Appendix J
Impacts of Increased Water Supply Storage on Water Quality

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Chatfield Reservoir Storage Reallocation Feasibility Study

Submitted to:
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1. Background

This document is an evaluation of potential water quality impacts from the proposed reallocation of flood control storage at Chatfield Reservoir, Littleton, Colorado, and was prepared as a component of the Chatfield Storage Reallocation project.

Interested parties were invited to participate in a water quality workgroup to determine the scope of the water quality modeling necessary for the Feasibility Report-Environmental Impact Statement (FR-EIS). Participants included representatives from the Chatfield Watershed Authority, Colorado State Parks, Colorado Division of Wildlife, the water providers, the U.S. Army Corps of Engineers (Corps), and Tetra Tech (who assisted the Corps in preparing the FR-EIS). Four workgroup meetings were held between April and September 2005. The workgroup reviewed, evaluated, and considered scoping comments on water quality; identified the water quality parameters of greatest concern; and developed the approach for addressing water quality concerns associated with storage reallocation at Chatfield Reservoir. This technical report documents the water quality analysis that was implemented under the direction of the water quality workgroup.

1.1. Technical Approach

Three broad categories of water quality parameters are evaluated in this technical report, based on recommendations from the project's water quality workgroup: nutrients, metals, and bacteria. Available physical, chemical, and biological data for the reservoir were evaluated, in conjunction with proposed changes in pool elevation from 5432 ft msl[1] (conservation pool, baseline) to 5444 ft msl (maximum proposed or "with project" conditions). The study provides a conservative analysis of water quality impacts for the Chatfield Storage Reallocation project using a simplified approach. It should be noted that uncertainty may be high when applying a simple model, because simple models generally do not fully represent the dynamic, time-variable nature of a system. For that reason, the analysis included conservative (i.e., worst-case) assumptions. Simple analytical approaches like the one applied here can be very useful analytical tools. Uncertainty may be reduced when using a complex analytical model; however this greatly increases data and resource requirements. The water quality workgroup considered more complex modeling approaches but ultimately determined that the approach described in this report was adequate and reasonable to evaluate the potential impacts associated with the proposed project. Furthermore, the Summary section (Section 7) of this technical report lists adaptive management measures to reduce any potential impacts to water quality at Chatfield Reservoir, should the proposed project be implemented.

The nutrient evaluation included two analyses, the first analysis used a simplistic but conservative regional nutrient loading model and the second analysis used a more detailed site-specific evaluation of nutrient loading to the Chatfield Reservoir. The first

[1] Note: MSL refers to Above Mean Sea Level

nutrient analysis used the EUTROMOD model to evaluate historical incoming total phosphorus loads, hydraulic residence time, and change in volume information to predict reservoir eutrophication potential and chlorophyll-a for the baseline and reservoir storage reallocation conditions. The second nutrient analysis was more site-specific and focused on the prediction of the change in hypolimnetic volume under the proposed reallocation condition and its impact on internal nutrient loading and reservoir nutrient concentrations. Oxygen demand in the quiescent hypolimnion can result in the development of hypoxic/anoxic conditions near the reservoir bottom. These conditions can limit aquatic life and mobilize constituents bound to reservoir sediments through oxidation-reduction. This is particularly true of sediment-bound nutrients such as phosphorus. An increased release of phosphorus has implications on the trophic nature of the reservoir.

In reviewing this technical report, it is important to consider that Chatfield Reservoir does not contribute phosphorus and would not under the proposed reallocation project. Instead, phosphorus inputs from the watershed upstream of Chatfield Reservoir influence concentrations in the reservoir. Changing the operation of Chatfield Reservoir could influence the reactivity of these minerals. The models described above were used to simulate the effects of proposed reservoir operations on water quality.

An increased reservoir-bottom surface area may lead to an increased release of metals bound to bottom sediments. Thus, the metals evaluation involved prediction of metals release under the proposed condition and a comparison to baseline conditions. The diffusive flux was estimated for the entire lake bottom, and it was assumed to be equivalent for anaerobic and aerobic conditions for all metals evaluated. This assumption was necessary since no definitive aerobic versus anaerobic fluxes could be identified in the literature. The fluxes varied based on the environmental setting of the waterbody, were either positive or negative, and varied by orders of magnitude.

