Cherry Creek Reservoir Model

and

Proposed Chlorophyll Standard

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Preface for report of September 24, 2008

This report includes the following changes compared to the draft report of May 20, 2008:

Section 6.1. “Direct relationships of chlorophyll with loading variables” was revised.

Following sections were added:

7.2 Loads to attain chlorophyll standard for 9 out of 10 years (current goal)

7.3.6 Future scenarios involving the Rueter-Hess Reservoir

7.4. Exploration of alternative chlorophyll standard

Thresholds as the upper chlorophyll concentration at which an 80% frequency (12 out of 15 years) is attained are added to tables presenting scenario results in Section 7.

In particular, additional scenarios were modeled according to the stakeholders’ suggestions. Confidence limits were shown for the most promising approach to setting the TMAL (which is the regression of chlorophyll on average inflow TP concentration). Regression statistics were used to assess uncertainty of these approaches (instead of further sensitivity analysis). Potential chlorophyll standards were explored from various approaches and the most feasible one proposed. Appendixes were added.

Summary & Conclusions

Based on 15 years of measured data including nutrients and chlorophyll concentration in the reservoir, and water and phosphorus entering and leaving the reservoir, various approaches were used that predict changes in the TMAL target variable "Jul-Sep chlorophyll concentration of the mixed layer" in Cherry Creek Reservoir.

Several challenges had to be overcome: (1) the apparent lack of a significant correlation between reservoir TP and chlorophyll especially in recent years (2) the difficulty in the identification of sediment derived P or internal loading, as is common in relatively shallow, mixed lakes and reservoirs, and (3) the prediction of sedimentation or gross retention of P, which is related to point (2). These challenges were addressed (1) by using a slightly changed chlorophyll-TP regression equation based on the previous TMAL (2000), (2) by quantifying internal load with three partially independent approaches, and (3) by applying a retention model specifically developed for shallow lakes by the OECD.

Compliance levels and 15-year averages and medians of the target variable chlorophyll were determined with different models for several example scenarios as summarized in the *Summary Table*. In particular, the way the reservoir works was explored with two basically different approaches: the traditional TP mass balance model where chlorophyll is predicted from the TP-Chl regression (Equation 15) and regression models that are based on direct correlations of chlorophyll with the variables to be managed. It became clear that hypothetical changes in external load, water inflow volume, and average TP concentration of the inflow water each result in substantially different chlorophyll concentration changes.

- **Average inflow TP concentration:** Chlorophyll responds almost equivalent to changes.

- **External load:** Chlorophyll responds in a small way.

- **Flows and hydrology:** When only flow is changed, while external load is considered constant, chlorophyll responses are negatively correlated so that flow decreases lead to chlorophyll increases (due to negatively correlated TP_{in}). However, when external flows and loads are assumed to change proportionally, so that TP_{in} is not much affected, the response is marginal.

- **Internal load:** Chlorophyll responds to drastic changes only.

These relationships have to be considered when applying methodology that should insure "reasonable" long-term water quality for Cherry Creek Reservoir. It is evident that the current TMAL based on loads will not achieve that goal. It is proposed here that instead, a methodology that considers average inflow TP concentration as control variable be used.

Summary Table. Summary of predictions of target chlorophyll concentration and frequencies of obtaining Jul-Sep chlorophyll below 15.5 and 18.5 µg/L for various scenarios. Directing variables are indicated in bold.

Flow Volume	TPin	External Load	Chlorophyll (ug/L) Average	Chlorophyll (ug/L) Median	<15.5 ug/L Chlorophyll Years (#)	<15.5 ug/L Chlorophyll Frequency	<18.5 ug/L Chlorophyll Years (#)	<18.5 ug/L Chlorophyll Frequency	Notes
TPin									
100%	**100%**	100%	20.0	19.0	0	0%	6	40%	1
			20.1	19.9	0	0%	0	0%	2
100%	**90%**	90%	17.5	16.6	3	20%	11	73%	1
			18.0	17.8	0	0%	12	80%	2
100%	**75%**	75%	13.9	13.2	11	73%	14	93%	1
			14.9	14.8	13	87%	15	100%	2
100%	**110%**	110%	22.6	21.4	0	0%	1	7%	1
			22.3	22.1	0	0%	0	0%	2
Flow									
100%	100%	100%	21.3	22.3	1	7%	5	33%	2
90%	111%	100%	24.4	25.5	1	7%	3	20%	2
75%	133%	100%	30.7	32.1	0	0%	0	0%	2
110%	91%	100%	18.9	19.8	3	20%	7	47%	2
Flow (External load prorated to inflow)									
100%	100%	100%	20.0	19.3	0	0%	4	27%	2
75%	95%	71%	19.3	19.1	0	0%	4	27%	2
50%	90%	45%	21.4	18.5	0	0%	6	40%	2
125%	102%	127%	21.2	20.6	0	0%	4	27%	2
External load									
100%	n.a..	**100%**	20.0	19.1	1	7%	7	47%	3
100%	n.a.	**90%**	19.3	18.5	3	20%	8	53%	3
100%	n.a.	**75%**	18.2	17.4	4	27%	8	53%	3
100%	n.a.	**110%**	20.7	19.8	1	7%	4	27%	3
Internal Load		***Internal load*** *(External load constant at 100%)*							
100%	100%	***100%***	21.3	22.3	1	7%	5	33%	2
100%	100%	***50%***	18.6	19.8	5	33%	7	47%	2
100%	100%	***0%***	15.9	15.3	8	53%	11	73%	2
100%	100%	***150%***	24.2	24.0	1	7%	3	20%	2
100%	100%	***200%***	27.2	25.8	0	0%	2	13%	2

n.a., not available

Notes:
1 Chlorophyll predictions based on direct regression of Chl on TPin
2 Chlorophyll predictions based on mass balance model prediction of TP and TP-Chl regression
3 Chlorophyll predictions based on direct regression of Chl on external TP load

Equivalence of Chlorophyll and lake TP (ug/L)
(based on Equation 15)

Chl	TP	Chl	TP
11.1	50	**23.5**	90
12.6	55	**25.2**	95
14.0	60	**26.8**	100
15.5	65	**28.6**	105
17.1	70	**30.3**	110
18.6	75	**32.0**	115
20.2	80	**33.8**	120
21.8	85	**35.6**	125

Long-term, 100% values for 1992-2006

	Average	Median
Flow Volume (AF):	13,817	12,799
Inflow TPin (ug/L):	209	201
External load (lbs/yr):	8,072	6,492
Internal load (lbs/yr):	1,895	1,383

Analysis respective a revision of the chlorophyll standard:

Limnological analysis indicates that Jul-Sep average chlorophyll concentrations should be below 22 µg/L to avoid most bloom conditions at individual chlorophyll concentration above 30 µg/L. Secchi transparency is adequate for contact recreation below a value of 21 µg/L Jul-Sep chlorophyll concentration.

List of possible chlorophyll standards (µg/L)

Characteristic	Standard	Comment	Report Section
Current: 1992-2006	26	Data	7.4.5
<30 µg/L blooms	22	Data	7.4.1
Secchi	21	Data	7.4.1
Comparison	25	Standards of other States	7.4.3
Rueter Hess Scenarios	18.5	Based on Chl-TP_{in}	7.3.6
Rueter Hess Scenarios	24.5	Based on TP load	7.3.6

Considering the uncertainties based on time lags, model predictions, climate change and aeration treatment, we propose a standard of 25 µg/L to be reached 8/10 years (at an 80% level) for the near future. This is slightly below the long-term 80% threshold observed in 1992-2006. However, this standard should be reduced in the future to approach the more stringent 21-22 µg/L level, with introduction of the Rueter Hess reservoir and possible beneficial effects of the lake treatment. This reduction could be proposed at the next scheduled Rulemaking Hearing in 2014, unless interim monitoring data suggest otherwise.

The large variability of hydrology has an all encompassing effect on Cherry Creek Reservoir water quality and has to be considered in any future TMAL. Applications of flow relationships in future TMDLs are recently proposed by EPA in the Draft Daily Load document (EPA 2007, June 22). The application of annual average TP inflow concentrations instead of TP loads in any TMAL would imply such hydrologic dependencies.

Acknowledgements

A project like this can only be accomplished with support from many knowledgeable persons. Foremost we are grateful for the support by GEI, in particular Craig Wolf, whose diligent and timely responses to numerous questions helped establish the greatest possible accuracy with respect to monitoring data and general understanding of the Cherry Creek Reservoir functioning.

Jim Saunders of the Standards Unit, Water Quality Control Division, Colorado Dept. of Public Health and Environment, reviewed an earlier version of the TP model. Numerous discussions about the quantification of internal load and retention have led to the calibrated parameters in Section 4. Joni Nuttle’s (also of the Division) insights and comments are appreciated.

Michelle Wind and later Sharon Davis, both of Brown & Caldwell, provided guidance and insight into the TMAL process.

Chuck Reed of the Authority responded promptly to any queries and requests we may have had.

Last, but not least are acknowledged the attentiveness of audiences of the numerous presentations whose comments and insights put this endeavor into perspective.

Table of Contents

Tables

Figures

Glossary

Authority: The Cherry Creek Basin Water Quality Authority

Division: Water Quality Control Division, Colorado Dept. of Public Health and Environment

Time-dynamic model (as opposed to “steady state”): Detailed model that predicts TP concentration throughout the season (Freshwater Research, 2000a). In particular, this model is a time-dynamic, total phosphorus (TP), mass balance model that predicts lake water TP concentrations over the year using a daily or weekly time step. Phytoplankton chlorophyll was empirically estimated from the model's predicted TP. It used two well-mixed lake water compartments and required basic lake morphometry, hydrology and external TP load as data inputs. Outputs included TP and chlorophyll concentrations.

Annual steady state model: A mass balance model used to predict scenarios (Freshwater Research, 2000b). This is the model that is to be updated in the current project and is described here.

Chlorophyll: A measure of algae biomass, the pigment that is analyzed in water is chlorophyll *a*. This measure of chlorophyll concentration in lake water is prone to analytical errors and its standardization is difficult, so that accuracy and precision are often low. The July-September average chlorophyll concentration in the upper 4 m mixed layer is currently used as the chlorophyll “standard” in Cherry Creek Reservoir.

Total phosphorus, TP: All phosphorus (P) that can be analyzed in a water or sediment sample. It includes phosphate (highly available for algae), particulate forms (includes algae and non-living suspended particles), and forms not easily available for algae.

Jul-Sep TP, July-September average (or “summer”) TP concentration in the upper 4 m mixed layer. Currently used as the “goal” to achieve the chlorophyll “standard”.

TP_{ann}, average mixed layer TP of the year, usually at least monthly samples.

TP_{in}, annual average inflow concentration (theoretically determined from L_{ext}/inflow volume)

$TP_{sed,}$ sediment P (mg/g dry-weight)

External load, L_{ext}: The sum of annual TP inputs from all external sources, i.e. stream, non-point and point sources, precipitation and alluvium. Units are mg per square meter of reservoir surface area per year (mg/m^2/yr). For comparison, loads are sometimes also presented in units of pounds per year. External load is a gross estimate. Much of its phosphorus is in a chemical form that is not available to algae.

Export, L_{out}: The mass of TP that leaves the reservoir via the outlet stream. Units are mg per square meter of reservoir surface area per year (mg/m^2/yr). For comparison, values are sometimes also presented in units of pounds per year.

Internal load, L_{int}: Annual TP inputs from internal sources, i.e. the sediments. Units are mg per square meter of reservoir surface area per year. Gross estimates are usually used, but net estimates, based on mass budgets, can also be calculated. Most of the TP in L_{int} is in a chemical form (phosphate) that is highly available to algae.

L_{int_1}, *based on Method 1*: From *in situ* P increases (not quite a gross estimate, since some settling may have happened during the period of calculation)

$$L_{int\_1} = (P\_t_2 \times V\_t_2 - P\_t_1 \times V\_t_1) / A_o - L_{ext\_t1-2} \times 1\text{-}R_{sed} + L_{out\_t1-2}$$

where, t_1 initial date and t_2 date at end of period
P_t the corresponding P concentration
V_t the corresponding lake volume
A_o the lake surface area
Period: active period, e.g., 134 days

L_{int_2}, *based on Method 2*: From annual P budgets (gross estimate)

$$L_{int\_2} = (R_{sed} - R_{meas}) \times L_{ext} / (1 - R_{sed})$$

where, $R_{meas} = (L_{ext} – L_{out}) / L_{ext}$
L_{out}, annual TP export via outlet (mg/m^2/yr)

L_{int_3}, *based on Method 3*: From the product of active area and release rate (gross estimate)

$$L_{int\_3} = RR \times AnF_{pred}$$

where, RR areal anoxic release rate of P (mg m^{-2} d^{-1})

AnF_{pred} represents the active sediment area of a polymictic lake that releases P (days/year)

Annual areal water load, q_s (m/yr): The annual outflow volume (Q, cubic m) per surface area (A_o, square m), where $q_s = Q/A_o$.

Annual water detention time or *annual water residence time*, tau (yr): lake volume (V) divided by annual outflow volume (Q), where tau= V/Q.

Settling velocity, *v* (m/yr): The average distance that TP settles downward within one year.

Phosphorus retention, R: Retention is a proportional value based on the external load. It can mean two different quantities: It can be a theoretical value due to sedimentation or a calculated value from a mass balance. When retention is measured from an annual P budget as R_{meas}= (in - out) / in, it is a net term that combines downward fluxes of settling and upward fluxes from the sediments (internal load). The proportion of TP load that is retained due to sedimentation, R_{sed} has to be modeled or predicted. In this way, R_{meas} is smaller than R_{sed} and the difference is due to internal load.

$R_{sed} = v/(v+q_s)$, with $v = k \times q_s \times \sqrt{tau}$:

$$R_{sed} = \frac{1}{1 + \dfrac{1}{k \circ \sqrt{tau}}}$$

where k is a calibrated constant.

Anoxic factor, AnF (days/summer or days/year): active period and area that releases P and contributes to internal load (Equation 8)

Polymixis: The mixing regime in lakes and reservoirs that describes frequent (daily to weekly in the summer) mixing of the whole water column. In Cherry Creek Reservoir is polymictic because of its relatively shallow depth and the bottom outlet.

Compliance: The definition of this term is ambiguous. It depends on whether it refers to the current regulatory wording, which states that the target has to be reached 9 out of 10 years, or whether it refers to the proposed frequency of 4 of 5 years, or another period. Therefore, the term was used loosely in the final version of this report or has been replaced with *Frequency of occurrences* below a certain threshold for all 15 study years, i.e. 1992 – 2006.

1. Introduction

1.1. Characteristics of Cherry Creek Reservoir affecting TMAL development

In general, the model application in the Cherry Creek Reservoir TMAL-Control Regulation framework follows these three steps. (1) A model based on the total phosphorus (TP) mass balance was developed for individual years with all available measured data (15 years: 1992-2006) and specific constants were calibrated. (2) The mass balance model and related models created from average long-term relationships were used to explore hypothetical scenarios. (3) Jul-Sept chlorophyll average concentrations were computed for various scenarios to determine compliance in the 15 years that can serve to set the TMAL.

Limnological characteristics of Cherry Creek Reservoir have been described in detail in many annual reports by GEI, former *Chadwick Ecological Consultants* like that of *2006* and will not be repeated here. However, it is important to realize that the following characteristics are particularly relevant to the TP modeling exercise:

- Morphometry: shallow & polymictic
- Geology: hardwater
- Reservoir, rather than lake
- Internal load (sediment released TP)
- Bottom outlet

The shape of the basin, the relatively shallowness, and the bottom outlet prevent summer stratification in Cherry Creek Reservoir so that it is classified as polymictic. Polymixis means that mixing of the whole water column happens frequently (daily to weekly in the summer). Downward fluxes like settling of particles are effected by the mixing state as well as upward fluxes, like internal load.

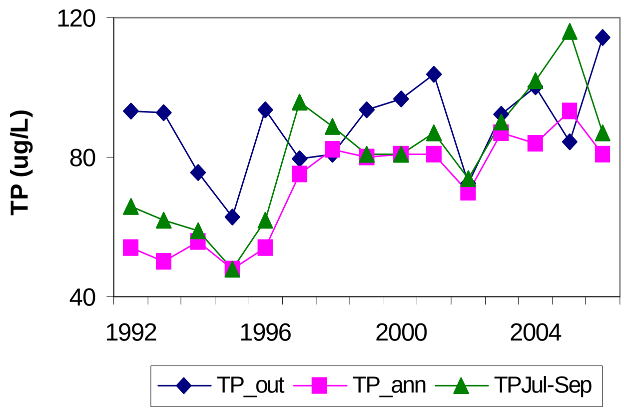
Geology affects the water of the reservoir. In the watershed of the Cherry Creek Reservoir there is sedimentary rock that is rich in phosphates and calcium. Consequently, its water is relatively hard. Calcium increases phosphorus (P) sedimentation while the nutrient-rich watershed encourages enriched conditions and a high trophic state in the reservoir.

The dam of a reservoir encourages settling of particles. Consequently downward fluxes as sedimentation are higher in reservoirs than in natural lakes.

Internal load or sediment released P is an important TP budget component. Its quantification is complicated by polymixis that prevents simple accumulation of P in the stagnant bottom waters.

Annual outflow TP concentration (TP_{out}) is larger than lake concentration because it leaves the lake via a bottom outlet from the deep water and is affected by internal load. A typical mass balance model predicts TP_{out} (Nürnberg 1998, 2005). TP_{out} is higher than both, mixed layer annual TP (TP_{ann}) and the target Jul-Sep TP concentration of the mixed layer due to sediment released phosphorus (Figure 1-1).

Figure 1-1. Comparison of different TP averages



In summary, Cherry Creek Reservoir's characteristic as a man made reservoir with bottom withdrawal, hardwater and polymixis render the TP settling properties different from systems usually studied (north temperate softwater lakes) and consequently sedimentation has to be calibrated for the mass balance model. Further, the quantification of internal load is challenging in shallow systems because there is no accumulation in stagnant water possible that could be used to determine the period of release and rates. Consequently, some of the model input and parameterization are based on best judgment and knowledge from other systems. Further a variety of different, often independent approaches were used to cross check the results achieved. Statistical analysis including bootstrapped confidence limits around compliance levels and sensitivity analysis give some measure of reliability.

1.2. Chlorophyll, Secchi transparency, cyanobacteria and nutrient limitation

Algae are the most conspicuous attributes of water quality and are often used to set water quality standards. Algae biomass is usually measured as the pigment chlorophyll *a* in a reservoir or lake. Since algae are dependent on nutrients in the water, typically correlations are found with the main nutrients phosphorus and sometimes nitrogen (N). In particular, summer average epilimnetic or mixed layer concentrations of the total compound, TP or TN, are correlated to chlorophyll and water transparency (for example, determined as Secchi disk depth) and are classified using trophic state limits to indicate general water quality (Table 1-1). A relationship between summer (July-September) chlorophyll, the TMAL "standard", and summer TP, the "goal", is to be used for the determination of the TMAL.

In Cherry Creek Reservoir these variables indicate eutrophic conditions (Table 1-1). But there is no synchronized trend with time (Figure 1-2) and chlorophyll is not significantly correlated with TP or TN (Figure 1-3). The regression of observed chlorophyll on TP Jul-Sep average concentrations is not significant and explains only 19% of the variance in chlorophyll (after log-transformation Jul-Sep averages of the mixed layer, n=15, R^2= 0.19, p=0.10) and the regression with TN explains no variance (R^2= 0.005).

Table 1-1. Trophic state categories based on summer water quality (Nürnberg 1996) and Cherry Creek Reservoir long-term summer averages (1992-2006)

	Cherry Creek Reservoir	Oligotrophic	Mesotrophic	Eutrophic	Hyper-eutrophic
Total phosphorus (µg/L)	**80**	< 10	10 - 30	31 - 100	> 100
Total nitrogen (µg/L)	**930**	< 350	350 - 650	650 - 1,200	>1,200
Chlorophyll (µg/L)	**20**	< 3.5	3.5 - 9	9.1 - 25	> 25
Secchi disk transparency (m)	**1.06**	> 4	2 - 4	1 - 2.1	< 1

Figure 1-2. Observed summer (Jul-Sep) TP, chlorophyll and TN averages with time. All units µg/L.

