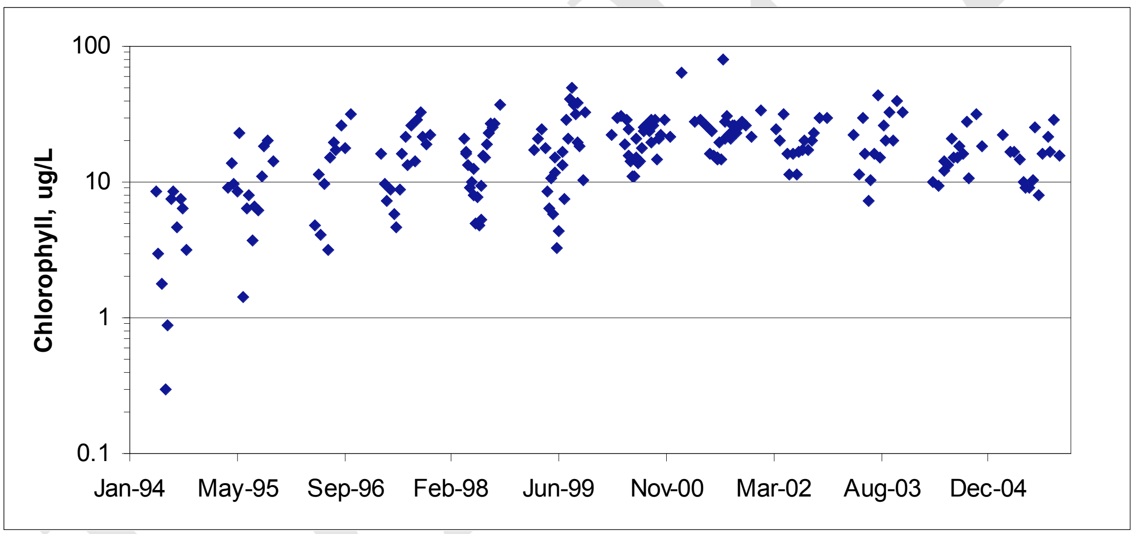

Figure 10. Period of record for chlorophyll measurements (log scale) in Cherry Creek Reservoir.

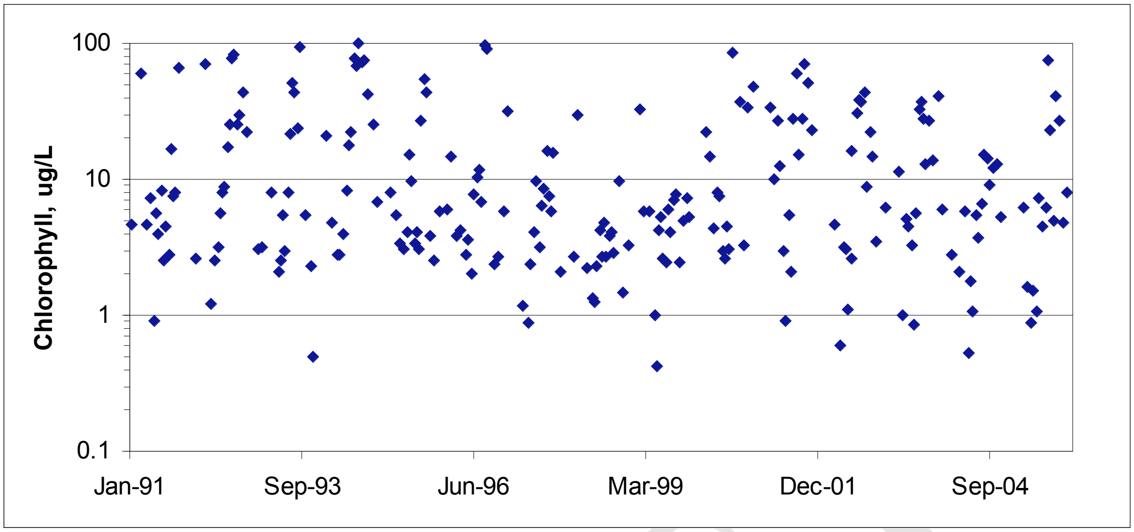

Figure 11. Period of record for chlorophyll measurements (log scale) in Bear Creek Reservoir.