While evaluation of nutrients and metals involved reservoir-wide assessments, the bacteria evaluation focused on localized impacts around the swim beach. Changes in waterfowl and shorebird usage of the reservoir could occur if the reservoir's littoral area increased. Any increase in bird use would be accompanied by an increase in bacteria loading. An increase in bacteria loading could impact bacteria levels at the swim beach. Therefore, the analysis conducted focused on evaluating the potential for increased bacteria levels at the swim beach.

1.2. Recent Changes in Water Quality Standards

This subsection describes recent changes in the water quality standards for phosphorus and chlorophyll-a at Chatfield Reservoir. The Colorado Water Quality Control Commission (CWQCC) implemented changes in these standards based on several factors related to existing water quality at Chatfield Reservoir. These factors are relevant to the discussion of the potential impacts of the proposed alternatives on water quality in this proposed reallocation project. For that reason, they are described in some detail below.

The technical analysis presented in this report was completed prior to the 2008 rulemaking for the Upper South Platte Segment 6b (Chatfield Reservoir), which resulted in new standards for phosphorus and chlorophyll. Effective March 30, 2009, the CWQCC revised the site-specific phosphorus standard and changed the chlorophyll goal to a standard for Chatfield Reservoir (Regulation Number [No.] 38). They also revised the Chatfield Reservoir Control Regulation (Regulation No. 73) to be consistent with the revised standards.

The previous phosphorus standard of 0.027 milligrams per liter (mg/L) and chlorophyll-a goal of 17 micrograms per liter (µg/L) (both effective May 30, 1985) are referred to in this report. As of March 2009, the standards are 0.030 mg/L for phosphorus and 10 µg/L for chlorophyll-a, measured through the collection of samples representative of the mixed layer during summer months (July, August, September). The maximum allowable exceedance frequency of these standards is once in five years. The assessment criterion used to determine whether Segment 6b is in attainment of the phosphorus standard is 0.035 mg/L, and the assessment criterion for chlorophyll is 11.2 µg/L. A distinction is made between the standard and an assessment threshold in Regulation No. 38, which states that these assessment thresholds shall be used when assessing whether Chatfield Reservoir is in attainment of the specified standards (for additional details see the "Development of Assessment Thresholds" paragraph below). The new allowable load of total phosphorus in Chatfield Reservoir is 19,600 pounds per year (lbs/yr) under a median inflow of 100,860 acre-feet per year (ac-ft/yr). According to Regulation No. 38, "The new allowable load better reflects the linkage between watershed total phosphorus load and the in-lake total phosphorus concentration."

A technical review of the scientific basis for the Chatfield Reservoir phosphorus standard resulted in the changes in standards. The CWQCC directed the Colorado Water Quality Control Division (CWQCD) to undertake the technical review for several reasons, as described in Regulation No. 38, including:

> The phosphorus standard has been exceeded in Chatfield Reservoir several times since approximately 1995, while the associated chlorophyll goal has not. The incongruity suggested that the original basis for linking chlorophyll and phosphorus concentrations in the lake should be revisited.

The following results of the technical review appear in Regulation No. 38. These are included here because they provide a context for the technical discussions presented in this water quality report.

Current Condition. Chatfield Reservoir presently has good water quality and uses are being attained. The Commission believes that good conditions have been maintained by having implemented effective phosphorus control strategies through adoption of Control Regulation No. 73. The data record amassed through more than 20 years of water quality monitoring shows that trophic condition has remained stable, and it provides a comprehensive basis for assessing the variability in those characteristics (chlorophyll and phosphorus) of trophic condition that are recommended as standards.

Characterizing Chlorophyll. Typical summer average chlorophyll is about 6 µg/l, and there has been no trend for increasing concentration over the 26-year period of study. Concentrations vary from year to year, but have exceeded 10 µg/l only 5 times in 24 years, and only twice since 1990.

Role of Phosphorus. The Commission believes that eutrophication of Chatfield Reservoir has been averted through the control of phosphorus loads from the watershed. Adoption of the control regulation made this possible by imposing concentration limits on point source discharges and by facilitating implementation of nonpoint source management. There has been no trend for increasing phosphorus in Plum Creek, where most of the development has occurred.