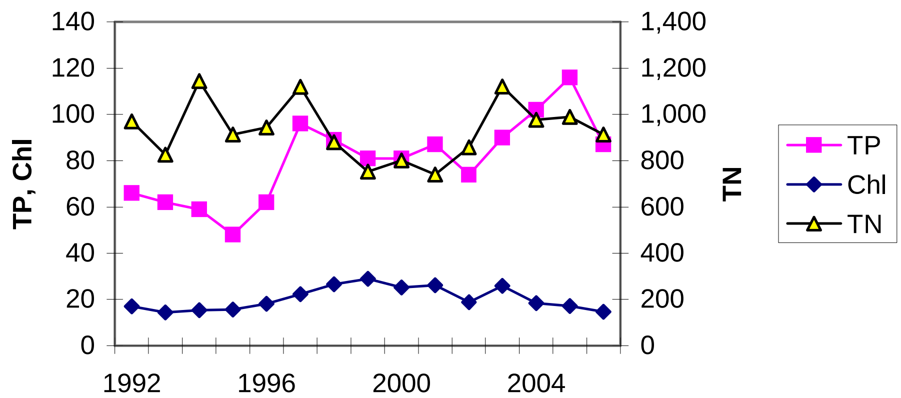
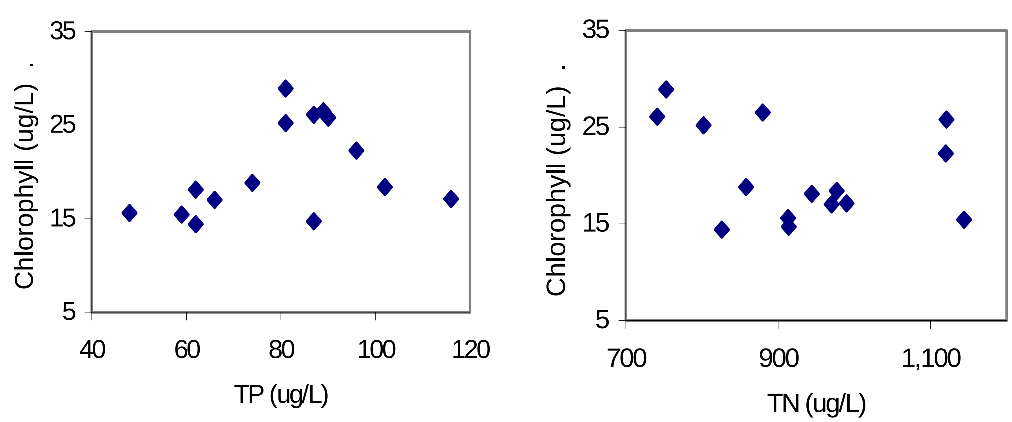
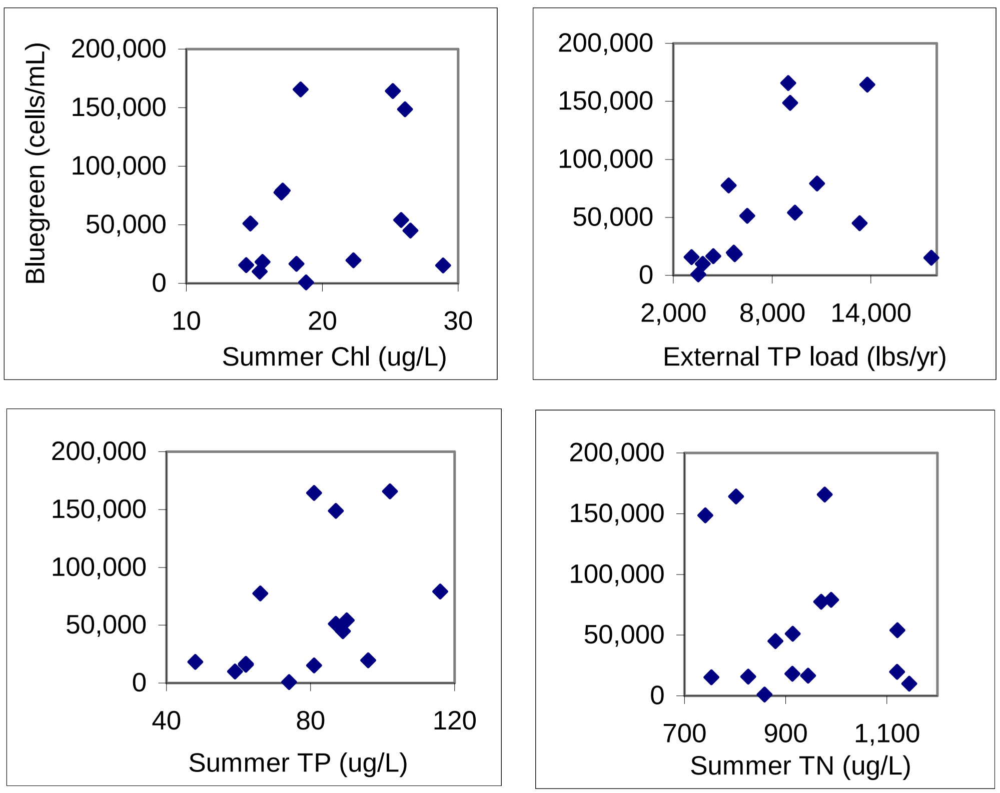


Figure 1-3. Observed chlorophyll versus observed TP and TN concentration July-September averages



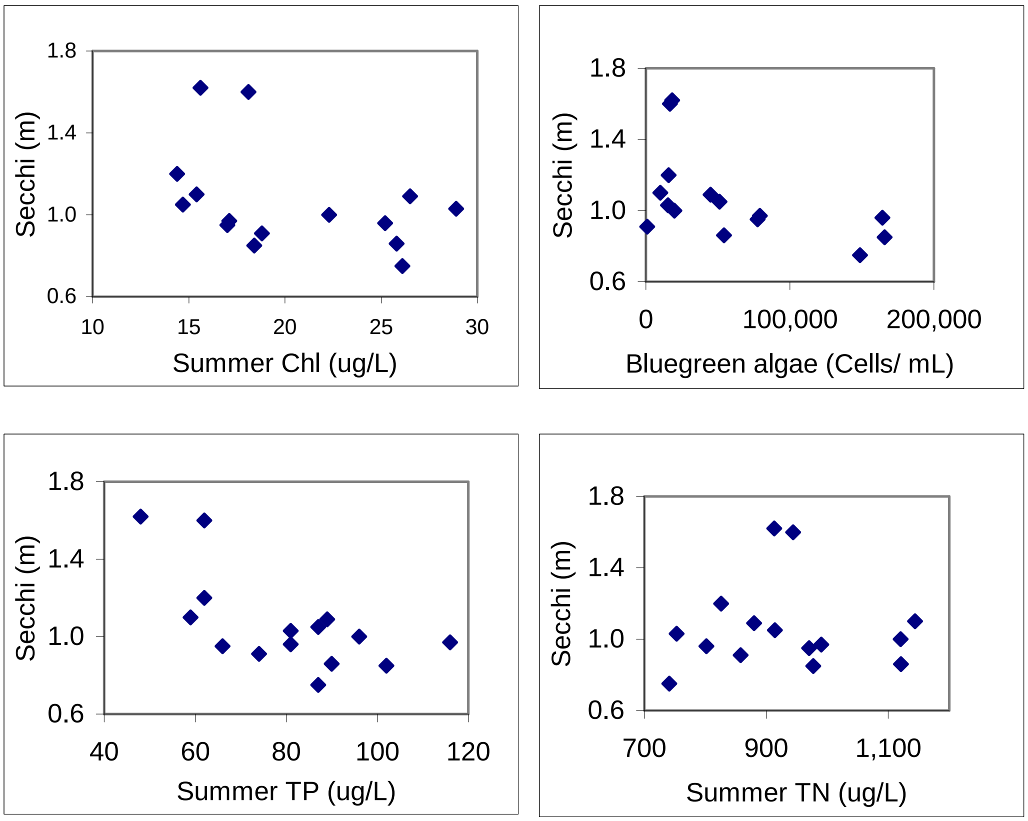
Cyanobacteria or bluegreen algae (“bluegreens”) affect water quality. Bluegreens not only create unsightly conditions, especially scum leading to low water transparency, but can be toxic to mammals and humans. The reason for a chlorophyll target is to control the overabundance of algae and especially of bluegreens as they are more prevalent at higher chlorophyll concentrations. Bluegreens are compared with chlorophyll, TP, TN and external TP load in Cherry Creek Reservoir (Figure 1-4). The log-log regression with TP is significant when the influential outlier of 2002 is removed (n=15, R^2=0.20, p=0.09; w/o outlier 2002: n=14, R^2= 0.34, p<0.05) and is also significant with external TP load (n=15, R^2=0.34, p=0.05; w/o outlier 1999: n=14, R^2= 0.57, p<0.01). Conversely TN is not correlated in any way (R^2=0.00).

Figure 1-4. Comparison of annual bluegreen algae biomass (Y-axis in cells/mL) with water quality indicators and external TP load.



The log-log regression of **Secchi transparency** on chlorophyll (Figure 1-5) is not significant, although there is a tendency of increased transparency with decreased chlorophyll (n=15, R^2= 0.19, p=0.10). However, the correlation with TP is highly significant (n=15, R^2= 0.48, p<0.01) and also with bluegreen algae biomass after the influential outlier of 2002, when bluegreen biomass was less than 2% of the long-term average, is removed in this regression (n=14, R^2= 0.47, p<0.01). There is no pattern detectable with TN (R^2= 0.005).

Figure 1-5. Comparison of Jul-Sep Secchi disk transparency with Jul-Sep Chlorophyll, bluegreen algae biomass, TP and TN.



In summary, although there is no significant direct correlation of chlorophyll with TP, there are many correlations that indicate the importance of TP in controlling water quality related to algae biomass in Cherry Creek Reservoir. In comparison, TN is not correlated in any relationships.

The result that TP is the important variable that controls algae rejects any hypotheses that nitrogen is more important in Cherry Creek Reservoir, despite evidence of occasional N-limitation in the reservoir, e.g., nutrient enrichment experiments by Lewis et al. (2004) in summer 2003 and recent analysis of TN:TP ratios by Craig Wolf, GEI (e-mail Feb 28, 2008). The GEI analysis indicates that nutrient limitation changes in some years from TP limitation to TP-TN co-limitation and occasional TN limitation, but not often during the summer period.

In general, nitrogen limitation only occurs in freshwater systems when algae are saturated with phosphorus. By reducing P below the saturation level, it again becomes the limiting nutrient and algae biomass declines. P reduction is usually easier to accomplish than N reduction, because cyanobacteria can incorporate atmospheric nitrogen gas (N_2). Therefore, phosphorus controls are still appropriate, so that it remains or again becomes the limiting nutrient.

2. Materials and Methods

2.1. Data Source

Data related to Cherry Creek Reservoir were provided by GEI. Such data include seasonal and annual averages of monitored concentrations of chlorophyll and TP, as well as mass balance data, hydrological and physical input for the model. Calculation methods and original data sources for this model input are specified in various reports and memos distributed by GEI.

Previous morphometric and hydrologic data and load calculations were revised to reflect the most recent knowledge. Accordingly, most of the data input of the previous TP model (1992-1999) has changed.

In particular, **morphometric** data are now based on US-ACE data that replaced those proposed by Knowlton and Jones and **hydrologic** data were revised by the US-ACE in their quality control program.

For the years 1999-2006 annual **TP export** was computed from a 7 m water sample at mid-lake station CCR-2 instead of the outflow station CC-0. Data for 1992-1998 are (still) based on outflow since no profiles exist. However, these data were statistically screened for outliers and a high August 1998 value was excluded (GEI, e-mail of Oct 15, 2007). Therefore, all TP export related values from 1998-2006 were changed.

The **reservoir phosphorus and chlorophyll concentrations** that are to be used as goal and standard are the composite of discrete samples from 1, 2, and 3 m depth (euphotic zone) of the July to September period. Whenever possible, average values of the three stations CCR-1, CCR-2 and CCR-3 were used.

2.2. Statistics

As central measure of long-term data distributions median and average were calculated. When variability is large and not normally distributed medians make more sense. Alternatively, logarithmic transformation to the base of 10 was used for normalization. Statistical tests were used to decide whether a pattern was likely "real" or due to chance alone. Usually linear regression analysis was performed on logarithmic-transformed data and three statistics are reported: (1) the sample size, n, (2) the proportion of the variability explained, R^2, and (3) the significance level, p. In testing correlations and regressions, generally a level of 95% or p=0.05 or less was applied. Levels of 0.001, 001 and 0.05 were reported. Important regression equations are presented with standard errors of the parameters in parentheses. The SYSTAT statistical program outlier procedure for regression analysis served to identify outliers.

To test whether model predictions were not significantly different from observations, regression analysis (deviation of slope from 1 and constant from 0) and paired t-tests were used.

Sensitivity analysis was performed to determine the importance of certain parameters on the model predictions.

3. Measured Mass Balance Components

3.1. TP components

External TP load varies about six-fold, export seven-fold and the proportion of external TP load retained or net retention, R_{meas}= (in-out)/in, from 0.46 to 0.75 between 1992 and 2006 (Table 3-1). Most of this variation is due to hydrology, in particular the inflow volume as presented in more detail in Section 3.2. However, there appears to be a tendency of decreased R_{meas} after 1998 (always <0.7), which could indicate increased sediment P release or decreased sedimentation, or could just be the consequence of different calculation methods (Section 2.1).

Table 3-1. Measured mass balance components

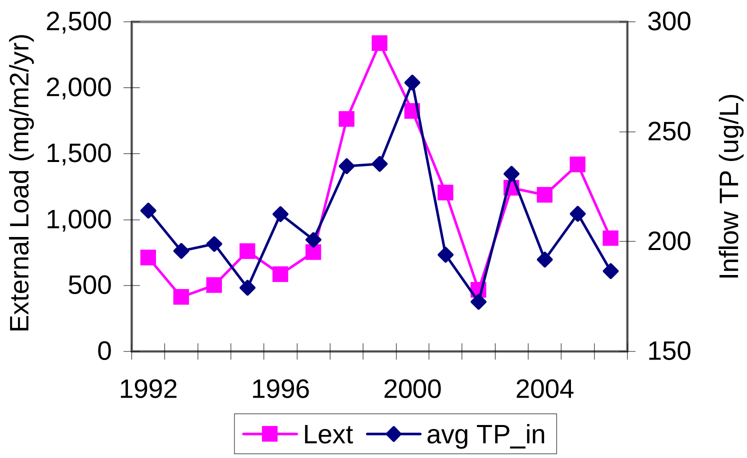
Year	External Load		Export	Retention
	(lbs/yr)	(mg/m^2/yr)	(mg/m^2/yr)	R_meas
1992	5,364	710	191	0.73
1993	3,114	412	123	0.70
1994	3,784	501	140	0.72
1995	5,736	759	190	0.75
1996	4,425	586	175	0.70
1997	5,675	751	212	0.72
1998	13,322	1,763	531	0.70
1999	17,672	2,339	863	0.63
2000	13,788	1,825	596	0.67
2001	9,099	1,204	515	0.57
2002	3,525	466	159	0.66
2003	9,390	1,243	401	0.68
2004	8,974	1,187	525	0.56
2005	10,725	1,419	486	0.66
2006	6,492	859	465	0.46
Median	**6,492**	**859**	**401**	**0.68**
Average	**8,072**	**1,068**	**371**	**0.66**

Note: To convert mg/m^2/yr into lbs/yr, multiply by 7.56

3.2. Observed interdependencies of inflow volume, concentration and external load

Loads are the product of water volume and concentration. Accordingly, the annual average inflow concentration (TP_{in}) can be computed from annual load divided by annual inflow volume. Its long-term variability is large, similar to that of external load (Figure 3-1).

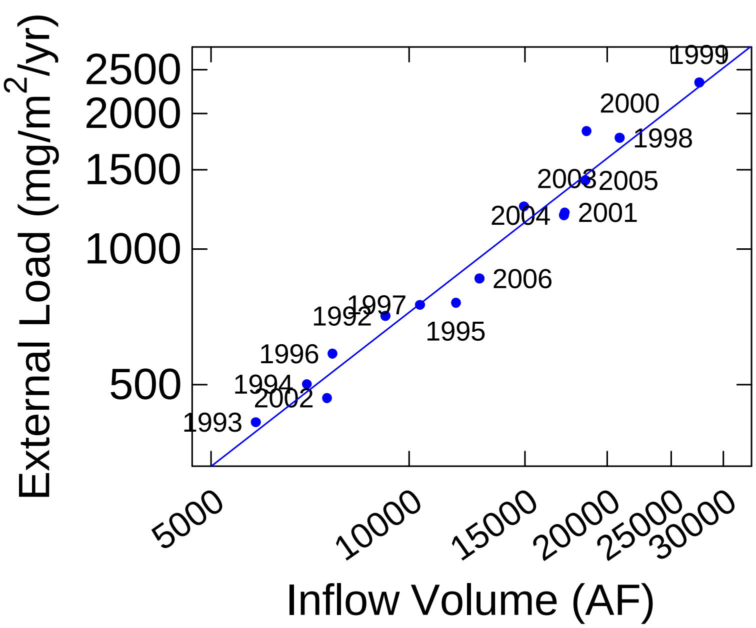
Figure 3-1. Annual changes of external load and inflow TP



Annual average inflow volume, TP inflow concentration and TP load are all interrelated. External load (L_{ext} in $mg/m^2/yr$) is highly significant and positive correlated with inflow volume (inflow_AF in AF) over the 15 observed years (R^2= 0.96, n=15, p< 0.0001, Equation 1, Figure 3-2. Standard Errors are reported in inner brackets.)

$L_{ext} = 10^{(-1.686\ (\pm 0.253)\ +\ 1.136\ (\pm 0.062)\ \times\ \log \text{inflow\_AF})}$ **Equation 1**

Figure 3-2. Annual external loads compared to inflow volume. Regression line for Equation 1 is shown.

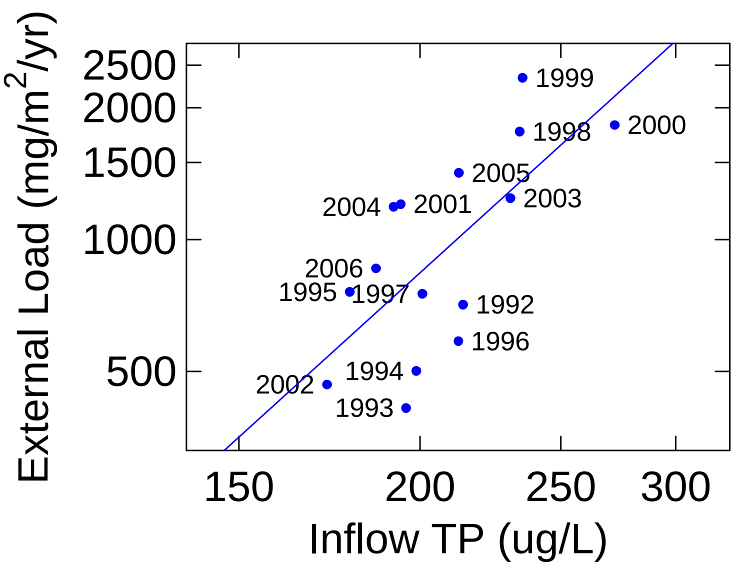


This means that Cherry Creek Reservoir is a hydrologic dominated system (annual flows vary almost six-fold, Figure 3-2), and the effect of the large variability of inflow volume on the size of external loading has to be considered in the TMAL model approach.