Long periods of record also are available for several water supply reservoirs along the Front Range. These reservoirs are particularly useful in the present context because the records are long and sampling generally includes all months of the year. There is evidence of a trend early in the record for Aurora Reservoir (Figure 12), but not for the other reservoirs (Figures 13-15).

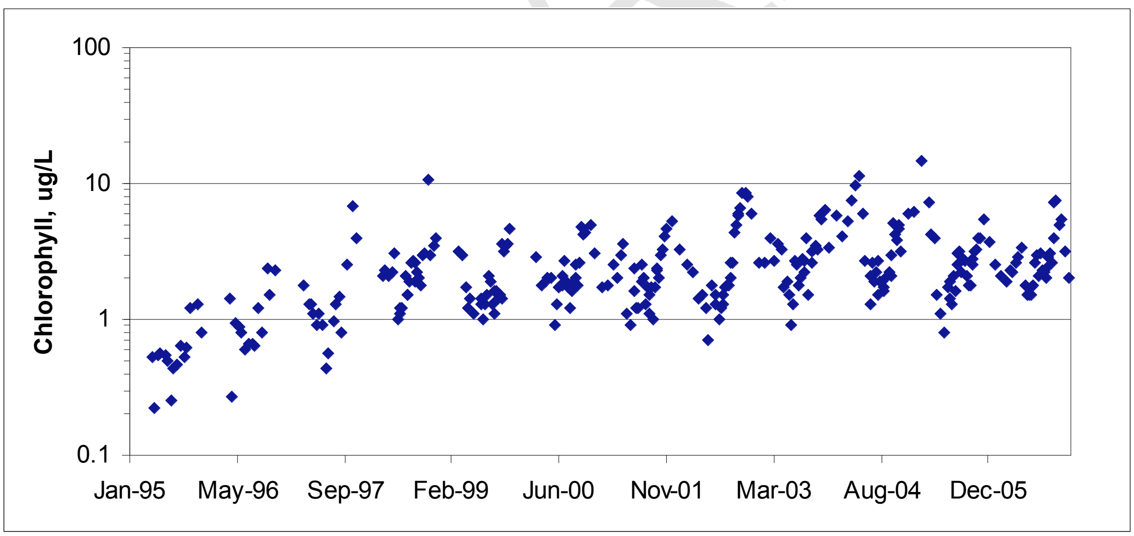

Figure 12. Period of record for chlorophyll measurements (log scale) in Aurora Reservoir.

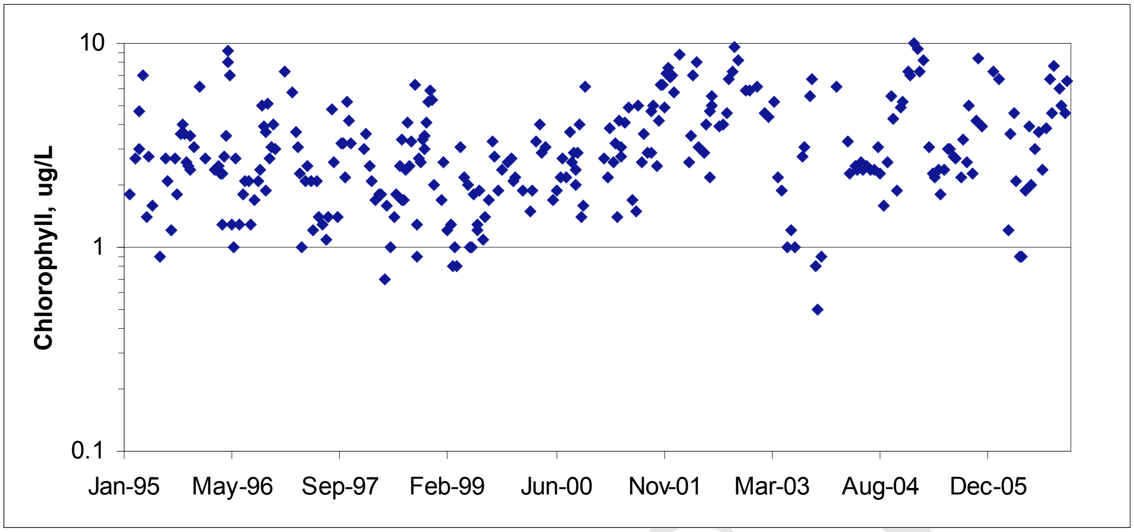

Figure 13. Period of record for chlorophyll measurements (log scale) in Standley Lake.