Characterizing Phosphorus. Typical summertime concentrations of phosphorus have been about 0.020 mg/L, and there has been no trend for increasing phosphorus in the lake. Summer median concentrations have exceeded 0.030 mg/L in only 3 of 24 years. It is appropriate to maintain phosphorus as a standard, rather than a goal, because of its importance in characterizing trophic condition, and because it is the direct link to the control regulation.

Old Relationship Between Chlorophyll and Phosphorus. At the time the technical review was conducted, the existing phosphorus standard was not consistent with the existing chlorophyll goal. Phosphorus concentrations at or below the level of the standard have yielded chlorophyll much lower than the goal. The mismatch is the result of relying entirely on one year of data and assuming that all variation in chlorophyll is explained completely by the phosphorus concentration in the reservoir.

Defining a New Chlorophyll-Phosphorus Linkage. The conventional regression approach previously used to link chlorophyll and phosphorus in the context of trophic conditions has shown its weaknesses. The CWQCD believes a better linkage is based on the simple ratio of chlorophyll to phosphorus, which records the net responsiveness of the resident algal community to the amount of phosphorus present in the lake. It is a "net" value because it reflects the balance of growth (nutrients, light, temperature) and loss (grazing, washout, settling) processes. The measured ratios offer an empirical basis for defining expectations for chlorophyll given the available phosphorus.

Revised Water Quality Standards for Chatfield Reservoir. With the benefit of the lengthy historical record now available, the CWQCC believes it is appropriate to set chlorophyll and phosphorus standards consistent with the trophic condition that has been maintained. The CWQCC adopted a chlorophyll standard of 10 µg/L and a phosphorus standard of 0.030 mg/L to preserve the intended trophic condition and protect uses. Each standard is to be attained in four of five years.

Development of Assessment Thresholds. For Chatfield Reservoir, a distinction is made between the standard and an assessment threshold. The assessment threshold is designed to address the concern about the risk of incorrectly counting an exceedance when a high summer value is the result of natural variability, but does not indicate a substantive change in trophic condition. The approach is justified by the special nature of the pollutants (chlorophyll and phosphorus are not toxic) and the site-specific nature of the concern about false exceedances. Another reason for establishing an assessment threshold that is different than the standard is that the site-specific standard is derived from historical data, which creates the expectation that a number of exceedances will occur. Natural variability, especially for chlorophyll, is sufficient to produce much more uncertainty in the assessed value than in the standard, which was derived from the set of all summer averages. The CWQCC is establishing assessment thresholds for Chatfield Reservoir nutrient standards based on this unique combination of circumstances and does not intend this action to be a precedent for other standards and/or other segments.

These changes in standards do not affect the nutrient modeling presented in this technical report. Figures 3-1 through 3-4 show the current phosphorus and chlorophyll-a standards. Discussion of the model results includes references to both the previous and current standards.

2. Chatfield Reservoir Physical Evaluation

In order to evaluate potential impacts on nutrients, metals, and bacteria, the first step was to characterize the reservoir's physical nature. This involved collection and evaluation of available physical data, and prediction of changes in residence time.

2.1. Physical Data

To support an estimation of changes in residence time and potential impacts on water quality conditions in the reservoir, a number of physical data sets were accessed for Chatfield Reservoir. First, the 1998 Chatfield bathymetry developed by the U.S. Army Corps of Engineers (USACE) was obtained. Bathymetry was provided in an x-y-z file format, and the data were used to generate a TIN (Triangulated Irregular Network) surface in ArcGIS (Figure 2-1). There were no shoreline data associated with the bathymetry data, therefore an NHD (National Hydrography Dataset) shoreline was used in the analysis. The TIN surface was ultimately used to compute the bottom surface area below various elevations (namely the hypolimnion) of the reservoir.

It should be noted that the elevations in the bathymetry data did not extend to the normal conservation pool elevation of 5432 ft msl. The maximum elevation in the x-y-z bathymetry file was 5421 ft msl which was below the normal pool elevation of 5432 ft msl. This was likely because the bathymetric collection period occurred during a dry year corresponding with a low reservoir level. This limitation did not detrimentally impact the analysis.