External load is also correlated with annual average inflow TP concentration (TP_{in}), although to a lesser extent. External load (L_{ext}, mg/m^2/yr) is significantly and positively correlated with TP_{in} over the 15 observed years (R^2= 0.46, n=15, p< 0.01, Equation 2, Figure 3-3. Standard Errors are reported in inner brackets.)

$$L_{ext} = 10^{(-3.99\ (\pm 2.102)\ +\ 3.007\ (\pm 0.907)\ \times\ \log TPin)}$$ **Equation 2**

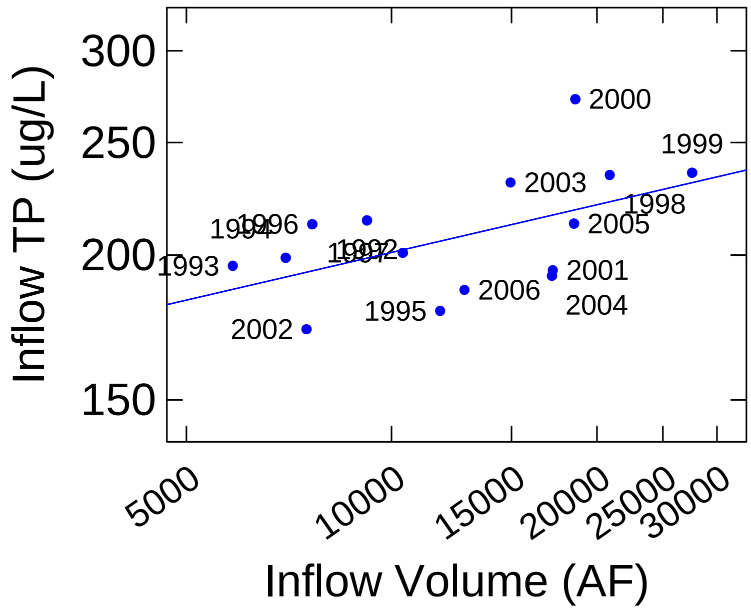
Figure 3-3. Annual external loads compared to annual average inflow TP concentration. Regression line is shown.



There is a tendency for TP_{in} to increase with higher inflows, that becomes less significant once the influential outlier of the year 2000 is removed (Figure 3-4, p<0.05, R^2= 0.27, n=15; without 2000: p=0.07, R^2= 0.24, n=14).

A slight relationship with flow volume can be explained from the calculation of the external load (from Craig Wolf, e-mail July 11, 2008): TP concentration in the inflows remains relatively constant during baseflow conditions, and only when flows are greater than the 90th percentile flow does TP concentration show an increase within a given year. Such flows are categorized as storm flow events, thus larger stormflow concentrations are applied to calculate loads. For example, Cherry Creek longterm (1992-2006) median base flow TP concentration is 203 µg/L and median storm flow TP concentration is 334 µg/L.

Figure 3-4. Inflow TP concentration (µg/L) compared to inflow volume (AF). Regression line is shown.

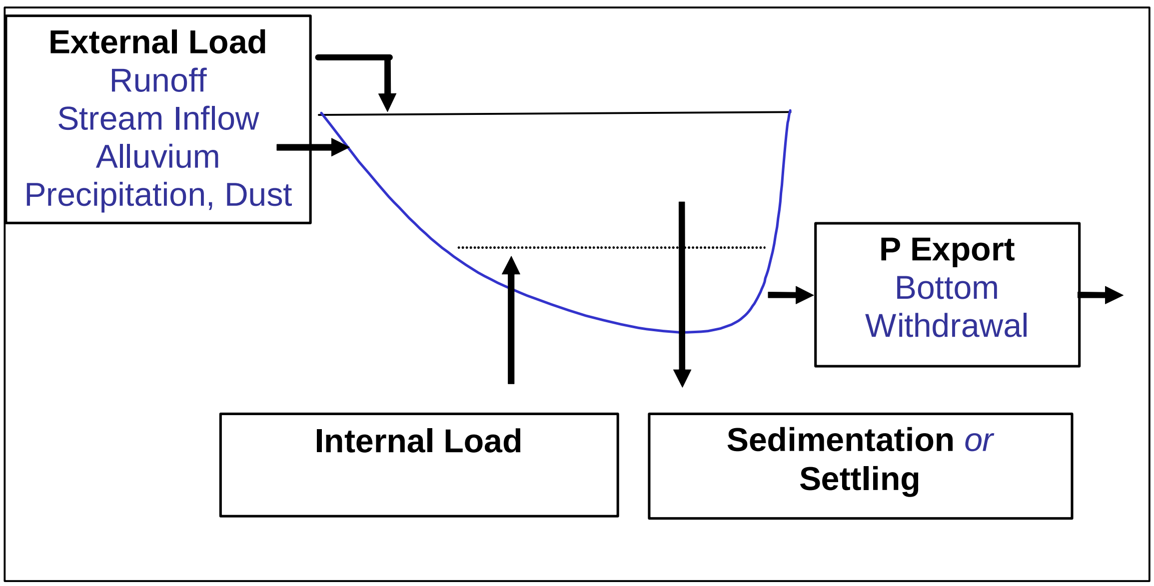


In conclusion, the effect of volume and TP_{in} cannot easily be separated and may contribute to the results when testing flow change scenarios. The interdependencies of loading, volume and concentrations explored in this section have to be considered when setting the TMAL.

4. Predicted Mass Balance Components

TP concentration was predicted by a mass balance model that includes external inputs or loads, and the downward and upward fluxes, or net retention. The up-ward flux is internal P load and was estimated with three different approaches. The down-ward flux is due to settling or sedimentation of particles and has to be modeled since it is almost impossible to measure sedimentation in polymictic reservoirs like Cherry Creek Reservoir. A schematic of the model is presented in Figure 4-1.

Figure 4-1. Schematic of the Cherry Creek Reservoir TP mass balance



4.1. Sedimentation and Retention

In an annual steady state mass balance, the proportion of TP load that is retained due to sedimentation (R_{sed}) is calculated from the annual average *settling velocity, v* (m/yr) and water load, q_s (m/yr, measured as outflow volume over lake area) according to following equation (Nürnberg 1984):

$R_{sed} = v/(v+q_s)$ **Equation 3**

Values of 10 to 30 m/yr for *v* were found empirically to fit annual mass balances in lakes and reservoirs (literature review in Nürnberg 1984). However, as they were developed for stratified lakes with soft to normal water characteristics they do not automatically apply to polymictic (occasionally mixed) hardwater Cherry Creek Reservoir. Therefore, sedimentation had been estimated by the Time-Dynamic Model (Freshwater Research 2000a) for 1992 to 1999. After testing these estimates with the new data inputs it was apparent that they are no longer applicable and the technical literature was searched for more applicable models.

Since the hydrology is quite variable in Cherry Creek Reservoir, a model was selected that predicts annual values of the settling velocity from annual *water detention time, tau* (also called *water residence time* with units of year, measured as lake volume divided by annual outflow volume), annual water load, q_s, and the constant k (e.g., Larsen and Mercier 1976):

$$v = k \times q_s \times \sqrt{tau}$$ **Equation 4**

Substituting v of Equation 4 with the v of Equation 3 and simplification leads to the following retention model

$$R_{sed} = \frac{1}{1+\frac{1}{k \circ \sqrt{tau}}}$$ **Equation 5**

$$R_{sed} = \frac{k \circ \sqrt{tau}}{1+k \circ \sqrt{tau}}$$ **Equation 6**

The original relationship was developed for natural lakes and simplified as k=1 (Larsen and Mercier 1976). This relationship was tested in the OECD project of the “Cooperative Programme for the Monitoring of Inland Waters” involving more than 200 lakes worldwide. A sub-study of 43 “Shallow Lakes and Reservoirs” consisted mainly of European, Australian and Japanese man-made reservoirs, some natural lakes and some dredged or dammed impoundments without inflow (Clasen 1980; Clasen 1981). All were considered polymictic or shallow. The Larsen Mercier and other existing models did not adequately predict TP in that dataset and therefore a model with the expression v= $a \times q_s \times tau^b$ was fitted. The best fit was reached for a= 2.271 and b=0.586 and subsequently “simplified” to a=2 and b=0.5 (Clasen 1981), which means k=2 in the context of Equations 4 to 6.

In another study (Hejzlar et al. 2006) k was determined as 1.84 for 119 records of European and North American reservoirs that included deep and shallow, oligotrophic and eutrophic reservoirs. This study also found, like others before, that retention of reservoirs is far higher than retention in natural lakes so that retention models differ for the two types of water bodies.

In all of these studies, no provision had been made to accommodate internal load separately from sedimentation in the P model, although more than 70% of the lakes and reservoirs in the OECD dataset were eutrophic and comparable to Cherry Creek Reservoir with lake TP concentrations between 30-100 µg/L and average inflow TP concentration between 100-1000 µg/L. Furthermore, sediment P release was deemed to occur in the more eutrophic OECD systems (Clasen 1980), as well as in the Hejzlar study, although here reservoirs with obvious and large amounts of internal load (determined from negative net retention in the mass balance) had been excluded. Consequently it can be argued that k is underestimated in both of these studies because of the omission of sediment released P and that their computed retention is actually a net estimate that includes upward fluxes.

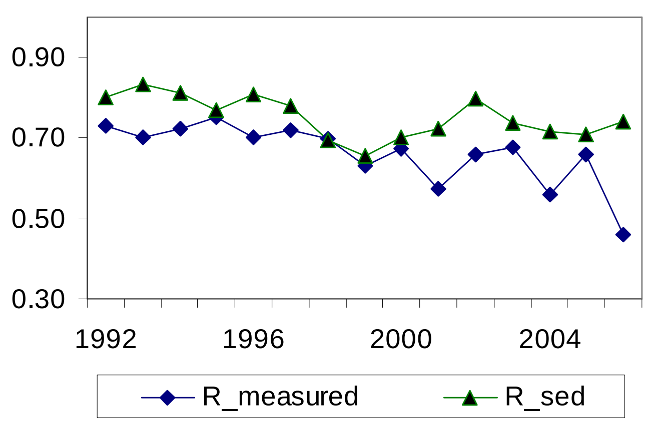
Only when internal load is explicitly considered as in the Cherry Creek Reservoir model presented here can sedimentation be modeled separately as gross retention R_{sed}. Therefore, *k* was calibrated specifically for Cherry Creek Reservoir. Its calibration requires that both, down- and up-fluxes be quantified to satisfy the rule of conservation of mass. Consequently, its calibration was done simultaneously with the estimation of internal load.

L_{int_1} (Section 4.2.1.) was used in the TP mass balance model to calibrate *k* for R_{sed}. Jul-Sep TP concentrations were predicted for different values of *k* and the value for the best fit was selected. In particular, values of *k* between 1 and 4 were applied and calibrated to the Jul-Sep TP averages (Section 5.1). A *k* value of 2.7 yielded the best fit. Using this value and annual water detention times and water loads based on 1992 – 2006 outflow volumes, the settling velocity, *v* (Equation 4), ranged from 6.7 – 17.6 m/yr with an average of 11.3 m/yr (median of 11.7 m/yr). This value is close to the estimate of the Dynamic Model (Freshwater Research 2000a) for year-round conditions without the spring calcium precipitation period (12.8 m/yr) and falls within the range of literature values (10 – 30, e.g., Nürnberg 1984).

Jim Saunders of the *Division* has suggested that perhaps the k value should be close to 1 so as not to overestimate internal load. However, this is lower than even the net estimates in the literature, cited above. Higher *k* values are also expected because reservoirs typically have higher settling velocity than natural lakes (e.g., v=12 m/yr in lakes vs. v=36 m/yr in reservoirs, Hejzlar et al. 2006),. Therefore, we do not propose to use any *k* values smaller than the chosen one of 2.7.

Inserting the chosen *k* value into the retention model (Equation 5 or 6) results in annual estimates of gross retention (R_{sed}) ranging from 0.66 – 0.83 and averaging 0.75 (median 0.74). As in any lake and reservoir with internal load, the difference between modeled and measured retention (Figure 4-2) is due to internal load, besides errors of estimates.

Figure 4-2. Comparison of measured net retention (from mass balance) and predicted gross retention (R_sed)



4.2. Internal load

Internal load is the phosphorus load that is released from the sediments. It originates from external inputs that settle and are transformed by geochemical processes in the sediments over time to be released when the sediment surfaces become anoxic (oxygen-free or reduced). The potential importance of internally derived phosphorus is higher than external load as it is in a form that is close to 90% biologically available and contributes to the growth of algae (Nürnberg and Peters 1984). In comparison, the average biologically available fraction (determined as SRP) of the external load from the inflow streams to Cherry Creek Reservoir was about 15% (for Cottonwood Creek, CT-2) to 77% (for Cherry Creek, CC-10) for the period of 1995-2005 (*Chadwick Ecological Consultants 2006*).

Quantifying internal load in a polymictic reservoir like Cherry Creek Reservoir is not easy because there is no well defined hypolimnion and summer stratification period. Consequently, internally derived P cannot be determined from accumulated hypolimnetic P concentration (Nürnberg 1987). Instead, mixing events combine P from external with internal sources so that the separation of P from the different sources has to be based on theoretical and empirical models. An attempt at the quantification of internal load in Cherry Creek Reservoir was made previously by a time-dynamic and an empirical mass balance model (Freshwater Research 2000b, a) that resulted in an average internal load value of 3,400 lbs/yr. Based on several assumptions and *in situ* P increases of just one summer AMEC Earth & Environmental et al. (2005) determined a value of 810 lbs/yr. Meanwhile, additional years of data have become available so that the quantification of internal load can be based on a total data set of 15 years. In addition, improved ways for internal load quantification have been developed including those for shallow polymictic lakes like Cherry Creek Reservoir (Nürnberg and LaZerte 2001; Nürnberg 2005).

Because of its importance and uncertainty, internal load was quantified in three different ways as (1) in situ internal load, (2) (net and gross) internal load from mass balances and (3) internal load from anoxic factor and release rate. Sections 4.2.1 to 4.2.3 explain these methods and Section 4.2.4 presents the resulting estimates.

4.2.1. Method 1: *In situ* internal load

In situ internal loads were determined according to Equation 7 from the increases of water column TP concentration between spring and fall under consideration of P export and input from external sources, corrected for sedimentation.

$$L_{int\_1} = (P\_t_2 \times V\_t_2 - P\_t_1 \times V\_t_1) / A_o - L_{ext\_t1\text{-}2} \times (1-R_{sed}) + L_{out\_t1\text{-}2} \qquad \textbf{Equation 7}$$

where,
- t_i with i=1 for initial date and i=2 for date at end of period
- P_t_i, the corresponding P concentration
- V_t, the corresponding lake volume
- A_o, the lake surface area
- $L_{ext\_t1\text{-}2}$, external load for the specified period
- $L_{out\_t1\text{-}2}$, export for the specified period
- $R_{sed,}$ proportion of settling external load

Jim Saunders of the Division suggested determining the period of release from dissolved oxygen (DO) and temperature profiles. First, the likely anoxic release period was estimated. Periods for DO values that showed a definite low of at most 3-4 mg/L (< 50% of saturation) were specified as hypoxic period. Such a relatively high DO value was chosen to prevent underestimation of hypoxia due to aeration of the mixed layer, which is common in shallow reservoirs like Cherry Creek. The period of hypoxia thus determined ranged from 56 - 119 days and typically started at the end of May or beginning of June and lasted until late July to September. Potential anoxia at the sediment surfaces is further supported by Craig Wolf's observations of low redox potentials in the summer of 2007 (e-mail of Oct 10, 2007.)

Next, this period was extended to cover the whole period with elevated temperature. Because the temperature values were still elevated at most dates marking the end of observed hypoxia, it is expected that sediment P release was still ongoing, even if DO profiles did not indicate hypoxic conditions. Since P release has been found repeatedly to be much enhanced at high temperatures (Liikanen et al. 2002), another period of likely P release was added to the one based on hypoxic conditions. The temperature at which hypoxia becomes evident in the spring, i.e. 17 ºC for 1998-2006, was chosen as threshold temperature. Consequently, the period when the whole water column temperature was above 17 ºC was added to that of the hypoxic period, and the release rate of the hypoxic period was assumed to be valid in this extended period as well. In addition, half of the sampling period in the spring (i.e., 7 days) was added to the period of likely P release to account for infrequent sampling between no hypoxia and the onset of hypoxic conditions.

The total period of P release from the sediments in Cherry Creek Reservoir thus determined ranged from 112-137 days for 1998-2006 and typically started at the end of May and lasted until Sept. For lack of temperature profile data, the average of 1998-2006 (124 days) was used in the years of 1992-1997. Detailed computations for the individual years are listed in Appendix A.

Winter anoxia was not found and P release from the sediments is not expected in years when the reservoir is not covered by ice. Very occasionally, cold winters induce ice cover, as was the case in 2006/7 and perhaps before 1992. Even if there is a short period of ice cover and low oxygen concentration in the bottom water, the temperature would be very low (2-6ºC) so that the P release rate would be very low as well. Furthermore, climate models for the Denver area predict rather warmer than colder winters in the future. For all these reasons estimates of L_{int_1} do not include any sediment released P for the winter.

4.2.2. Method 2: From mass balance

An annual *net* internal load (after sedimentation) was computed from a phosphorus mass balance according to (Nürnberg 1984):

$$net\ L_{int} = (R_{sed} - R_{meas}) \times L_{ext}, \qquad \textbf{Equation 8}$$

where, $R_{meas} = (L_{ext} - L_{out}) / L_{ext}$

L_{out}, annual TP export via outlet ($mg/m^2/yr$)

Gross internal load was then calculated from the net value by considering sedimentation of internal load that has happened over the year (Nürnberg 1998, in general: *gross* L_{int} = *net* L_{int} / (1 - R_{sed})), as in

$L_{int\_2} = (R_{sed} - R_{meas}) \times L_{ext} / (1 - R_{sed})$ **Equation** 9

L_{int_2} can be quite variable due to errors in the mass balance and values are less reliable for individual years. It serves as a check of the other estimates only and cannot be used for the prediction of TP because it is calculated directly from the mass balance and would deliver TP_{out}.

4.2.3. Method 3: Anoxic factor x release rate

A third method for the quantification of internal load was developed in Nürnberg 2005. It is based on the prediction of the extent of anoxic sediment surface area (or "active area that releases P, AnF_{pred}, Nürnberg 1995) and the P release rate for the active period and area (in mg per m^2 of active sediment surface and day of release, i.e. units are $mg/m^2/d$, RR). L_{int_3} delivers the only estimate presented here that is independent of the modeled retention R_{sed} (Section 4.1). Therefore, it serves as a check of the other two estimates.

$L_{int\_3} = AnF_{pred} \times RR$ **Equation 10**

where, RR, areal anoxic release rate of P ($mg\ m^{-2}\ d^{-1}$)

AnF_{pred}, predicted anoxic factor (days/year).

The anoxic factor represents the number of days per year or season that a sediment area, equal to the lake surface area, is anoxic. The observed factor is determined from DO profiles. In polymictic lakes, these anoxic factors are relatively small because of the mixing and aeration of the water layers. Nonetheless, a large surface area of eutrophic sediments is often hypoxic and active in releasing phosphorus. Nürnberg (2005) found that this active sediment area of a polymictic lake can be predicted from an anoxic factor model, AnF_{pred} (Equation 11).

$AnF_{pred} = -35.4+44.2 \log (TP_{ann}) + 0.95\ z/A_o^{0.5}$ **Equation 11**

where, TP_{ann}, measured average annual total phosphorus concentration (µg/L)

$z/Ao^{0.5}$, a morphometric factor
z, mean depth (m)
A_o, lake surface area (km^2).

Applying this model to Cherry Creek Reservoir, AnF_{pred} ranged from 41 - 54 days $summer^{-1}$ and averaged 49 (median 51) days $summer^{-1}$. An AF_{pred} of 50 days can be visualized as the following hypoxic conditions in time and space. Taking the average period of release (124 days) as determined from DO and temperature for L_{int_1} in Section 4.2.1 as a guideline when the sediments are active, about 40% of the surface area would be involved in release. Deeper sediments are most vulnerable to stagnant conditions and it can be assumed that the sediment area below 4 meters (13 feet), which represents 40% of the surface area, is involved in P release. Such ample conditions supportive of anoxic P release can be explained by the high organic content of Cherry Creek Reservoir sediments. Loss on ignition as a measure of organic content was comparably high at 30% in the deep basin and 45% in shallow areas (sampled Oct 6, 1999 by Chadwick Ecological Consulting).