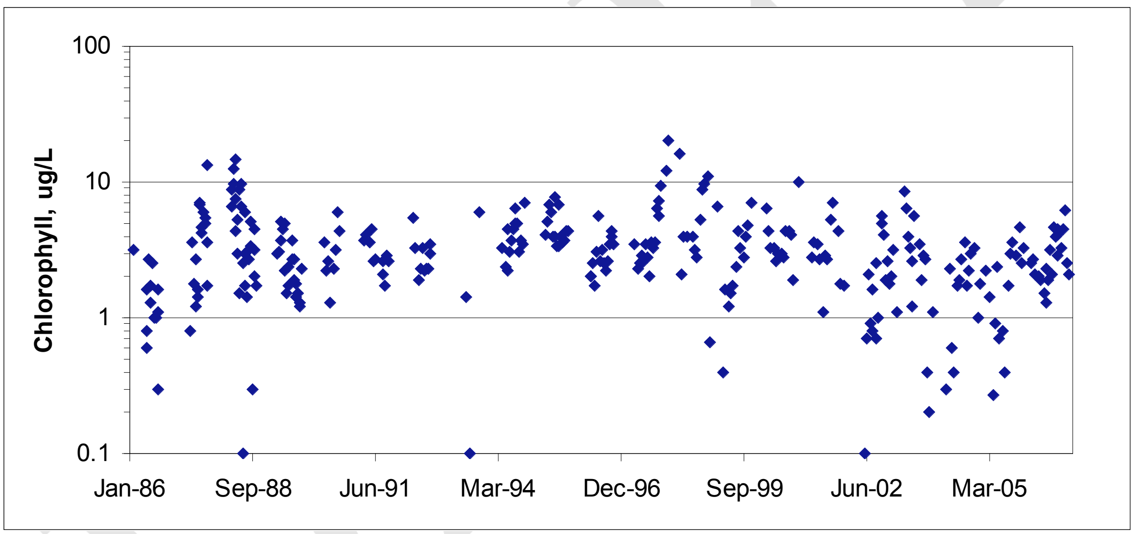

Figure 14. Period of record for chlorophyll measurements (log scale) in Arvada Reservoir.

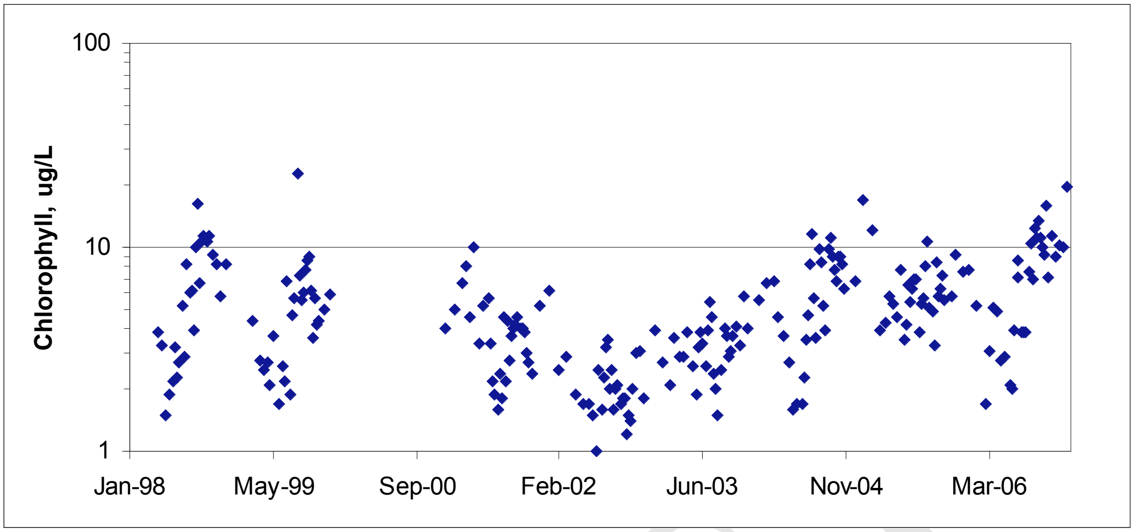

Figure 15. Period of record for chlorophyll measurements (log scale) in Quincy Reservoir.