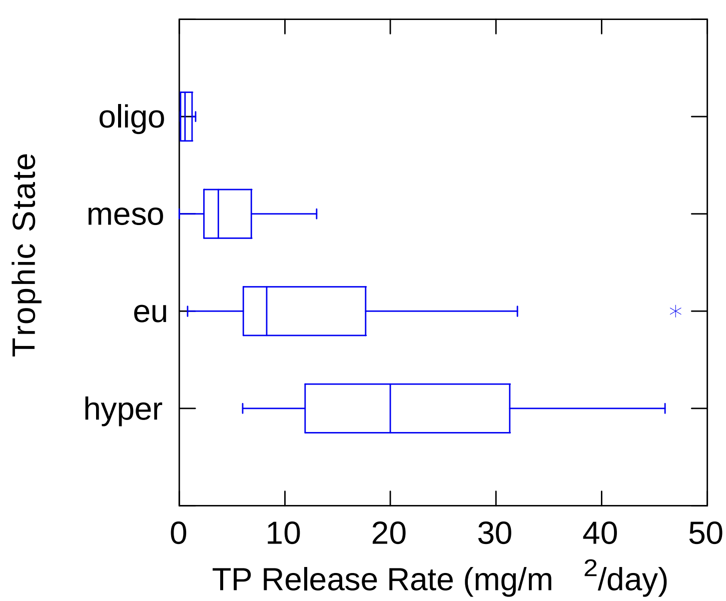
The summer average release rate is a more theoretical and integrated quantity, since it has to be representative of a rate for the whole period of release. Direct measurements of such a theoretical anoxic release rate are almost impossible to obtain and there are none available in Cherry Creek Reservoir. Therefore, the release rate was predicted from 0-5 cm sediment TP concentration (TP_{sed}) of the deeper sites according to Equation 12 (log, logarithm to base of 10, n= 63, R^2=0.21, $p<0.001$ Nürnberg 1988).

$$\text{Log (RR)} = 0.8 + 0.76 \log (TP_{sed}) \qquad \textbf{Equation 12}$$

Average TP_{sed} of 0.67 mg/g dry-weight (sampled Oct 6, 1999 by Chadwick Ecological Consulting) predicts a RR of 4.64 mg/m^2/d. Eutrophic conditions like those of Cherry Creek Reservoir typically support higher release rates than that as seen in a compilation of RR for 91 world-wide lakes and reservoirs (Figure 4-3, Nürnberg, unpublished studies). However, considering the low TP and high calcium in Cherry Creek Reservoir sediments, RR may indeed be comparably low.

For comparison, RRs were back-calculated from the other two internal load estimates as division by AnF_{pred} (Equation 10). Computed that way, an average rate of 5.1 (median 3.8) for L_{int_1} and of 6.6 (median 5.3) mg/m^2/d for L_{int_2} were determined.

Figure 4-3. Dependence of RR on trophic state compiled from 91 lakes and reservoirs.



Note: The central vertical lines are medians and the outside vertical lines are the 25% and 75% hinges.

4.2.4. Results of internal load

The three internal load estimates are compared in Figure 4-4 for the 15 years of available observations. The 15-year medians of the three methods range from 183 to 255 mg/m^2/yr and the averages range from 194 to 321 mg/m^2/yr (Table 4-1). Medians are less influenced by extreme values and are more meaningful here. Annual estimates differ between the methods. While extreme values of L_{int_2} (1998, 2006) are partially due to errors in the mass balance, annual variability of internal load can be expected in Cherry Creek Reservoir as a consequence of weather patterns that influence mixing of the water layers, variable distribution of loading and export throughout the summer, and many other variables that cannot be modeled. (However, variation in average deep summer temperature could not explain the annual variation of L_{int_1} , 2000-2006 at 7 m depth: 19.6 – 21.5 ºC, median 21.3 ºC).

Figure 4-4. Comparison of three different internal load estimates.

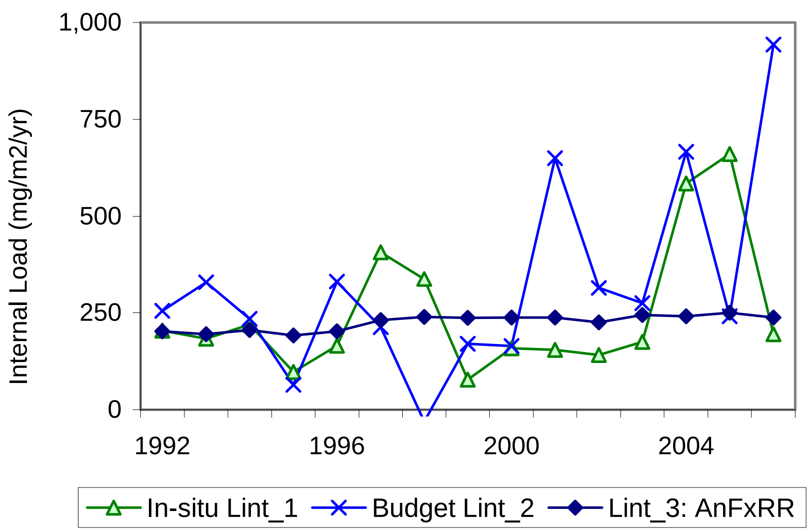


Table 4-1. Internal load estimates by three different approaches.

Year	**Internal Load (mg/m^2/yr)**		
	In situ (1)	**Mass Balance (2)**	**AnFxRR (3)**
	< gross	gross	gross
1992	204	255	202
1993	183	330	195
1994	220	234	205
1995	98	64	192
1996	165	332	202
1997	407	213	231
1998	338	-31	239
1999	78	170	237
2000	158	164	238
2001	154	650	238
2002	141	315	225
2003	175	275	244
2004	584	667	241
2005	660	241	250
2006	195	943	238
Median	**183**	**255**	**237**
Average	**251**	**321**	**225**

Note: To convert mg/m^2/yr into lbs/yr, multiply by 7.56

L_{int_1} has the smallest median which is expected because L_{int_1} is a partially net estimate due to some settling that has happened throughout the release period. In contrast, both other methods deliver gross estimates. Method 2 incorporates errors of the mass balance and therefore delivers highly variable results with unrealistically high values for 2006 and one negative value in 1998. Method 3 estimates are less variable because they are based on a constant release rate of 4.64 mg/m^2/day.

As annual variability is best captured by $L_{int\_1,}$ these values were used for predicting TP concentration in Section 5.1. Also, the lower, partially net estimate of L_{int_1} assists in estimating the lower Jul-Sep TP values as opposed to TP_{out} which the mass balance model nominally predicts (Equation 14). L_{int_1} was also used in the scenario of changes in internal load (for constant external load, Section 7.3.5). Of the three L_{int} estimates, only L_{int_3} was well correlated with external load and it was used in all scenarios of the mass balance approach, where external load changed. In this context, L_{int_3} was adjusted to the L_{int_1} so that Jul-Sep TP instead of TP_{out} was estimated (Section 6.2.2,).

5. Model output: TP and Chl

5.1. Prediction of seasonal TP

Usually a TP model based on the P mass balance predicts outflow TP concentration (Nürnberg 1998, 2005). In Cherry Creek Reservoir, annual TP_{out} is usually larger than lake concentration (both, annual and Jul-Sep averages) because it leaves the lake from the deep water at the bottom of the dam which has higher concentration due to sediment release (Table 5-1, Figure 5-1, see also Section 1.1). Therefore, Jul-Sep TP (used to determine the TP goal, July – September average lake TP concentration of the mixed layer) would be overestimated by the model of Equation 13 that predicts annual outflow concentration from gross internal loads.

Annual $TP_{out} = (L_{ext} + \text{gross } L_{int}) / q_s \times (1-R_{sed})$ **Equation 13**

Where:

q_s, annual water load (m/yr)
L_{ext}, external load (mg/m^2/yr)
L_{int}, internal load (mg/m^2/yr)
R_{sed}, modeled phosphorus retention due to sedimentation of external and internal load

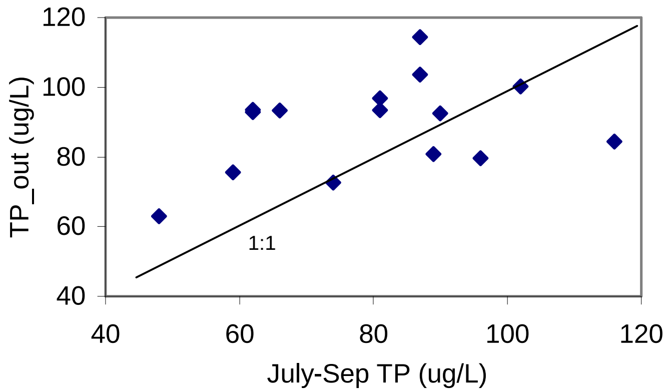
However, L_{int_1} is a partially net estimate and hence lower than a gross estimate. It appears that the slightly lower value takes the difference between TP_{out} and Jul-Sep TP into account and so it can be used in the prediction of Jul-Sep TP according to Equation 14.

Jul-Sep TP = $(L_{ext} + L_{int\_1}) / q_s \times (1-R_{sed})$ **Equation 14**

Table 5-1. Observed TP concentrations in the outflow and the mixed-layer reservoir and predicted Jul-Sep TP (all units µg/L).

Year	Observed TP			Predicted TP
	Annual Outflow	Annual	July-Sep	July-Sep
1992	93	54	66	88
1993	93	50	62	74
1994	76	56	59	74
1995	63	48	48	66
1996	94	54	62	77
1997	80	75	96	96
1998	81	82	89	98
1999	93	80	81	90
2000	97	81	81	97
2001	104	81	87	76
2002	73	70	74	57
2003	93	87	90	86
2004	100	84	102	96
2005	84	93	116	106
2006	114	81	87	67
Median	**93**	**80**	**81**	**86**
Average	**89**	**72**	**80**	**83**

Figure 5-1. Annual outflow TP concentration versus Jul-Sep TP



Jul-Sep averages of predicted and observed TP concentrations are significantly correlated (Figure 5-2, $p<0.01$, $R^2= 0.38$, n=15). Eight predictions are higher while six are lower than observed, rendering the model slightly conservative. However, there is a trend with time and all under-predictions happen in the recent years since 2001 (Figure 5-3, Table 5-1). It would be interesting to know, whether there is an increase in a P source that is not accounted for. (In 2003-2006 observed TP concentration were as high as or higher than before, except for 1997.)

Figure 5-2. Comparison of observed Jul-Sep TP averages with those predicted from the TP model. The line of perfect prediction (1:1) is indicated.

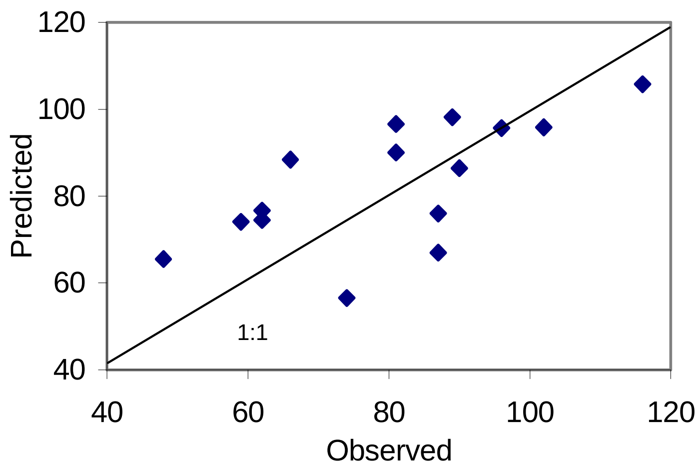
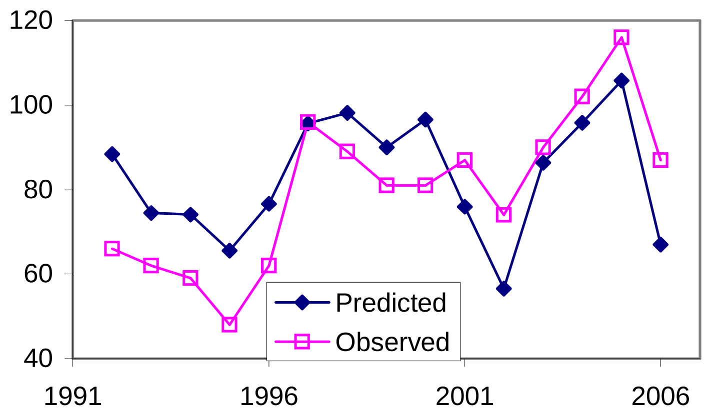


Figure 5-3. Comparison of observed with predicted Jul-Sep TP averages plotted against time.



5.2. Prediction of seasonal chlorophyll

Summer (Jul-Sep) average chlorophyll concentrations used in the TMAL process are to be computed from TP averages predicted for certain loading scenarios. However, in Cherry Creek Reservoir summer average chlorophyll does not seem to be related to TP concentration as discussed in Section 1.2 (Figure 1-3) and the regression of observed chlorophyll on TP Jul-Sep average concentrations is not significant (n=15, R^2= 0.19, p=0.10).

Therefore, regression equations in the previous TMAL reports (Freshwater Research 2000a, b) were tested and the following was used.

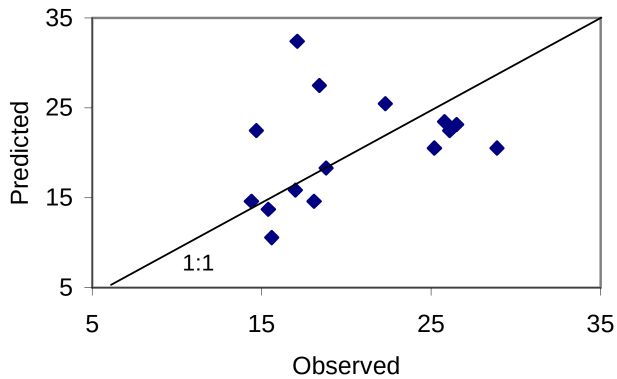
Chl = $10^{(2.697 + 1.268 \times \log TP\_mg)}$ **Equation 15**

where chlorophyll in µg/L and TP_mg in mg/L.

(Originally, a factor of 1.0683 had been used to adjust the relationship of TP vs. chlorophyll so that a 60 µg/L TP concentration would correspond to a chlorophyll concentration of 15 µg/L. However, the inclusion of revised and recent data supports the relationship without the scaling factor.)

Using the model of Equation 15, predicted chlorophyll concentrations are not significantly correlated with observed chlorophyll (n=15, R^2= 0.19, p<0.10, Figure 5-4). However, year 2005 was marked as an influential outlier by the SYSTAT criteria. The TP concentration was the highest on record at 116 µg/L in 2005 (Table 5-1), the next highest was 102 µg/L in 2004, so that predicted chlorophyll was comparably high as well. When year 2005 is excluded the regression is significant (n=14, R^2= 0.35, p<0.05). Predictability of chlorophyll is also supported by the fact that the intercept is not significantly different from zero while the slope is not significantly different from one and that the t-test does not reveal any significant difference.

Figure 5-4. Predicted from observed TP (with Equation 15) versus observed chlorophyll



Additional analyses by Craig Wolf of GEI support this regression equation. It lies in the centre of annual regressions of individual values for 1992 – 2006 (analyzed according to e-mail April 21, 2008). Consequently, chlorophyll was predicted from Equation 15 in the model exercise described in the present report and chlorophyll equivalents corresponding to certain Jul-Sep TP averages are presented in Table 5-2.

Table 5-2. Chlorophyll equivalents for Jul-Sep averages of TP according to Equation 15. All units are in µg/L.

TP	Chl pred	TP	Chl pred
20	**3.5**	75	**18.6**
25	**4.6**	80	**20.2**
30	**5.8**	85	**21.8**
35	**7.1**	90	**23.5**
40	**8.4**	95	**25.2**
45	**9.7**	100	**26.8**
50	**11.1**	105	**28.6**
55	**12.6**	110	**30.3**
60	**14.0**	115	**32.0**
65	**15.5**	120	**33.8**
70	**17.1**	121	**34.2**

There appears to be a recent deviating trend in the model performance similar as for TP predictions. The three last years (since 2004) are severely overestimated by the model while in the previous years there is a tendency to underestimation (Figure 5-5). In comparison, recent TP predictions from measured TP were underestimates (Figure 5-3). Nonetheless, chlorophyll prediction from modeled TP concentration seems to be only slightly improved (Figure 5-6). Further monitoring of chlorophyll and TP in Cherry Creek Reservoir may be needed to explain these trends.

Figure 5-5. July-September averages of observed chlorophyll values and those predicted from observed TP concentration (with Equation 15).

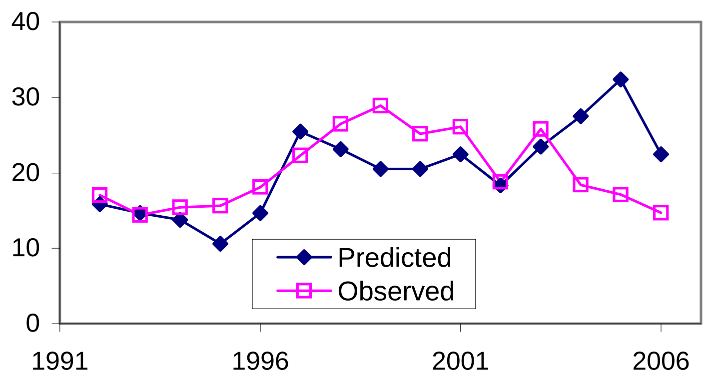
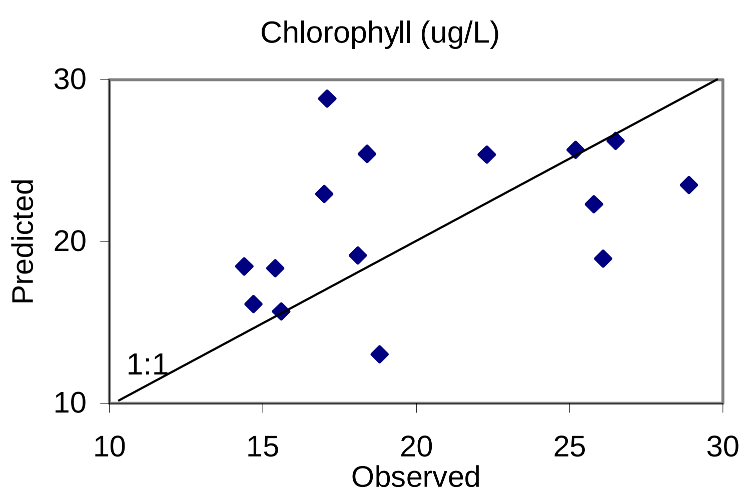


Figure 5-6. Same as Figure 5-4, except that chlorophyll values are predicted (Equation 15) from *predicted* (Equation 14) TP concentration



6. Approaches to TMAL

For the TMAL and scenario modeling it is necessary to establish and use relationships between manageable input variables and the target (response) variable. The prime variable to be managed is external TP input or loading and the ultimate target variable is Jul-Sep average chlorophyll concentration of the upper layers that are usually well mixed in Cherry Creek Reservoir.

If there are any significant empirical relationships between the input and the target variable, these can be used to determine possible responses to future changes of the input variable values. Such relationships are explored in Section 6.1. The traditional way of modeling chlorophyll is via TP concentration in the reservoir as presented in Section 5. The application of this approach in the TMAL is described in Section 6.2.

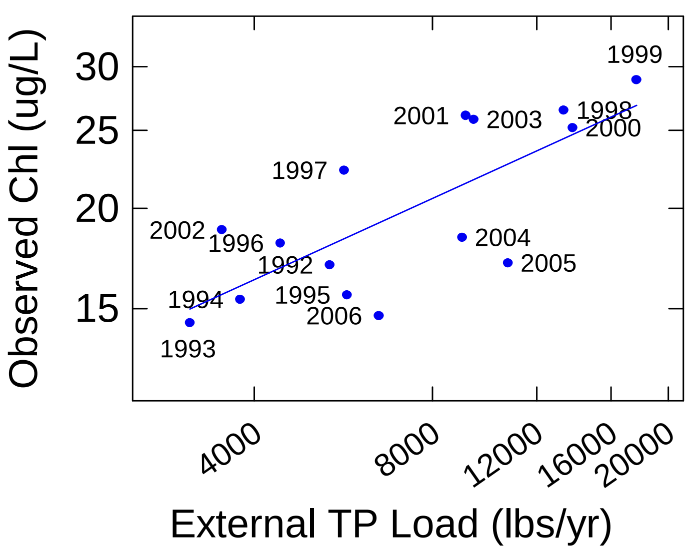
The input variable *TP load* consists of the hydrological aspect of water volume and the TP concentration (Section 3.2). Consequently, relationships concerning these variables were considered in both approaches.

6.1. Direct relationships of chlorophyll with loading variables

The TMAL target variable of Jul-Sep chlorophyll is highly significantly positively correlated with external TP input (Load_lbs in lbs/yr, R^2= 0.55, n=15, p< 0.001, Figure 6-1).

$$Chl = 10^{(0.001\ (\pm 0.323)\ +\ 0.336\ (\pm 0.084)\ \times\ \log Load\_lbs)}$$ **Equation 16**

Figure 6-1. Observed July-September averages of chlorophyll versus external TP load, regression line is shown



It is interesting to note that only at external loads below 6,500 lbs/yr chlorophyll concentrations are below 15 µg/L (but higher concentrations exist, too). According to the regression equation (Equation 16), an external load of 3,150 lbs/yr is equivalent to the chlorophyll standard concentration of 15 µg/L.