The presence of seasonal patterns in chlorophyll concentration is potentially important in relation to the time windows selected for assessing protection of uses. A winter maximum, for example, might cause the annual average to be greater than the summer average. Most lakes show some seasonality, which fits one of two patterns – a peak in winter or a bimodal (spring and fall) pattern. Some lakes, like Dillon (Figure 8), show no apparent seasonality, in which case there should be a good correspondence between averages for different time periods. Standley Lake typifies the pattern with a winter maximum (Figure 16). All months are well-represented in the data set, and there is a clear maximum in January. This pattern also occurs in Aurora Reservoir (November maximum) and probably in Cherry Creek Reservoir (although sample size is very small in winter months).

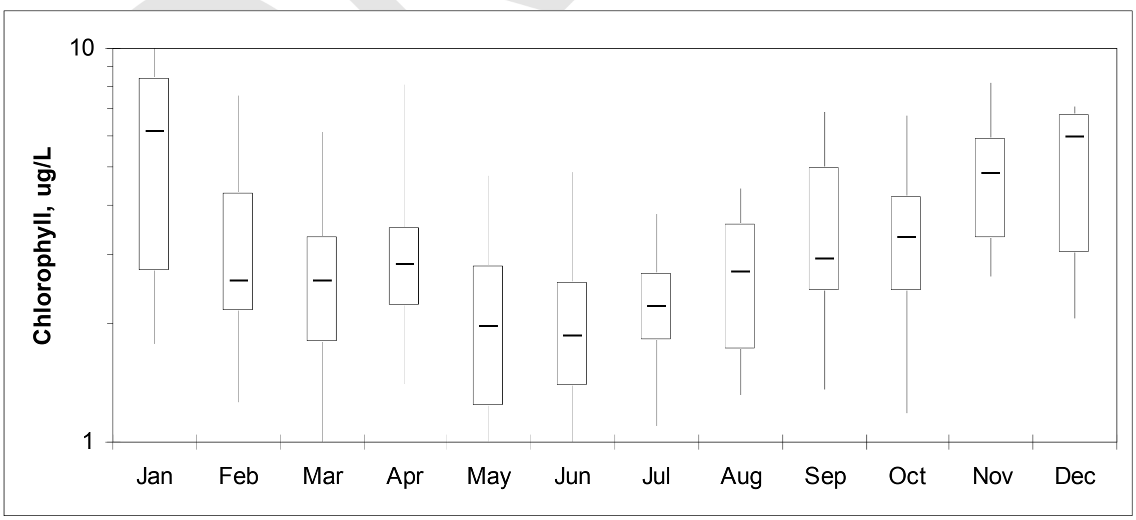

Figure 16. Monthly distributions of chlorophyll concentrations reported for Standley Lake, 1995-2006. The distribution of concentrations reported in each month is represented with a box-and-whisker diagram showing 5th, 25th, 75th, and 95th percentiles. The median value for each month is shown as a dash within the box.

The bimodal pattern is shown most clearly with data from Bear Creek Reservoir (Figure 17), where seasonal peaks occur in February and August/September. Chatfield shows a muted version of the bimodal pattern.