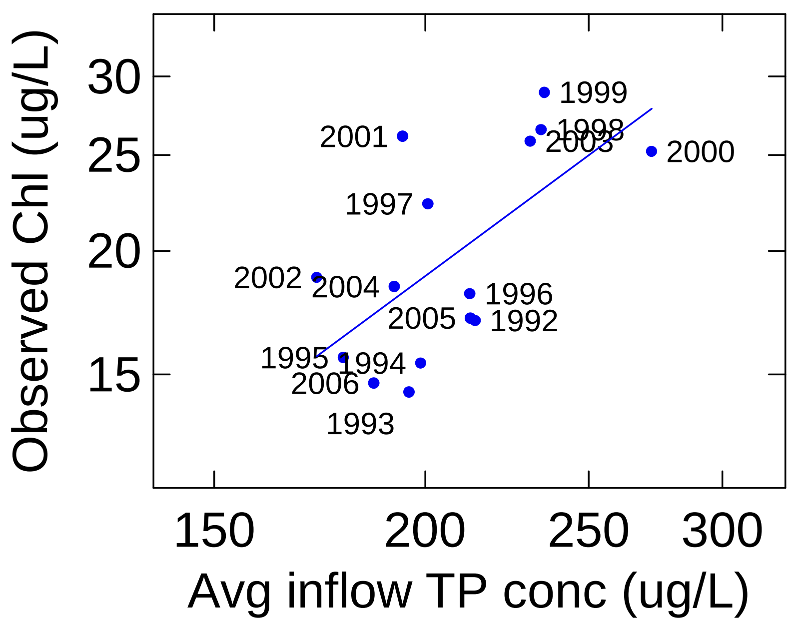
In comparison the correlation of external load with Jul-Sep TP averages is much weaker (R^2= 0.34, n=15, $p< 0.05$).

The significant relationship between chlorophyll and external load lends credibility to the whole concept of TMDLs and TMALs and its application to Cherry Creek Reservoir. Furthermore, it can be used to tentatively compare chlorophyll responses to loading changes as presented in Section 7.3.4.

External TP load is the product of water volume and TP concentration of the combined inflows. Specifically, annual average inflow TP concentration is computed from the quotient of load divided by inflow volume. TP_{in} is significantly positively correlated with chlorophyll (R^2= 0.39, n=15, $p< 0.01$, Equation 17, Figure 6-2).

$$Chl = 10^{\,(-1.625\ (\pm 1.004)\ +\ 1.261\ (\pm 0.433)\ \times\ \log TP\_in)}$$ **Equation 17**

Figure 6-2. Observed July-September averages of chlorophyll versus average annual inflow TP concentration, regression line is shown



It is interesting to note that only at an average annual inflow TP concentration below 200 µg/L chlorophyll concentrations below 15 µg/L are found (but higher concentrations exist, too). According to the regression equation (Equation 17), an inflow concentration average of 167 µg/L is equivalent to the chlorophyll standard concentration of 15 µg/L.

In Cherry Creek Reservoir external load is almost completely controlled by inflow volume (Section 3.2). While chlorophyll is highly correlated to external load, the usefulness of this relationship in setting the TMAL is only limited, because water volume that represents a large part of its variability, is not manageable. More meaningful for management purposes are relationships with average inflow TP concentration. Larsen and Mercier (1976) have also pointed out that average inflow concentration is more important than load for TP concentration and water quality of lakes and reservoirs.

6.2. TP mass balance model

The mass balance approach for setting the TMAL is based on the prediction of average lake Jul-Sep TP concentrations from annual hydrological characteristics and TP budgets according to the models described in Sections 4 and 5. The target variable chlorophyll is then predicted from the predicted TP. Some of the measured model inputs have to be predicted so that hypothetical scenarios can be computed. In particular, the water budget can be simplified (Section 6.2.1) and the internal load can be determined by a numeric relationship with external TP load (Section 6.2.2). Further, to separate the importance of inflow volume versus inflow concentration in controlling the target variable chlorophyll, separate model sequences were developed (Sections 6.2.3 and 6.2.4).

6.2.1. Simplification of water budget

Observed inflow volumes for 1992-2006 were used in all scenario modeling to provide an estimate of natural hydrological variance. Because the mass balance model depends on values for outflow rather than inflow for the hydrological variables like water detention time, tau, and water load q_s, outflow volume was determined from inflow volume in future scenarios, as follows.

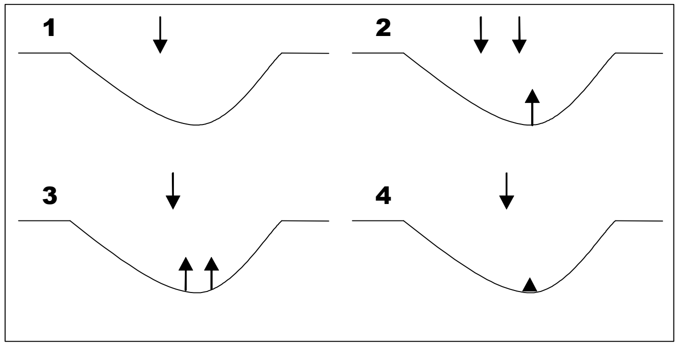
Outflow Volume = Inflow Volume – Evaporation **Equation 18**

where, Evaporation = 2,500 AF (average of 1992-2006 volume difference between inflow and outflow)

6.2.2. External and internal load relationship

Because of the large annual variability of internal load estimates, an attempt was made to use a correlation with another available variable, rather than using a constant load as done previously (Freshwater Research 2000b). It has been argued and observed repeatedly in the scientific literature that internal is related to external TP inputs (e.g., Nürnberg and LaZerte 2001, 2004; Coveney et al. 2005). In general it can be expected that internal load follows external load after a time lag that depends on water renewal time and the amount of change. A conceptual paradigm is presented in Figure 6-3. Cherry Creek Reservoir may be between Stage 2 and 3 because of TP decreases in the watershed and inflows. Future BMPs or in lake restoration treatment may eventually result in smaller internal loads as assumed in Stage 4.

Figure 6-3. Paradigm of long-term equilibrium relationships between external and internal loads (Nürnberg and LaZerte 2004)



Note: Presumed stages during the eutrophication process in lakes and reservoirs with respect to internal P load from the lake bottom (upwards arrow) in response to external load (downwards arrow). During Stage 1, external load happens, but no internal load. Even if the hypolimnia may be anoxic, there is not enough reductant-soluble P in the sediment surfaces to be released. In Stage 2 the external load increases, due to anthropogenic sources from development, and sediment P release will eventually commence, depending on the oxygen state of the sediment surfaces. Even when management efforts reduce the P load from the watershed as in Stage 3 internal load will still occur until more reductant-soluble sediment P has been flushed out (Stage 4).

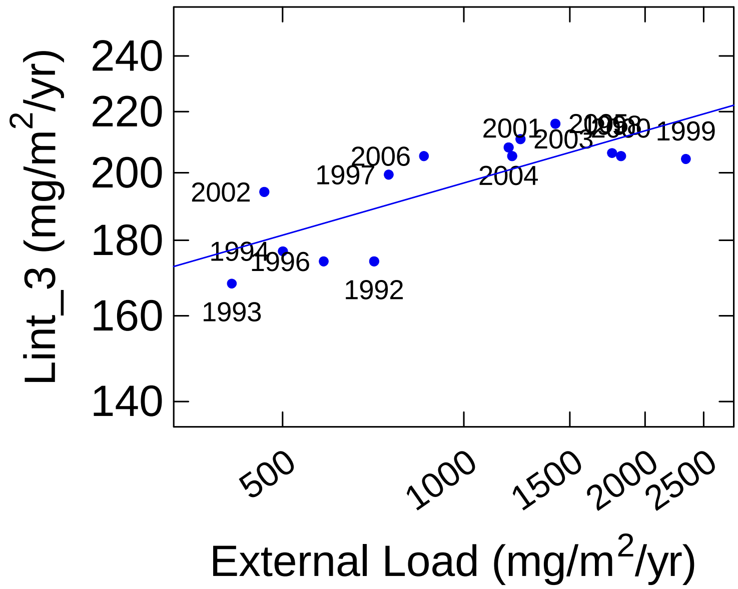
Consequently it can be assumed that internal load will eventually decrease or increase with external load in Cherry Creek Reservoir. To predict internal load (L_{int_pred}, mg/m^2/yr) in the TMAL model, we propose to use a correlation with external load as there is a significant correlation of L_{int_3} with external load (R^2= 0.53, n=15, p< 0.002). The other two internal load estimates are not correlated (R^2= 0.04 for L_{int_1}, R^2= 0.006 for L_{int_2}. Mathematically, the relationship occurs because Lint$_{_3}$ is based on $AnF_{pred,}$ Equation 10, which is predicted from TP, which is related to external load.)

Because L_{int_3} is a gross estimate that would predict TP_{out} instead of Jul-Sep TP it was adjusted to be similar to partially net L_{int_1}. It was decreased by about 15% to compare more closely to long-term median L_{int_1} that successfully predicts Jul-Sep TP. This is equivalent to using a release rate of 4.0 mg/m^2/day instead of 4.64 in Equation 10.

In scenario modeling, L_{ext} would be computed according to changes in inflow volume or inflow concentration and internal load would be modeled in dependence of that external load (Equation 19, Figure 6-4, R^2= 0.53, n=15, p< 0.002). Such predicted internal load estimates represent long-term responses to changes in external load and do not incorporate any time-lag effects due to sediment P storage.

$$L_{int\_pred} = 10^{(1.915\ (\pm 0.097)\ +\ 0.125\ (\pm 0.033)\ \mathrm{x}\ \log Lext)}$$ **Equation 19**

Figure 6-4. Measured adjusted internal load (L_{int_3}) versus observed external load. The line represents the regression line.



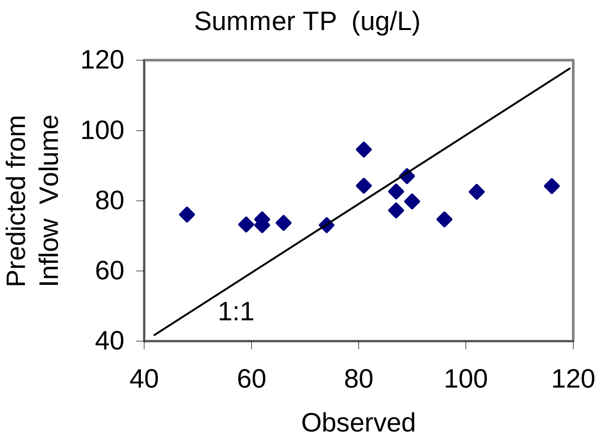
6.2.3. Predictions based on *external load-inflow volume* relationship

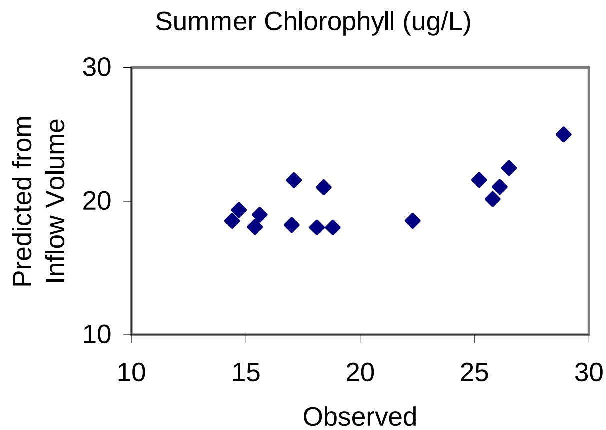
In this sub-model external load is computed from the current long-term relationship with annual inflow volume (i.e., external load-inflow regression equation, Equation 1). In this way, a model sequence is constructed that is capable of testing the influence of changes in hydrology in scenarios for conditions of current long-term inflow concentrations. (This approach was used in the Scenario Model of Freshwater Research 2000b).

In this approach following model components are used: observed inflow volume, outflow volume as computed by subtracting evaporated volume (Section 6.2.1), external load predicted from inflow volume (Equation 1 of Section 3.2) and internal load predicted from external load (Equation 19 of Section 6.2.2). TP and chlorophyll concentrations are predicted according to the formulas of Section 5.

Such predicted and observed concentrations are not significantly different from each other (paired t-test on log-log transformed data, for TP, $p=0.83$; for chlorophyll $p=0.88$, Figure 6-5) and significantly correlated (regression for TP $R^2= 0.23$, $p<0.05$, w/o influential outlier of 1999: $R^2= 0.42$, $p<0.02$; for chlorophyll $R^2= 0.48$, $p<0.01$). However, figures and regression equations show that there are deviations especially for TP concentrations and lower chlorophyll concentrations so that there is uncertainty associated with these predictions. Nonetheless they can be used in an exploration of the importance of inflow volume on the target variable, chlorophyll (Section 7.3.2).

Figure 6-5. Predicted (based on TP loads predicted from inflow volume) versus observed Jul-Sep TP and chlorophyll concentrations.



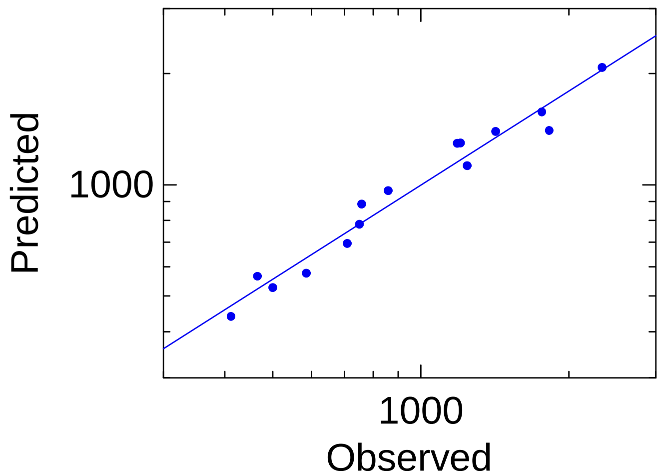


6.2.4. Predictions based on constant *average TP inflow concentration*

In this sub-model mass balance components are again computed from relationships with measured annual inflow volumes; however, here the average TP inflow concentration (TP_{in}) is kept constant for all years. In this way a model sequence is constructed that is capable of testing the influence of changes in inflow TP concentrations while keeping inflow volumes at current variability.

As in the previous sub-model, outflow volume is computed by subtracting evaporated volume from inflow volume (Section 6.2.1), and internal load is estimated from external load (Equation 19 of Section 6.2.2). In this approach however, external load is determined from the inflow volume times average annual inflow TP concentration (i.e., 209 µg/L for 1992-2006). These loads are significantly correlated with observed loads (R^2= 0.97, p<0.0001, and the regression line is not sign different from the 1:1 line of perfect prediction, Figure 6-6).

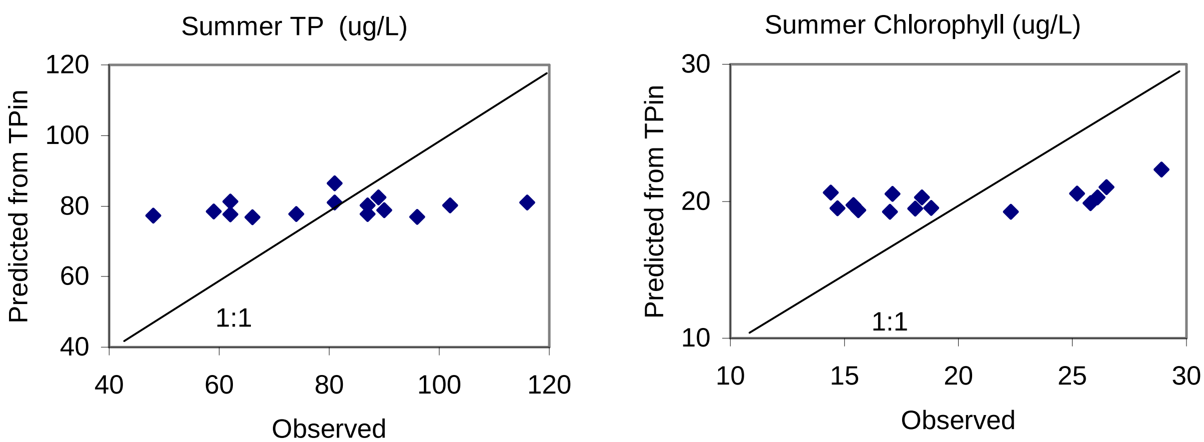
Figure 6-6. Comparison of external load, predicted from a constant inflow TP concentration of 209 µg/L versus observed external load, regression line is shown.



TP and chlorophyll concentrations can then be predicted according to the regression equations presented in Section 5. From the scatter plots (Figure 6-7) it is obvious that predicted TP and chlorophyll are almost constant, representing the long-term average. By holding TP_{in} constant and varying flow volume to change external load, no change in reservoir TP and chlorophyll is predicted.

This result means that almost all inter-annual variation in Jul-Sep TP and chlorophyll concentration is due to the TP_{in} component of the external load.

Figure 6-7. Predicted (based on TP loads with average inflow concentration of 209 µg/L) versus observed Jul-Sep TP and chlorophyll concentrations.



7. Compliance levels resulting from different approaches

Chlorophyll concentrations were predicted from different approaches and for different scenarios to increase the understanding of the interactions of flow, load and concentration, besides the determination of the TMAL value. First, the current compliance of measured data is presented (Section 7.1); next, compliance for various scenarios is presented (Section 7.2). The results of the different approaches are listed in separate tables. In particular, chlorophyll predictions for individual years (1992-2006) and averages, medians and ranges are presented, including the resultant frequency of obtaining the current chlorophyll standard of 15 µg/L (criteria <15.5). Because most of the scenarios result in low or zero frequency, results for a slightly higher value of 18 µg/L (<18.5) are included as well. The choice of this threshold is arbitrary but its relationship with other water quality variables in Cherry Creek Reservoir are discussed in Section 7.4.

7.1. Current compliance

The current Jul-Sep average chlorophyll standard is 15 µg/L and is to be reached 90% of the time (or 1 out of 10 years). Measured Jul-Sep chlorophyll concentration is below 15.5 µg/L only 3 out of 15 years and the 15-year average is 20.3 and the median is 18.4 µg/L. Consequently, current compliance or frequency of reaching the target is on average 20% (Table 7-1). The current chlorophyll level that was reached 93% of the time is 26.6 µg/L, while a concentration of 25.8 µg/L was reached 80% or 3 out of 15 years.

Averages and frequencies were also determined for approaches described in Section 6 that are used in scenario modeling. Averages were similar and medians were higher than those of the measured chlorophyll data, while frequencies were comparable or lower (Table 7-1). Consequently, compliance levels computed by these approaches are conservative. For comparison as explained in Section 7.4, frequencies were also calculated for a threshold of 18 µg/L chlorophyll.

Table 7-1. Current annual measured and predicted chlorophyll concentrations and their frequency of being below the thresholds of 15.5 and 18.5 µg/L. Thresholds for an 80% frequency and measured values for external load, inflow volume and inflow average TP, TP_{in}, are also shown.

Year	Ext.Load	Inflow	TPin	Chlorophyll (µg/L)				
				Measured	Predicted			
	(lbs)	(AF)	(ug/L)		f(Load)	f(TPin)	Mass Balance	
							Load	TPin
					1	2	3	4
1992	5,364	9,210	214	17.0	18.0	20.6	18.2	19.2
1993	3,114	5,851	196	14.4	15.0	18.4	18.5	20.6
1994	3,784	6,998	199	15.4	16.0	18.8	18.1	19.7
1995	5,736	11,788	179	15.6	18.4	16.4	19.0	19.4
1996	4,425	7,654	213	18.1	16.8	20.4	18.0	19.5
1997	5,675	10,391	201	22.3	18.3	19.0	18.5	19.2
1998	13,322	20,902	234	26.5	24.4	23.1	22.5	21.0
1999	17,672	27,604	235	28.9	26.8	23.2	25.0	22.3
2000	13,788	18,611	272	25.2	24.7	27.9	21.6	20.6
2001	9,099	17,246	194	26.1	21.4	18.2	21.1	20.3
2002	3,525	7,511	173	18.8	15.6	15.7	18.0	19.5
2003	9,390	14,953	231	25.8	21.7	22.7	20.2	19.9
2004	8,974	17,203	192	18.4	21.3	17.9	21.1	20.3
2005	10,725	18,534	213	17.1	22.7	20.4	21.6	20.6
2006	6,492	12,799	187	14.7	19.1	17.3	19.3	19.5
Average	**8,072**	**13,817**	**209**	**20.3**	**20.0**	**20.0**	**20.0**	**20.1**
Median	**6,492**	**12,799**	**201**	**18.4**	**19.1**	**19.0**	**19.3**	**19.9**
Min	**3,114**	**5,851**	**173**	**14**	**15**	**16**	**18**	**19**
Max	**17,672**	**27,604**	**272**	**29**	**27**	**28**	**25**	**22**
Frequencies								
<15.5 ug/L Chl, years				3	1	0	0	0
Frequency in %:				20%	7%	0%	0%	0%
<18.5 ug/L Chl, years				8	7	6	4	0
Frequency in %:				53%	47%	40%	27%	0%
Threshold for 80% frequency, µg/L:				25.9	23.0	22.7	21.6	20.6

Threshold is the upper chlorophyll concentration at which the 80% frequency 12 out of 15 years is attained.

Predicted chlorophyll concentrations are as follows:

1, as function of TP load based on regression equation 16 (Section 6.1)
2, as function of TP_{in} based on regression equation 17 (Section 6.1)
3, from mass balance approach with external load predicted from inflow volume according to regression equation 1 (Section 6.2.3).
4, from mass balance approach for constant TP_{in} (Section 6.2.4)

7.2. Loads to attain chlorophyll standard for 9 out of 10 years (current goal)

The necessary reductions to obtain the present chlorophyll standard were computed (a) for TP_{in} from the chlorophyll regression and from the mass balance approach, and (b) for external phosphorus load from the chlorophyll regression (Table 7-2). To determine these reductions, TP_{in} or load was reduced by a certain amount for each year and compliance for the study period was calculated. Mass balance estimates of loads were not calculated because they cannot be precise without consideration of their concurrent water volume.

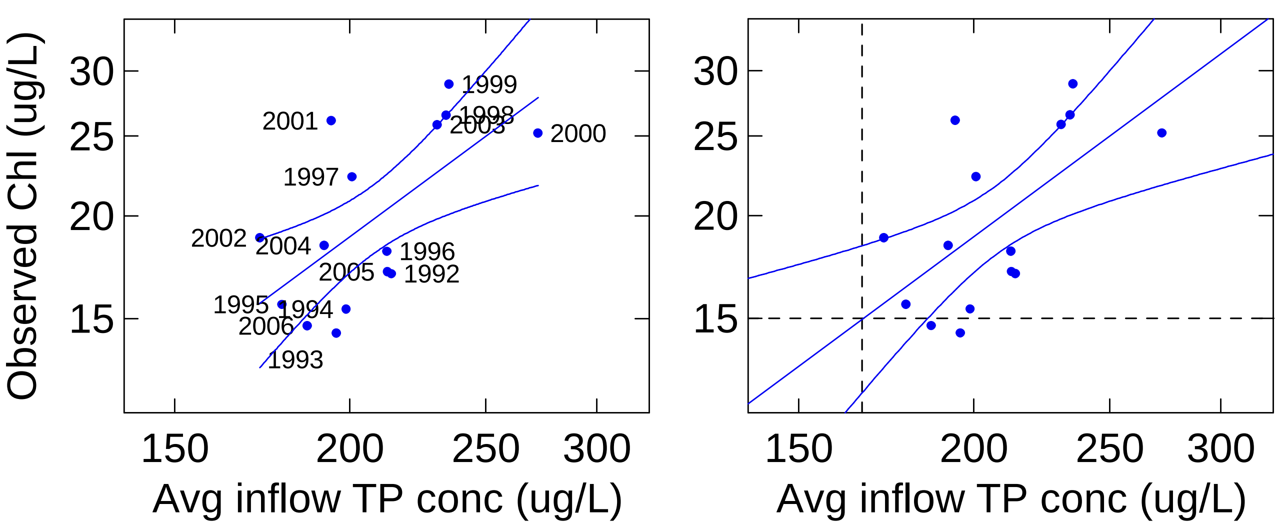
Table 7-2. Necessary reduction to obtain the current goal to reach compliance 9 out of 10 years at a Jul-Sep chlorophyll concentration average of 15 (i.e., less than < 15.5) µg/L

Approach	Reduction %	TPin µg/L	Reduction %	Load lbs/yr
Chlorophyll regression	27.5%	151	75%	2,018
Mass Balance Model	25%	157		

Results show that TP_{in} would have to be decreased by at least 25% and external load by 75% to reach compliance.

These reduction estimates are quite uncertain because they are based on extrapolation below the range of observed data in the regressions. This effect is illustrated in Figure 7-1 that explores the requested compliance level by setting the significance level p to 0.80 for an alpha of 0.20. All values below the upper limit (confidence band representing p=0.80) in the regression plot are within the required 90% compliance. It is obvious from the plots that extrapolation beyond the observed values inflates confidence limits so that the required point is far to the left off the graph and well below 150µg/L. This means that the uncertainty due to extrapolation of the regression decreases the level of TP_{in} at which 90% compliance can be expected to be considerably less than 150 µg/L.

Figure 7-1. Observed July-September averages of chlorophyll versus average annual inflow TP concentration, regression line and confidence band for p=0.80 are shown



7.3. Scenarios

Many hypothetical scenarios were systematically calculated to investigate the effect of changes in inflow concentration, TP_{in}, inflow volume, climatic changes and changes in internal and external loads (sections 7.3.1 to 7.3.5). Several additional scenarios for future conditions were modeled with output of the watershed model used by Brown and Caldwell (Section 7.3.6).

7.3.1. Average inflow concentration, TP_{in}

Two approaches were used to determine compliance changes due to changes in inflow TP concentration. One is based on the direct regression equation where chlorophyll is a function of TP_{in} (Section 6.1) and the other is based on TP_{in} in the budget approach (Section 6.2.4). Three scenarios were modeled: two, where TP_{in} is reduced to 90% and 75% of average current long-term conditions (100%), and one, where it is increased to 110%. Results, expressed as averages and medians of the two approaches are similar, but in the budget approach chlorophyll is far less variable between years because it is based on a long-term constant TP_{in} (Table 7-3). Consequently, compliance frequencies are different for the two approaches, when the averages are close to the target value, but they are similar in most scenarios. This similarity lends support to the results. It is apparent that compliance is highly sensitive to TP_{in} and it is a variable that ought to be managed. It is important to remember that modeled changes of TP_{in} result in proportional changes of external load, while hydrology and inflow volume are not changed.

To get a feeling for the possible ways of reducing external loading, a cursory analysis of partitioned flows was conducted. (Note that this analysis is based on partitioned inflow data provided by GEI and not on detailed watershed modeling like that by Brown & Caldwell.) External load can be partitioned into the portion that can be controlled with BMPs, like the storm water of Cherry Creek and Cottonwood Creek as opposed to the part that cannot be changed. The uncontrollable part (i.e., total load w/o stormflow) includes all baseflows, contributions from the alluvium, precipitation, and the residual contribution from wetlands used to balance flows. Inflow concentrations are different for the different portions and vary with time (Figure 7-2).

Storm water flows of the two main creeks, Cherry (CC-10 combined with Shop Creek, SC-3) and Cottonwood (Stations CT-1&2), have the highest concentration, with an average of 356 and 276 µg/L. In comparison, flows from all other sources combined (precipitation, alluvium and wetland-residual, and baseflow of the creeks) have an average inflow concentration of only 171 µg/L.

Table 7-3. Chlorophyll concentrations and their frequency of being below the chlorophyll thresholds of 15.5 and 18.5 µg/L for changes in inflow TP concentration determined from two different approaches (regression with Chlorophyll, f(TP_{in}), and mass balance model, Budget).

TPin (ug/L):	209		188		157		230	
TPin, % of long-term average:	100%		90%		75%		110%	
Ext Load, % of long-term average:	100%		90%		75%		110%	
	Chlorophyll (ug/L)							
Year	f(TPin)	Budget	f(TPin)	Budget	f(TPin)	Budget	f(TPin)	Budget
1992	20.6	19.2	18.0	17.3	14.3	14.4	23.2	21.2
1993	18.4	20.6	16.1	18.7	12.8	15.8	20.7	22.6
1994	18.8	19.7	16.4	17.8	13.1	15.0	21.2	21.7
1995	16.4	19.4	14.4	17.3	11.4	14.3	18.5	21.5
1996	20.4	19.5	17.9	17.5	14.2	14.7	23.0	21.4
1997	19.0	19.2	16.6	17.2	13.2	14.3	21.4	21.3
1998	23.1	21.0	20.2	18.7	16.1	15.2	26.0	23.5
1999	23.2	22.3	20.3	19.8	16.2	16.0	26.2	25.0
2000	27.9	20.6	24.4	18.3	19.4	14.9	31.5	22.9
2001	18.2	20.3	15.9	18.1	12.7	14.8	20.5	22.6
2002	15.7	19.5	13.7	17.6	10.9	14.8	17.7	21.5
2003	22.7	19.9	19.8	17.7	15.8	14.5	25.6	22.1
2004	17.9	20.3	15.7	18.0	12.5	14.8	20.2	22.6
2005	20.4	20.6	17.9	18.3	14.2	14.9	23.1	22.9
2006	17.3	19.5	15.2	17.4	12.0	14.4	19.5	21.6
Average	**20.0**	**20.1**	**17.5**	**18.0**	**13.9**	**14.9**	**22.6**	**22.3**
Median	**19.0**	**19.9**	**16.6**	**17.8**	**13.2**	**14.8**	**21.4**	**22.1**
Min	**15.7**	**19.2**	**13.7**	**17.2**	**10.9**	**14.3**	**17.7**	**21.2**
Max	**27.9**	**22.3**	**24.4**	**19.8**	**19.4**	**16.0**	**31.5**	**25.0**
Frequencies								
<15.5 ug/L Chl, years	0	0	3	0	11	13	0	0
Frequency in %:	0%	0%	20%	0%	73%	87%	0%	0%
<18.5 ug/L Chl, years	6	0	11	12	14	15	1	0
Frequency in %:	40%	0%	73%	80%	93%	100%	7%	0%
Threshold for 80% frequency, µg/L	22.7	20.6	19.9	18.4	15.8	15.0	25.7	22.9

Exploratory scenarios can be constructed that would reach the chlorophyll standard based on the reduction of storm water load and average inflow TP concentration (Table 7-4). For example, to reach compliance by decreased load from storm water alone, the storm water load and concentration would have to be cut to 25% of the current values, to about 70 µg/L for Cherry Creek and 90 µg/L for Cottonwood Creek. Considering that the average inflow TP of the combined flows besides storm water is 171 µg/L, this is impossible to achieve.

Figure 7-2. Average inflow TP trend with time for specific sources (note the different scales)

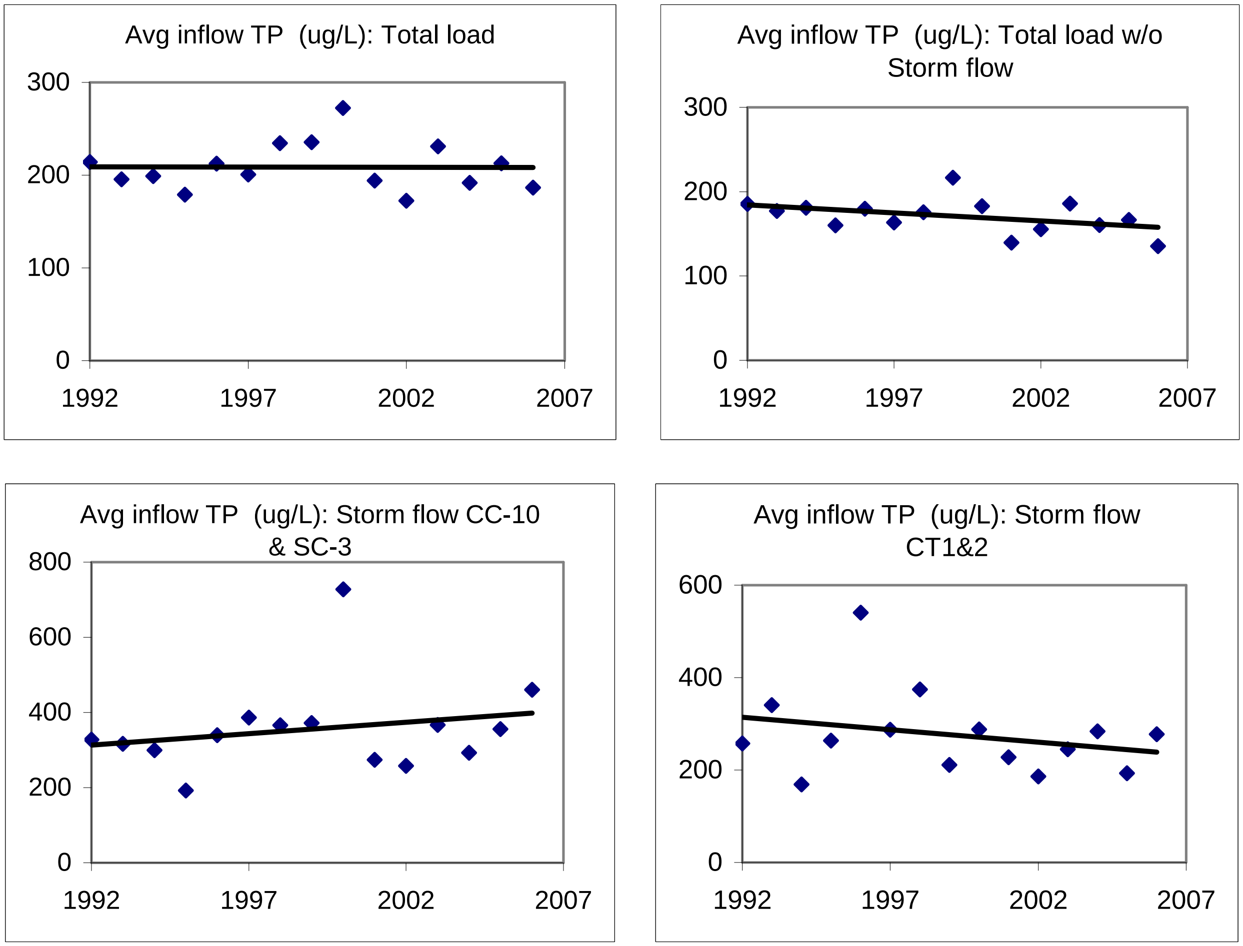


Table 7-4. Scenarios of a reduction of storm water TP concentration on the 15-year average chlorophyll concentration

External Load		TPin (ug/L)	Predicted	# years below/ total # years	
Total	**Storm load**		**Chl (ug/L)**	<15.5 ug/L	<18.5 ug/L
100%	100%	209	20.1	0%	0%
90%	75%	188	18.1	0%	12%
80%	50%	167	16.1	27%	100%
70%	25%	146	13.8	100%	100%

Current inflow TP of baseflow and other fluxes (see text)	171 ug/L
Current TP of Cherry Creek storm water:	356 ug/L
Current TP of Cottenwood Creek storm water:	276 ug/L

7.3.2. Inflow volume (unchanged load relationships)

If the amount of wet versus dry years changes, but the external load/inflow volume relationship (which is an indirect indicator of TP_{in}) remains the same (Equation 1 in Section 3.2) chlorophyll concentration and compliance levels are not much affected (Table 7-5). This result happens despite drastic changes in inflow volume as well as external load, because the inflow concentration TP_{in} remains almost constant. To actually change chlorophyll concentrations the parameters of the regression that reflect TP_{in} have to change.

Table 7-5. Chlorophyll concentration and their frequency of being below the chlorophyll thresholds of 15.5 and 18.5 µg/L for changes in external load as a function of inflow volume

Inflow Volume, % of long-term avg:	**100%**	**75%**	**50%**	**125%**
Ext Load, % of long-term average:	100%	71%	45%	127%
TPin, % of long-term average:	100%	95%	90%	102%
Year	Chl (ug/L) based on Inflow Volume			
1992	18.2	18.1	20.4	18.9
1993	18.5	21.0	40.6	18.0
1994	18.1	19.1	26.5	18.1
1995	19.0	18.2	18.5	20.1
1996	18.0	18.6	23.6	18.3
1997	18.5	18.0	19.2	19.4
1998	22.5	20.4	18.5	24.5
1999	25.0	22.4	19.7	27.4
2000	21.6	19.8	18.2	23.4
2001	21.1	19.4	18.1	22.8
2002	18.0	18.7	24.1	18.3
2003	20.2	18.8	18.0	21.6
2004	21.1	19.4	18.1	22.7
2005	21.6	19.8	18.2	23.4
2006	19.3	18.3	18.2	20.6
Average	**20.0**	**19.3**	**21.4**	**21.2**
Median	**19.3**	**19.1**	**18.5**	**20.6**
Min	**18.0**	**18.0**	**18.0**	**18.0**
Max	**25.0**	**22.4**	**40.6**	**27.4**
Frequencies				
<15.5 ug/L Chl, years	0	0	0	0
Frequency in %:	0%	0%	0%	0%
<18.5 ug/L Chl, years	4	4	6	4
Frequency in %:	27%	27%	40%	27%
Threshold for 80% frequency, µg/L:	21.6	19.9	23.7	23.4

7.3.3. Climatic changes –flow volume

The results are different if climate changes are modeled as changes of flows without synchronized changes in TP_{in}. In this case, increased flows dilute TP_{in} and consequently increase compliance, while the opposite occurs for decreased flows. In the example scenarios, outflow (which is inflow w/o evaporation) was changed while external load was kept constant. Jul-Sep TP concentration was computed for these changes according to the TP model (Section 5.1) and then chlorophyll predicted from the regression (Section 5.2). Resultant average TP_{in} for Table 7-6 is calculated from equivalent inflow changes. The results show that draught conditions likely decrease water quality, if the TP load is kept at the current level.

Table 7-6. Chlorophyll concentrations and their frequency of being below the chlorophyll thresholds of 15.5 and 18.5 µg/L for climate changes affecting only flows

Outflow Volume, % of long-term avg:	**100%**	**90%**	**75%**	**110%**
Ext Load, % of long-term average:	100%	100%	100%	100%
TPin, % of long-term average:	100%	111%	133%	91%
Year	Chl (ug/L) as function of flows			
1992	23.0	26.2	33.1	20.3
1993	18.5	21.1	26.6	16.4
1994	18.4	21.0	26.4	16.3
1995	15.7	17.9	22.6	13.9
1996	19.1	21.9	27.6	17.0
1997	25.4	29.0	36.6	22.5
1998	26.2	30.0	37.8	23.2
1999	23.5	26.9	33.8	20.8
2000	25.7	29.4	37.0	22.8
2001	18.9	21.6	27.3	16.8
2002	13.0	14.9	18.8	11.5
2003	22.3	25.5	32.1	19.8
2004	25.4	29.1	36.6	22.5
2005	28.8	33.0	41.5	25.5
2006	16.1	18.4	23.2	14.3
Average	**21.3**	**24.4**	**30.7**	**18.9**
Median	**22.3**	**25.5**	**32.1**	**19.8**
Min	**13.0**	**14.9**	**18.8**	**11.5**
Max	**28.8**	**33.0**	**41.5**	**25.5**
Frequencies				
<15.5 ug/L Chl, years	1	1	0	3
Frequency in %:	7%	7%	0%	20%
<18.5 ug/L Chl, years	5	3	0	7
Frequency in %:	33%	20%	0%	47%
Threshold for 80% frequency, µg/L:	25.5	29.1	36.7	22.6

7.3.4. External TP load

Changes in external load can be due to changes in inflow volume, inflow TP concentration TP_{in} or both. Changes due to inflow volume while TP_{in} is not much changed as presented in Section (7.3.2) barely affect compliance levels (Table 7-5); instead, the effect is large if changes are due to TP_{in} while inflow volume is not changed (Table 7-3).

A more direct approach is based on the regression equation where chlorophyll is a function of external load (Section 6.1). In this approach external load is not separated into flows and concentration. The results (Table 7-7) are between the approaches of separate flows (Table 7-6) and concentration (Table 7-3), which lends support to all three approaches.