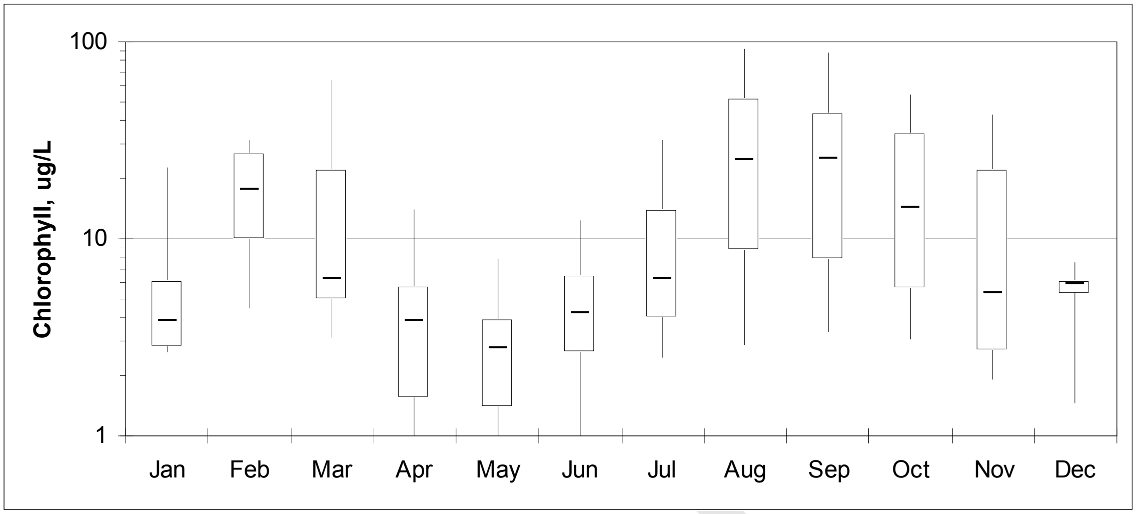

Figure 17. Monthly distributions of chlorophyll concentrations reported for Bear Creek Reservoir, 1990-2005. The distribution of concentrations reported in each month is represented with a box-and-whisker diagram showing 5th, 25th, 75th, and 95th percentiles. The median value for each month is shown as a dash within the box.

Monthly median concentrations can be used to draw additional conclusions about temporal patterns (Table 4). For the Front Range reservoirs, the highest median tends to occur in the fall as stratification begins to erode, and the smallest median is almost always in June. Lake Dillon has the highest and lowest medians under ice cover. Low concentrations in March are not surprising given the duration of ice cover and the tendency of light penetration to decrease as snow builds up.

Table 4. Monthly median chlorophyll concentrations (ug/L) in lakes with adequate records. Medians are based on the useful period of record. Some months are poorly represented in the record and have been combined with an adjacent month to increase confidence in the median. The month with the highest median is shown in bold and the lowest is shown in italics.

Lake	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dillon	**5.5**	4.2	*3.3*		4.1	4.3	4.5	4.0	4.7	4.7	4.0	
Aurora	2.6		2.9	2.2	1.6	*1.4*	1.9	1.9	2.3	4.1	**5.0**	3.7
Arvada	2.6		2.6	2.4	2.5	2.6	3.0	3.6	3.6	**4.5**	2.5	*2.0*
Quincy	5.4		3.9	3.7	2.8	*2.7*	4.2	5.4	6.4	5.5	5.7	**6.8**
Bear Creek	6.1		6.2	3.8	*2.8*	4.2	6.3	24.9	**25.5**	14.5	5.3	5.8
Cherry Cr	22.6		21.4	16.8	12.2	*11.1*	16.2	23.4	23.3	**28.3**	21.4	
Standley	**6.1**	2.5	2.5	2.8	1.9	*1.8*	2.2	2.7	2.9	3.3	4.8	5.9
Chatfield	4.4		**10.4**	8.2	3.8	*3.0*	3.9	8.1	7.2	8.9	7.8	
Count Min	0	0	1	0	1	5	0	0	0	0	0	1
Count Max	2	0	1	0	0	0	0	0	1	2	1	1

Evaluation of Seasons for Chlorophyll Assessment
Four time windows are examined in terms of suitability for meeting regulatory needs – annual, stratification season, recreation season, and summer. Is it necessary to determine all four averages in order to assess attainment, or is it possible to select one averaging period that serves all purposes satisfactorily? This facet of the analysis is based on comparisons of averages of the log-transformed data (i.e., not the medians reported in Table 4). The frame of reference for evaluating the usefulness of a particular averaging period is by comparison to summer (Jul-Sep), which has a long history of use in Colorado.

The summer and the recreation season are the shortest time periods under consideration, making either one a potentially efficient approach to data collection. Average chlorophyll concentration in the recreation season correlates well with that in the summer (r^2=0.98; Figure 18). The summer value is typically the larger of the two, making it more conservative from a regulatory perspective. Close agreement of the 95th percentile values for the two periods suggests that blooms would be represented adequately by either time window. The summer average also correlates well with the stratification season average (r^2=0.93; Figure 20) and is larger, again making the summer average the more conservative measure of algal abundance. The 95th percentile values for summer and stratification seasons are very close, indicating comparable coverage of blooms.