Table 7-7. Chlorophyll concentrations and their frequency of being below the chlorophyll thresholds of 15.5 and 18.5 µg/L for changes in external load

Ext Load, % of long-term average:	**100%**	**90%**	**75%**	**110%**
Year	Chl (ug/L) as function of external load			
1992	18.0	17.3	16.3	18.5
1993	15.0	14.4	13.6	15.4
1994	16.0	15.4	14.5	16.5
1995	18.4	17.7	16.7	19.0
1996	16.8	16.2	15.3	17.4
1997	18.3	17.7	16.6	18.9
1998	24.4	23.5	22.1	25.2
1999	26.8	25.9	24.3	27.7
2000	24.7	23.8	22.4	25.5
2001	21.4	20.7	19.5	22.1
2002	15.6	15.0	14.2	16.1
2003	21.7	20.9	19.7	22.4
2004	21.3	20.6	19.4	22.0
2005	22.7	21.9	20.6	23.4
2006	19.1	18.5	17.4	19.8
Average	**20.0**	**19.3**	**18.2**	**20.7**
Median	**19.1**	**18.5**	**17.4**	**19.8**
Min	**15.0**	**14.4**	**13.6**	**15.4**
Max	**26.8**	**25.9**	**24.3**	**27.7**
Frequencies				
<15.5 ug/L Chl, years	1	3	4	1
Frequency in %:	7%	20%	27%	7%
<18.5 ug/L Chl, years	7	8	8	4
Frequency in %:	47%	53%	53%	27%
Threshold for 80% frequency, µg/L:	23.0	22.2	20.9	23.7

7.3.5. Internal TP load

Changes in internal load (L_{int_1}) could be a consequence of lake treatment that may decrease sediment loading or due to further eutrophication and loading from the watershed that could lead to increases. Changes in internal load cannot increase water quality to compliance levels, even if all internal load can be treated (Table 7-8). However, increased internal load can have a significant effect on chlorophyll according to the model. Effects may even be enhanced beyond predictions because of the high availability of sediment released P.

Table 7-8. Chlorophyll concentrations and their frequency of being below the chlorophyll thresholds of 15.5 and 18.5 µg/L for changes in internal load

Internal load	**100%**	**50%**	**0%**	**150%**	**200%**
% of long-term average					
Year	Chl (ug/L) predicted from TP budget model				
1992	23.0	19.8	16.7	26.3	29.6
1993	18.5	14.9	11.6	22.1	26.0
1994	18.4	14.9	11.6	22.0	25.7
1995	15.7	14.6	13.5	16.8	18.0
1996	19.1	16.5	14.0	21.9	24.6
1997	25.4	19.9	14.7	31.2	37.2
1998	26.2	23.6	21.0	28.9	31.7
1999	23.5	23.0	22.5	24.0	24.5
2000	25.7	24.4	23.1	27.0	28.3
2001	18.9	17.6	16.3	20.3	21.7
2002	13.0	11.1	9.3	15.0	17.0
2003	22.3	20.6	18.9	24.1	25.8
2004	25.4	20.2	15.3	30.9	36.5
2005	28.8	23.2	17.8	34.8	40.9
2006	16.1	14.3	12.4	18.0	20.0
Average	**21.3**	**18.6**	**15.9**	**24.2**	**27.2**
Median	**22.3**	**19.8**	**15.3**	**24.0**	**25.8**
Min	**13.0**	**11.1**	**9.3**	**15.0**	**17.0**
Max	**28.8**	**24.4**	**23.1**	**34.8**	**40.9**
Frequencies					
<15.5 ug/L Chl, years	1	5	8	1	0
Frequency in %:	7%	33%	53%	7%	0%
<18.5 ug/L Chl, years	5	7	11	3	2
Frequency in %:	33%	47%	73%	20%	13%
Threshold for 80% frequency, µg/L:	25.5	23.0	19.3	29.3	32.6

7.3.6. Future scenarios involving the Rueter-Hess Reservoir

Brown and Caldwell provided watershed model output data that include annual TP loads, reservoir inflow volumes and inflow TP concentration at the reservoir, for five future development scenarios (Appendix C):

A. Without the Rueter Hess Reservoir
B. With Rueter Hess Reservoir, "Baseline Model"
C. Baseline Model (B) with Tier 1 - BMP Alternatives
D. Baseline Model (B) with Tier 2 - BMP Alternatives
E. Baseline Model (B) with waste water treatment plant (WWTP) discharge of 0.1 mg/L.

Results from the watershed model cannot be directly inserted into the regression models used in the reservoir model (Section 6.1) for two reasons: 1. The watershed model is not based on the entire period 1992-2006 used for the reservoir modeling project, only on the years 1995-2002; and 2. modeled current conditions result in slightly higher values than observed data used to develop the reservoir models. To render the models (Brown and Caldwell watershed model and reservoir models) compatible, percent deviations from current scenarios were calculated and applied to the regression models.

The long-term changes in the scenarios predict increased flow, increased, similar or decreased TP load, but consistently decreased average inflow concentration TP_{in} (Appendix C). It is apparent that using TP_{in} is preferable to using loads for predicting future chlorophyll because loads are dependent on flows, and these flow scenarios are much larger than for current conditions. Larger flows can cancel out the problem of larger loads with respect to water quality and chlorophyll as discussed previously. This is also evident from the model results of these scenarios (Table 7-9).

Because TP_{in} is 15-24 % smaller in all future scenarios A to E, chlorophyll compliance is predicted to improve based on the TP_{in}–chlorophyll regression. However, future external loads are variable depending on the scenarios and hence compliance is not always improved according to the TP load–chlorophyll regression.

In summary, there is no difference between the scenarios with (B) and without the Rueter Hess Reservoir (A) and chlorophyll can be expected to be below 15.5 µg/L about 53% of the time using the TP_{in}–chlorophyll regression. Furthermore, there is no difference between scenario B and Scenario E that increases the WWTP discharge to 0.1 mg/L using either the TP_{in}–chlorophyll or the TP load–chlorophyll regression.

Table 7-9. Average chlorophyll concentrations and their frequency of being below the chlorophyll thresholds of 15.5 and 18.5 µg/L for scenarios predicted by the Brown & Caldwell watershed model ("of current" means *of current long-term average*)

Based on the chlorophyll regression with TP_{in}						Threshold*
Scenarios		TP_{in} in % of current	Chlorophyll average (µg/L)	Frequency <15.5	Frequency <18.5	Chlorophyll 80% Frequency (µg/L)
A	Without Rueter Hess Reservoir	84%	16.1	53%	80%	18.5
B	With Rueter Hess Reservoir, "Baseline Model"	85%	16.2	53%	80%	18.5
C	Baseline Model (B) with Tier 1 - BMP Alternatives	79%	14.8	73%	93%	17.0
D	Baseline Model (B) with Tier 2 - BMP Alternatives	76%	14.2	73%	93%	16.3
E	Baseline Model (B) with WWTP Discharge of 0.1 mg/L	85%	16.3	53%	80%	18.5
Based on the chlorophyll regression with TP load						Threshold*
Scenarios		TP load in % of current	Chlorophyll average (µg/L)	Frequency <15.5	Frequency <18.5	Chlorophyll 80% Frequency (µg/L)
A	Without Rueter Hess Reservoir	146%	22.7	0%	20%	27.5
B	With Rueter Hess Reservoir, "Baseline Model"	101%	20.1	7%	47%	24.4
C	Baseline Model (B) with Tier 1 - BMP Alternatives	94%	19.6	13%	47%	23.8
D	Baseline Model (B) with Tier 2 - BMP Alternatives	91%	19.4	20%	47%	23.6
E	Baseline Model (B) with WWTP Discharge of 0.1 mg/L	102%	20.1	7%	47%	24.5

* Threshold is the upper chlorophyll concentration at which the 80% frequency 12 out of 15 years is attained.

7.4. Exploration of alternative chlorophyll standard

Since the current chlorophyll standard of 15 µg/L cannot be reached for any realistic scenario Freshwater Research was asked to determine whether there are any indicators that would support higher values and what that value would be. Alternative standards were explored with three different approaches, including limnology, the ecoregion principle and experience from other studies related to water quality standards. Further, the importance of the time frame for compliance and realistic attainability were explored.

7.4.1. Limnology based standards

An attempt was made to find a reasonable standard that would still protect water quality. There are several ways to determine such targets in a more direct way than summer averages of TP or chlorophyll, including (1) maximum chlorophyll summer concentration, (2) the frequency of chlorophyll concentrations above 30 µg/L as estimate of cyanobacteria blooms, and (3) Secchi disk transparency.

Maximum chlorophyll concentration

The maximum summer chlorophyll concentration represents the worse monitored conditions and was therefore proposed several decades ago in the context of water quality evaluation (Jones et al. 1979,). While there are many relationships between average and maximum chlorophyll concentration available in the limnological literature, it is best to use patterns within the lake in question (France et al. 1994). Consequently we compared average summer chlorophyll with summer maximum chlorophyll in Cherry Creek Reservoir (Figure 7-3, Table 7-10).

It is important to consider that the maximum summer chlorophyll is really only the maximum recorded value and higher values may have occurred between sampling events. Therefore, the term "maximum chlorophyll concentration" depends on the frequency of sampling, because extremes are more likely to be detected when monitoring events are frequent.

Table 7-10. Statistics for observed chlorophyll concentration for July-September, sorted for increasing average. Maximum concentrations above 30 µg/L are indicated in bold. Number of total samples and those below 20 and 30 µg/L are indicated separately.

Year	Average	Minimum	Maximum	Sample number			Frequency	
				n total*	<20	<30	<20	<30
2007	12.6	4.4	23.5	6	5	6	83%	100%
2006	14.7	6.0	24.1	6	5	6	83%	100%
1993	14.8	6.6	22.1	6	5	6	83%	100%
1994	15.4	10.3	20.1	6	6	6	100%	100%
1995	15.6	6.1	**35.4**	6	5	5	83%	83%
2005	17.1	9.0	25.5	6	5	6	83%	100%
1992	17.4	1.3	**41.3**	6	4	5	67%	83%
1996	18.1	3.3	27.0	6	3	6	50%	100%
2004	18.4	14.4	26.6	6	5	6	83%	100%
2002	18.8	15.2	21.5	7	4	7	57%	100%
1997	22.1	12.7	**34.0**	21	9	19	43%	90%
2000	25.1	13.8	**45.7**	26	7	21	27%	81%
2003	25.8	17.6	**38.6**	7	1	5	14%	71%
2001	26.1	11.8	**79.8**	26	7	23	27%	88%
1998	26.5	15.9	**46.0**	26	8	18	31%	69%
1999	28.9	4.6	**50.8**	26	8	9	31%	35%

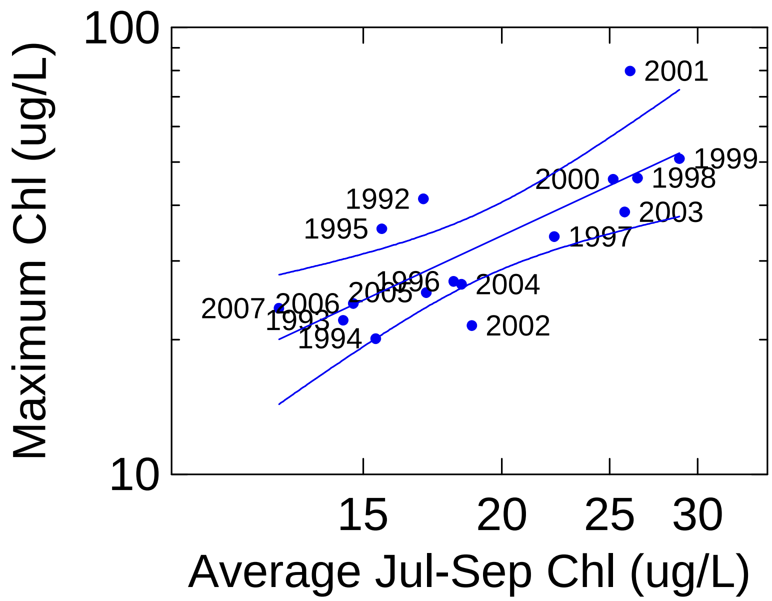
*High sample number (n total) represents weekly duplicate sampling

The regression of maximum on average chlorophyll concentration developed for Cherry Creek Reservoir (Equation 20, Figure 7-3) was used to explore a possible standard.

Maximum Chlorophyll $=10^{(0.030\ (\pm 0.320)\ +\ 1.156\ (\pm 0.249)\ \times\ \log \text{Jul-Sep Chl})}$ **Equation 20**

Predicted maximum chlorophyll are above 30 µg/L at about 18 µg/L Jul-Sep average chlorophyll (for a TP value of 73 µg/L, Table 7-11), so that below this value of 18 µg/L algal blooms are less likely.

Figure 7-3. Comparison of Jul-Sep average with summer maximum chlorophyll. (Regression line is shown for n=16, R^2=0.61, p<0.0001. Note the relationship includes values for the year 2007.)



Frequency of chlorophyll concentrations above 30 µg/L

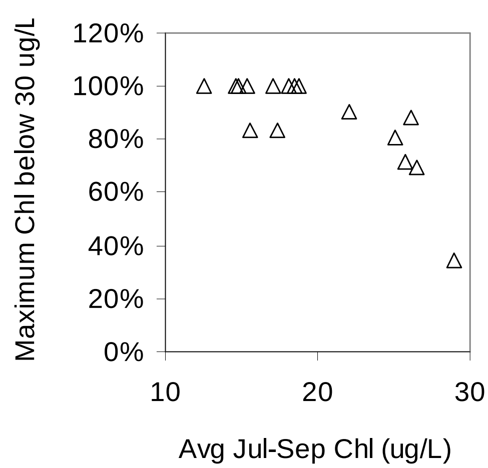
When summer chlorophyll concentrations are above a certain level, algae blooms increase as the proportion of cyanobacteria increases compared to the total algal biomass. Based on this observation, Walker (1985) used a chlorophyll concentration above 30 µg/L as indication of a "nuisance algal bloom". He also developed a model that predicts the frequency (% of summer) of such nuisance blooms from summer average chlorophyll concentration. Many studies since then have found that individual chlorophyll concentrations of 30 µg/L or higher (Bachmann et al. 2003) coincide with bluegreen algal blooms and undesirable water quality.

In Cherry Creek Reservoir chlorophyll maxima above 30 µg/L were consistently (6/6 yrs) found when chlorophyll Jul-Sep averages were above 22 µg/L (Table 7-10, Figure 7-4). For averages below 22.1 µg/L, higher than 30 µg/L maxima were found in only 2 out of 10 years (at quite low averages of 15.6 µg/L in 1995 and 17.4 µg/L in 1992 that would be difficult to avoid in the future Table 7-10). Such non-linear response of bloom frequency to average summer chlorophyll increases indicates a threshold and is found in many lakes (Walker 1985). Consequently, it appears that a Jul-Sep average value of 22 µg/L chlorophyll is a threshold above which algae, most likely nuisance blue greens, proliferate so that this value could serve as target.

Table 7-11. Comparison of TP with predicted summer average and maximum chlorophyll and Secchi transparency from regressions developed on Cherry Creek Reservoir TP data.

TP (µg/L)	Chlorophyll (µg/L)	Maximum Chlorophyll (µg/L)	Secchi (m)
50	11.1	17.4	1.37
55	12.6	20.0	1.29
60	14.0	22.7	1.22
65	15.5	25.5	1.16
67.5	16.3	27.0	1.14
70	17.1	28.5	1.11
74.5	18.5	31.2	1.07
75	18.6	31.5	1.06
80	20.2	34.6	1.02
82.5	21.0	36.2	**1.00**
85	21.8	37.9	0.98
90	23.5	41.2	0.95
95	25.2	44.6	0.92
100	26.8	48.0	0.89
105	28.6	51.6	0.86
110	30.3	55.3	0.84
115	32.0	59.0	0.82
120	33.8	62.8	0.79
125	35.6	66.6	0.77
130	37.4	70.6	0.76

Figure 7-4. Comparison of average summer chlorophyll with frequencies at which individual chlorophyll concentrations were above 30 µg/L.



Secchi disk transparency

Transparency determined by Secchi disk depth is often used to indicate water quality for swimmability and contact sport. Standards involving Secchi transparency are a threshold of 1 m (40 in), based on the notion that the swimmers are supposed to see their feet (e.g. water quality standard of the province of Ontario, MOE 1994).

The TP-Secchi regression for Cherry Creek Reservoir is highly significant (n=15, R^2= 0.48, p<0.01), Section 1.2) and the regression equation (Equation 21) can be used to arrive at a likely transparency for a certain level of TP and predicted chlorophyll concentration.

$$\text{Secchi} = 10^{(1.193\ (\pm 0.338) - 0.622\ (\pm 0.179) \times \log TP)} \qquad \textbf{Equation 21}$$

A chlorophyll value of 21 µg/L corresponds to a Secchi transparency of 1.00 m (40 in) (for a TP value of 82.5 µg/L, Table 7-11).

In summary, this limnological analysis indicates that Jul-Sep average chlorophyll concentrations should be below 22 µg/L to avoid most bloom conditions at chlorophyll concentration above 30 µg/L. Secchi transparency is adequate for contact recreation below a value of 21 µg/L. However, it is necessary to consider that in the 15 years of chlorophyll monitoring in Cherry Creek Reservoir there is a gap between 18.8 and 22.1 µg/L (Table 7-10) leading to an uncertainty about the exact threshold.

Possible Standard consistent with limnological considerations: 21-22 µg/L, 80% of the time (for 12/15 yrs similar to the study period).

7.4.2. Ecoregion principle

When determining water quality targets it is useful to compare the water body in question with similar waters in its ecoregion (e.g., Omernik 1987). This concept realizes that the trophic status of lakes and reservoirs changes with geological regions. Typically, an area is divided into regions based on land surface form and use, natural vegetation, and soils. Next, certain lake characteristics, like average TP or summer chlorophyll are compiled for each region separately. Then the characteristic of each individual lake is compared with measures of the central tendency (median) for all lakes in that region. A lake should fall below the median, i.e. it should belong to the half of the better lakes. As a target the upper threshold for a quarter of the best lakes has been recommended. This approach has been applied in the USA and values based on lakes of the Storet US-EPA database are available for different ecoregions. Cherry Creek Reservoir belongs to Ecoregion IV, Subregion 26, “the Great Plains Grass and Shrublands, south western Tablelands”. Table 7-12 summarizes values for this region.

A comparison with Cherry Creek Reservoir long-term data shows a far lower water quality than the Ecoregion values. This approach is probably not helpful for setting targets in Cherry Creek Reservoir for the following reasons: (1) Overall medians of the medians of all four seasons are reported in EPA 2001, so that the listed values are lower than expected for the growing season. (2) No distinction has been made with respect to shallow versus stratified and natural lake versus reservoir. Because shallow man-made reservoirs typically have a higher trophic state as recognized by targets from other regions (7.4.3), the values probably underestimate attainable conditions. Consequently, the Ecoregion approach was not used for proposing a chlorophyll standard in Cherry Creek Reservoir.

Table 7-12. Year-round observed and target values for water quality characteristics of Ecoregion IV, subregion 26, *the Great Plains Grass and Shrublands, south western Tablelands* (EPA 2001) compared with Cherry Creek Reservoir long-term average summer values.

Characteristic	Range	Lower 25%, Target	Cherry Creek Reservoir
Chlorophyll (µg/L)	**0.7 – 18.6**	**1.2**	**20**
TP (µg/L)	2 - 145	20	80
Secchi (m)	0.3 – 2.9	1.7	1.06

7.4.3. Experience in other studies

While above analyses investigate conditions specific for Cherry Creek Reservoir or its region, it is of interest to compare potential standards with those established for other lakes and reservoirs in other jurisdictions. Various chlorophyll criteria have been adopted by US states in their water quality standards. This variability may be partially due to the non-conservative nature of chlorophyll, its proneness to analytical errors, and its high variability in space and time, but the main reasons for this variability are probably differences in natural conditions and user expectations. Table 7-13 presents an overview of chlorophyll *a* standards established or proposed by individual states.