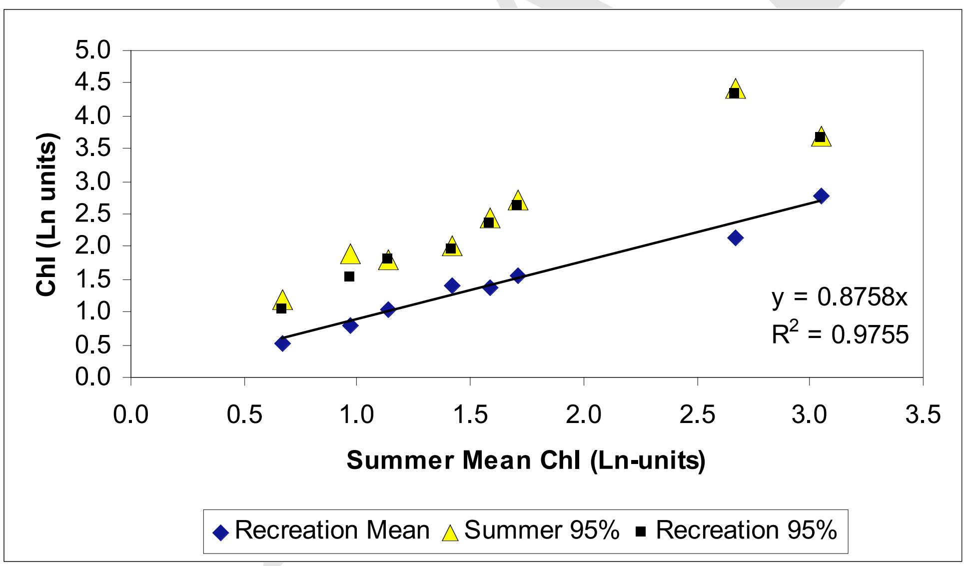

Figure 18. Relationship among means and 95th percentile values for the summer and recreation averaging periods. Each point represents the useful period of record for one lake. All values have been ln-transformed. The trend line for means has been forced through the origin.

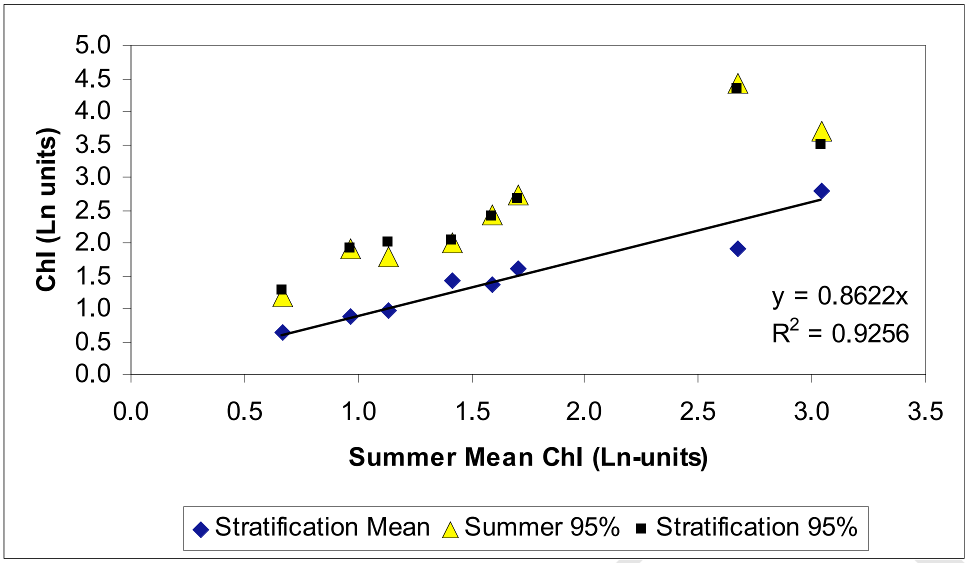

Figure 19. Relationship among means and 95th percentile values for summer and stratification averaging periods. Each point represents the useful period of record for one lake. All values have been ln-transformed. The trend line for means has been forced through the origin.

Finally, the summer average correlates well with the annual average (r2=0.86; Figure 20), and the averages are similar in magnitude. The correspondence between the 95th percentiles is not quite as strong as in the two previous comparisons, but still convincing. In some instances, blooms during the winter months may be larger than those recorded during the stratification season.

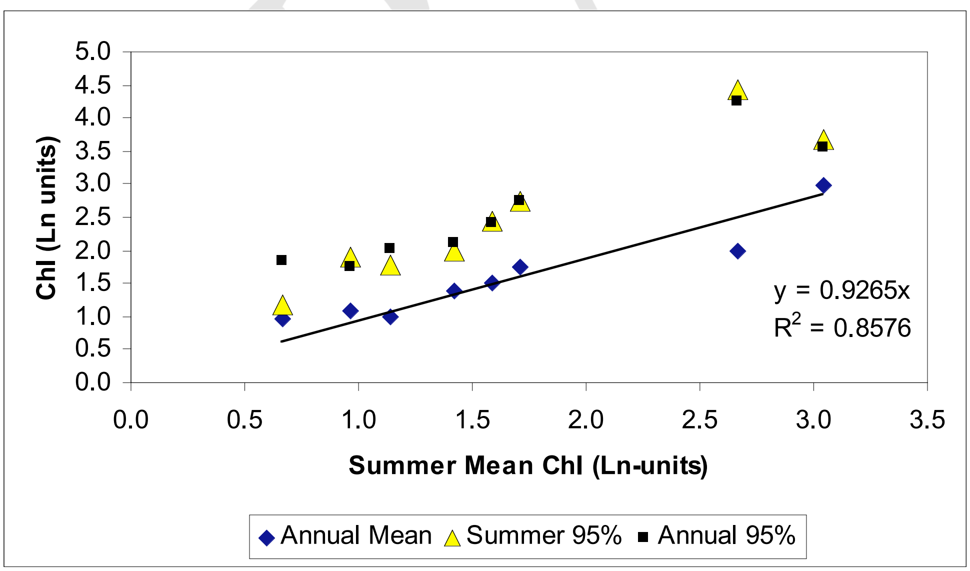

Figure 20. Relationship among means and 95th percentile values for the summer and annual averaging periods. Each point represents the useful period of record for one lake. All values have been ln-transformed. The trend line for means has been forced through the origin.

Comparisons of Averages Within Lakes

In a general sense, the summer mean is a good surrogate for algal abundance in other averaging periods. The summer mean is well-correlated with other means and it tends to be equal to or greater than the others. Thus, it is both representative and protective of all uses. How well does this generalization hold up for individual lakes?

The weighted mean and variance of the log-transformed concentrations were estimated for each of the four averaging periods of the useful data record for each lake. It was assumed that variances were unequal. Welch's approximate t-test method was used to compare the means. Results of the comparisons support the view that the summer mean is a good basis for assessing attainment (Table 4). The most consistent patterns show that the annual mean tends to be larger than the stratification season mean and the summer mean to be larger than the recreation season mean. The summer mean tends not to differ from the annual mean and the recreation season mean tends not to differ from the stratification season mean.

Table 5. Comparison of mean chlorophyll concentrations among four averaging periods. All pairwise comparisons are shown. When a cell contains a symbol, it indicates a significant difference at alpha=0.05 (2-tailed). For example, the greater than symbol (<) indicates that the annual mean was significantly different, and larger, than the stratification mean in Aurora Reservoir.

	Annual			Stratification		Summer
Lake	Strat	Summer	Recr	Summer	Recr	Recr
Dillon						
Aurora	>	>	>		>	>
Arvada						
Quincy	>			<		>
Bear Creek		<		<		>
Cherry Creek	>		>	<		>
Standley	>		>			>
Chatfield						

Conclusions and Recommendations

1) The term "growing season" is not useful in the context of nutrient criteria. There is a legacy of imprecise usage and no formal definition of the term. Moreover, a single definition would be unlikely to serve all regulatory needs related to averaging period. The term *chlorophyll averaging period* is therefore recommended.
2) Four averaging periods were examined, and clear patterns emerged from comparisons of the corresponding chlorophyll values.
    a. The annual mean tends to be larger than the stratification season mean. This is surprising insofar as stratification includes summer months when algal growth rates are higher.
    b. The summer averaging period, which is the basis for assessing attainment in some control regulations, has consistently higher mean chlorophyll than the recreation season. Concentrations in June tend to be the lowest of all months.

c. The summer mean tends not to differ from the annual mean and the recreation season mean tends not to differ from the stratification season mean.

3) If it were necessary to choose a single averaging period for assessing attainment, summer (Jul-Sep) would be the best of the ones tested. It is an appropriate surrogate for the annual mean, and it is conservative (i.e., higher) with respect to the stratification averaging period. Similarly, the summer averaging period would be conservative with respect to the recreation season, and this is useful whether the objective is bloom frequency or mean concentration.
4) A preference for one time window does not preclude selection of a different one or an additional one where it is better suited to regulatory needs. For example, assessment of direct use water supply reservoirs might be based on an annual average. Of course, any lake in that category would have to be monitored in all months.

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