Table 7-13. Chlorophyll standards in various US States

State	Applications	Chlorophyll (µg/L) Standard	Period
Colorado	**Cherry Creek Reservoir, shallow**	**15**	**Jul-Sep**
Alabama	Lake Weiss reservoir in the Coosa River Basin	20	Apr-Oct
Georgia	Different for specific lakes and reservoirs Shallow reservoirs have the higher values	5 to 27	Apr-Oct
Kansas	Primary contact recreation and domestic water supply	12	n.a.
	Secondary contact recreation (fishing)	20	n.a.
Minnesota, shallow lakes and reservoirs:			
	Northern Lakes and Forest	9	Jun-Sep
	North Central Hardwood Forest	20	Jun-Sep
	Western Corn Belt Plains	30	Jun-Sep
Minnesota, deep lakes and reservoirs:			
	Northern Lakes and Forest	9	Jun-Sep
	North Central Hardwood Forest	14	Jun-Sep
	Western Corn Belt Plains	22	Jun-Sep
Minnesota, Trout lakes		3 or 6	Jun-Sep
Minnesota and Wisconsin	Lake Pipin	30	summer
Montana	Flathead Lake, largest natural lake in western US	1	Annual
New Jersey	Wanaque Reservoir	10	Jun 15- Sep 1
Oklahoma	Sensitive Public and Private Water Supplies (SWS).	10	long-term
Oregon, incl. Umatilla Indian Reservation	shallow lakes, rivers, reservoirs	15	average of
	natural stratified lakes	10	at least 3 samples
Pennsylvania	Green Lane Reservoir, Montgomery County	20	Apr-Sep
North Carolina	Trout lakes	15	n.a.
	other lakes and reservoirs>10 acres	40	n.a.
South Carolina	Blue Ridge Mountains ecoregion	10	n.a.
	All others	40	n.a.
Tennessee	Pickwick Reservoir on TN River	18	Apr-Sep
Texas	7 Reservoirs	20	Growing Season
Washington, DC	Anacostia Watershed	25	Jul-Sep

n.a., not available
Source: Individual states and EPA websites searched for "chlorophyll standard"

All standards apply to the mixed or photic zone and most apply to the entire growing season, which depends on location. Most states separate between natural lakes, reservoirs, and shallow water bodies, so that the natural lakes have the most stringent standards. State-wide standards can be different for different ecoregions and water bodies (MI).

In contrast to these standards, the current standard for Cherry Creek Reservoir applies to the period that is most likely to have maximal phytoplankton biomass: the months of Jul-Sep are warmest, have high light availability and are most affected by sediment released phosphorus. Consequently a value that is comparable to standards for the whole growing season would be lower. (This is also supported by monitoring data from GEI. For example, the long-term average of annual June averages is 10.7 µg/L, while the July average is 19.5 µg/L. August and September long-term averages are even higher at 25 and 24 µg/L). On the other hand, most standards in Table 7-13 appear to be set as upper limit, while the current Cherry Creek Reservoir limit is less stringent and has to be reached (only) 90% of the time.

Various methods were used to achieve the setting of those standards. In particular, the efforts for Pennsylvania, Green Lane Reservoir are interesting to note. A model analysis involved several alternate chlorophyll standards before concluding that *"Watershed and water quality modeling have demonstrated that reasonable and feasible allocation strategies are not available to achieve in-lake chlorophyll-a concentrations of 10 µg/L or 15 µg/L"* (Tetra Tech 2003, p. 73). Consequently, the recommended standard was set as 20 µg/L "seasonal" average (most likely for April through September).

Other states used an approach that considers perception of users as in Minnesota and Texas. In a much cited study, user perception was considered in the target of 30 µg/L for Lake Pipin at the border of Minnesota and Wisconsin (Heiskary and Walker 1995). Similarly, user perception was considered in setting standards for seven Texas reservoirs: *"When the mean summer concentration of chlorophyll in a reservoir was between 20 and 25 µg/L, approximately 25% of the respondents perceived the reservoir as being at least slightly impaired for recreational use"* (*Development Of Use-Based Chlorophyll Criteria For Recreational Uses Of Reservoirs* by Peggy W. Glass, 2006 Water Environment Foundation).

In summary, chlorophyll standards established in water bodies of other States that include those of shallow reservoirs in situations similar to Cherry Creek Reservoir range typically from 20 to 40 µg/L (Table 7-13), except in Oregon (15 µg/L) and a Tennessee reservoir (18 µg/L). However most of these standards rely on averages of a longer period (e.g., Apr-Oct, Jun-Sep), including months with less favourable growing conditions and these standards would probably be at least 25 µg/L or higher if based for the Jul-Sep period that the Cherry Creek Reservoir standard is based on.

7.4.4. Other influences

Equilibrium considerations and time lag

The modeled scenarios present conditions at equilibrium so that any modeled changes cannot be considered to occur instantaneously. Therefore, it seems appropriate to consider a lag-time for the reservoir to approach equilibrium conditions whereever changes are predicted. Most often the water renewal rate and lake water to inflow volume ratio are used to estimate the duration until a lake or reservoir approaches equilibrium conditions after major changes in its input.

Cherry Creek Reservoir water detention time fluctuated between 0.5 and 3.5 years (long-term median 1.13, average 1.52 years) so that approximately four years should suffice to establish equilibrium conditions due to hydrology. Other implied changes have a slightly longer period of equilibration.

(1) Internal load was modeled as a linear relationship of external load (Section 6.2.2), while the time of response will lag behind external load changes due to the more conservative P in sediments.

(2) Scenarios involving the Rueter Hess Reservoir (Section 7.3.6) will take at least as long as it is built and filled (at least five years, Bill Ruzzo, pers. comm.) and even then some acclimation period is typically considered for reservoirs (Ostrofsky 1978).

Unconsidered influences

In 2008 a **lake aeration treatment** was commenced. The effect of such treatment on the proliferation of phytoplankton is not clear. Applications in other lakes and reservoirs showed less algae (success), no effect, or increased algal blooms, depending on the importance of sediment released P, mixing conditions and climatic effects (Cooke et al. 2005). Monitoring in the future will reveal the effect in Cherry Creek Reservoir.

The **long-term climate** is supposed to change. Forecasts are likely to include dryer and hotter summers that would increase algae growth conditions and hence the Jul-Sep chlorophyll averages.

Time period for calculating compliance

In 12 out of 15 years (12/15) the chlorophyll Jul-Sep averages were below 25.9 µg/L during the study period 1992-2006. This value would be similar for 8/10 years, but higher for 4/5 years because of the large hydrological variability. If a standard of 26 µg/L were to be used for example, in the five year period between 1997-2001 compliance would have been 3/5 or 60% (two exceedances and one at the standard value, 22, 26, 29, 25, 26 µg/L, Table 7-1, rounded values were used for simplification), but the 10 year period 1992-2001 would comply in 8/10 years or 80%.

Consequently I propose that any level of compliance be based on at least a 10 year period because of the high hydrological variability in Cherry Creek Reservoir. For example, an 80% compliance level should be computed as 8/10 years or 12/15 years.

7.4.5. Proposed chlorophyll standard for Cherry Creek Reservoir

Potential standards and their derivations are listed in Table 7-14. If the conditions of the current algal blooms are deemed acceptable to the stake holders and public in general, the standard should be set to coincide with the observed 80% frequency at 26 µg/L (Table 7-1).

Limnological deliberations based on the observation from other systems that nuisance bluegreen blooms increase at chlorophyll concentration above 30 µg/L and Secchi transparency determine that a lower threshold of 21 – 22 µg/L would warrant acceptable water quality, even for contact sport, most of the time.

In comparison to chlorophyll targets in similar water bodies in other States, a 25 µg/L target seems feasible for Cherry Creek Reservoir.

Assuming that both models, the *watershed model* and the *regression model for changes of chlorophyll dependent on average inflow* TP_{in} are adequate, the Jul-Sep chlorophyll average should decrease in the future after a lag-time for equilibration under Scenarios A-E to 18.5 µg/L.

In summary, considering the uncertainties based on time lags, model predictions, climate change and aeration treatment as discussed above, we propose a standard of 25 µg/L to be reached 8/10 years (at an 80% level) for the near future. This is slightly below the long-term 80% threshold observed in 1992-2006. However, this standard should be reduced in the future to approach the more stringent 21-22 µg/L level, with introduction of the Rueter Hess reservoir and possible beneficial effects of the lake treatment. This reduction could be proposed at the next scheduled Rulemaking Hearing in 2014, unless interim monitoring data suggest otherwise.

Table 7-14. List of possible chlorophyll standards (µg/L)

Characteristic	Standard	Comment	Report Section
Current: 1992-2006	26	Data	7.1
<30 µg/L blooms	22	Data	7.4.1
Secchi	21	Data	7.4.1
Comparison	25	Standards of other States	7.4.3
Rueter Hess Scenarios	18.5	Based on Chl-TP_{in}	7.3.6
Rueter Hess Scenarios	24.5	Based on TP load	7.3.6

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Appendix A. Determination of internal load L_{int_1}

Computations are described in Section 4.2.1 Method 1: *In situ* internal load

	Late May, early June (Early Summer)					Late Aug, Sep or early Oct (Fall)				
Year	**Day**	**Elevation (ft)**	**Volume 10^6 m^3**	**minTP (ug/L)**	**TP (kg)**	**Day**	**Elevation (ft)**	**Volume 10^6 m^3**	**maxTP (ug/L)**	**TP (kg)**
1992	20-May	5,550.3	15.80	24	379	16-Sep	5,550.0	14.77	69	1,019
1993	28-May	5,549.8	14.77	35	517	09-Sep	5,548.9	13.78	70	964
1994	31-May	5,550.2	15.80	31	490	05-Sep	5,549.1	14.77	74	1,093
1995	30-May	5,550.4	15.80	50	790	06-Sep	5,550.0	14.77	62	916
1996	21-May	5,550.3	15.80	37	584	10-Sep	5,549.6	14.77	66	975
1997	20-May	5,550.0	15.80	45	711	02-Sep	5,550.1	15.80	111	1,753
1998	03-Jun	5,550.4	15.80	46	727	08-Sep	5,550.5	15.80	74	1,169
1999	25-May	5,550.8	15.80	80	1264	07-Sep	5,550.1	15.80	96	1,520
2000	30-May	5,550.4	15.80	60	943	22-Aug	5,550.6	15.80	89	1,409
2001	12-Jun	5,550.2	15.80	71	1116	07-Aug	5,550.5	15.80	86	1,355
2002	03-Jun	5,550.6	15.80	54	847	13-Aug	5,549.8	14.77	76	1,118
2003	03-Jun	5,550.3	15.80	55	867	26-Aug	5,550.1	15.80	81	1,279
2004	24-May	5,550.6	15.80	41	652	01-Sep	5,550.1	15.80	119	1,886
2005	23-May	5,550.4	15.80	77	1214	20-Jul	5,550.0	15.80	135	2,133
2006	24-May	5,549.7	14.77	71	1045	07-Sep	5,548.0	13.78	76	1,041
Avg 1992-2006			**15.7**	**52**	**810**			**15**	**86**	**1,309**
Med 1992-2006			**15.8**	**50**	**790**			**16**	**76**	**1,169**
Max			**15.8**	**80**	**1,264**			**16**	**135**	**2,133**
Min			**14.8**	**24**	**379**			**14**	**62**	**916**

Changes between summer and fall						
Year	**Lake Change**	**Outflow (kg)**	**Ext. Load (kg)**	**qs**	**R_pred**	**Leftover Lext (kg)**
1992	640	136	508	2.04	0.80	101
1993	447	128	272	1.32	0.83	45
1994	603	22	163	1.85	0.81	31
1995	126	374	1,002	3.01	0.77	231
1996	390	253	665	1.87	0.81	127
1997	1,043	354	931	2.66	0.78	204
1998	442	913	1,488	6.56	0.69	456
1999	256	946	2,833	9.23	0.66	974
2000	465	138	777	6.15	0.70	233
2001	239	177	543	4.97	0.72	151
2002	270	50	166	2.18	0.80	34
2003	412	100	336	4.34	0.74	89
2004	1,234	801	1,662	5.23	0.72	470
2005	919	258	745	5.75	0.71	218
2006	-3	860	1,068	4.06	0.74	276
Avg 1992-2006	**499**	**367**	**877**	**4.1**	**0.75**	**243**
Med 1992-2006	**442**	**253**	**745**	**4.1**	**0.74**	**204**
Max	**1,234**	**946**	**2,833**	**9.2**	**0.83**	**974**
Min	**-3**	**22**	**163**	**1.3**	**0.66**	**31**

Final computation of in-situ internal load, L_{int_1}

Year	In-situ Lint (kg)	In-situ Lint mg/m2	of Hypoxia Days	Summer Temp >17 C	Additional period of high Temp Days	Total Period Days	Period boost	In-situ Lint mg/m2/yr
1992	675	197	119	n.a.	n.a.	123	1.03	**204**
1993	530	155	104	n.a.	n.a.	123	1.18	**183**
1994	594	173	97	n.a.	n.a.	123	1.27	**220**
1995	270	79	99	n.a.	n.a.	123	1.24	**98**
1996	516	150	112	n.a.	n.a.	123	1.10	**165**
1997	1,192	348	105	n.a.	n.a.	123	1.17	**407**
1998	899	262	97	29-Sep	28	125	1.29	**338**
1999	228	66	105	18-Sep	18	123	1.17	**78**
2000	371	108	84	23-Sep	39	123	1.46	**158**
2001	264	77	56	25-Sep	56	112	2.00	**154**
2002	287	84	71	24-Sep	49	120	1.69	**141**
2003	423	123	84	23-Sep	35	119	1.42	**175**
2004	1,565	456	100	22-Sep	28	128	1.28	**584**
2005	958	280	58	30-Sep	79	137	2.36	**660**
2006	581	169	106	16-Sep	16	122	1.15	**195**
Avg 1992-2006	**624**	**182**	**93**		**39**	**123**	**1.39**	**251**
Med 1992-2006	**530**	**155**	**99**		**35**	**123**	**1.27**	**183**
Max	**1,565**	**456**	**119**		**79**	**137**	**2.36**	**660**
Min	**228**	**66**	**56**		**16**	**112**	**1.03**	**78**

Appendix B. Support of release rates used in L_{int_3}

Release rates compared to trophic state for lakes from the literature.

o, oligotrophic; m, mesotrophic; e, eutrophic; and h, hypereutrophic

Lake	Trophic State	RR ($mg/m^2/d$)	Lake	Trophic State	RR ($mg/m^2/d$)
Red Chalk	o	0.03	Jorzec	e	12.11
Piburger	o	0.25	Magog	e	13.50
Grane Langso	o	0.80	Ryssbysjon	e	14.50
Monate	m	0.00	Trummen	e	15.00
Kinneret	m	0.80	Fureso	e	17.30
Titisee	m	1.40	Nakanoumi	e	22.00
Chub	m	1.59	Lugano_Ponte	e	22.19
Wononscopo_S	m	2.10	Lough_Neagh	e	23.85
Mohegon	m	3.00	Warner	e	26.00
Wabamun	m	5.00	Mendota	e	31.40
Gravenhurst	m	5.27	Rotsee	e	32.00
Wononscopo_D	m	7.30	Ringsjoen_W	h	6.00
Majcz	m	8.34	Twin_W	h	6.60
Linsely_Pond	m	10.00	Twin_E	h	7.52
Memphremagog, Fitch Bay	m	10.00	Satoftasjon	h	9.00
Ursee	m	13.00	Katepwa	h	10.00
Fysingen	e	0.80	Mission	h	10.00
Gribso	e	1.20	Pasqua	h	10.00
St.George_E	e	2.22	Cedar	h	11.90
Panguitch_M	e	3.10	Echo	h	12.00
Loosdrecht	e	4.00	Esrom	h	12.30
Norrviken_72	e	4.98	Onondaga	h	13.30
Long, Wash.	e	5.00	Arungen	h	15.97
Vombsjon	e	6.01	Hallesoe	h	19.00
Sammamish	e	6.40	Ringsjoen_E	h	20.00
Pusiano	e	6.60	Greifensee	h	20.15
Varese	e	6.70	Hartbeesport	h	24.00
Edinboro	e	6.80	Vallentunasj	h	30.00
Erie	e	7.40	Finjasjon	h	31.00
Inulec	e	8.00	Charles_East	h	31.30
Suwa	e	8.50	Mendota	h	31.40
Glebokie	e	8.54	Kulsoe	h	31.50
Waramaug	e	9.07	Stigsholmsoe	h	32.00
Alserio	e	10.47	Kvindsoe	h	33.00
Constance, Ober	e	11.40	Bergundasjon	h	40.00
Shagawa	e	12.10	Stone	h	42.50

The release rate used in the determination of L_{int_3} was compared to release rates in temperate North American and European lakes of certain trophic state, as collected from the literature

(Nürnberg, unpublished studies). It is obvious that most of the eutrophic lakes have a release rate of 4 $mg/m^{-2}/d$ or above. Based on the trophic state of Cherry Creek Reservoir which is at the higher end of eutrophy with an average Jul-Sep TP concentration of 80 µg /L (Table 1-1), its release rate can be expected to be at least similar or even higher. On the other hand, the low sediment concentration and the fact that Cherry Creek Reservoir is an artificial impoundment may be the reason for lower release rates than is typical for eutrophic lakes.

Appendix C. *Brown and Caldwell* Watershed model

Sep 19, 2008

	Observed			B&C Modeled Current		
Year	USACE Inflow (af/yr)	USACE External Load (lbs/yr)	Conc. (mg/)	Model Predicted Total Inflow (ac-ft/year)	Model Predicted Total Load (ac-ft/year)	Conc. (mg/)
1995	11,788	5,736	0.180	14,988	10,552	0.260
1996	7,654	4,425	0.213	6,258	4,269	0.252
1997	10,391	5,659	0.201	12,231	8,280	0.250
1998	20,902	13,322	0.235	17,727	11,586	0.241
1999	27,604	17,672	0.236	20,649	13,511	0.241
2000	18,611	13,788	0.273	16,979	10,251	0.223
2001	17,246	9,099	0.195	16,115	9,146	0.209
2002	7,511	3,525	0.173	9,452	5,722	0.223
Median	**14,517**	**7,418**	**0.207**	**15,552**	**9,699**	**0.241**
Average	**15,213**	**9,153**	**0.213**	**14,300**	**9,165**	**0.237**

Scenario:	A			B		
Year	Model Predicted Total Inflow (ac-ft/year)	Model Predicted Total Load (ac-ft/year)	Conc. (mg/)	Model Predicted Total Inflow (ac-ft/year)	Model Predicted Total Load (ac-ft/year)	Conc. (mg/)
1995	27,562	15,554	0.208	18,963	10,958	0.213
1996	14,697	8,271	0.208	8,784	5,050	0.212
1997	24,028	13,536	0.208	16,739	9,318	0.205
1998	29,892	16,395	0.202	22,479	12,136	0.199
1999	31,685	17,255	0.201	22,256	12,011	0.199
2000	24,346	12,645	0.192	16,825	8,878	0.195
2001	22,511	11,169	0.183	15,965	7,935	0.183
2002	16,624	8,593	0.191	11,619	6,155	0.196
Median	**24,187**	**13,090**	**0.202**	**16,782**	**9,098**	**0.199**
Average	**23,918**	**12,927**	**0.199**	**16,704**	**9,055**	**0.200**

Scenario:	C			D			E		
Year	Model Predicted Total Inflow (ac-ft/year)	Model Predicted Total Load (ac-ft/year)	Conc. (mg/)	Model Predicted Total Inflow (ac-ft/year)	Model Predicted Total Load (ac-ft/year)	Conc. (mg/)	Model Predicted Total Inflow (ac-ft/year)	Model Predicted Total Load (ac-ft/year)	Conc. (mg/)
1995	18,963	10,194	0.198	18,962	9,862	0.192	18,962	11,007	0.214
1996	8,784	4,696	0.197	8,784	4,592	0.193	8,784	5,078	0.213
1997	16,739	8,657	0.191	16,739	8,350	0.184	16,739	9,367	0.207
1998	22,479	11,280	0.185	22,478	10,851	0.178	22,478	12,213	0.201
1999	22,256	11,158	0.185	22,256	10,747	0.178	22,256	12,080	0.200
2000	16,825	8,313	0.182	16,825	8,026	0.176	16,825	8,923	0.196
2001	15,965	7,443	0.172	15,965	7,218	0.167	15,965	7,975	0.184
2002	11,619	5,723	0.182	11,619	5,555	0.176	11,619	6,191	0.197
Median	**16,782**	**8,485**	**0.185**	**16,782**	**8,188**	**0.178**	**16,782**	**9,145**	**0.200**
Average	**16,704**	**8,433**	**0.187**	**16,704**	**8,150**	**0.181**	**16,704**	**9,104**	**0.201**