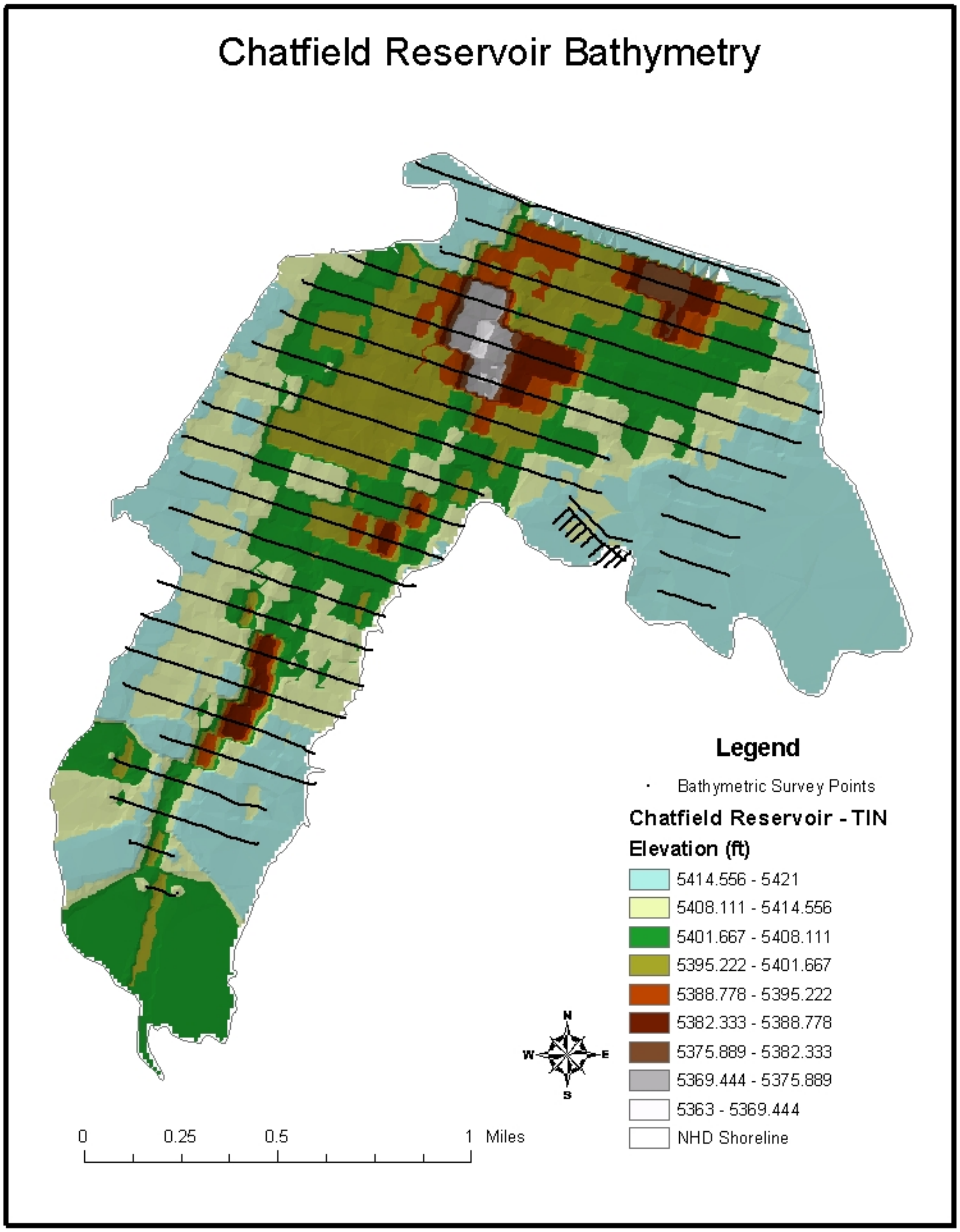


Figure 2-1. Chatfield Reservoir Bathymetry - 1998 survey (Source: USACE, 1998).

Area-capacity tables presented in Figures 2-2 and 2-3 were provided by the USACE for the 1998 survey (USACE, 2001). These plots were used to extrapolate reservoir surface areas and capacities for elevations above the maximum elevation of 5421 ft msl from the bathymetric survey (i.e., estimate the volume and area for the conservation pool elevation and the proposed 12 ft rise above the conservation pool elevation – which are both above 5421 ft msl).

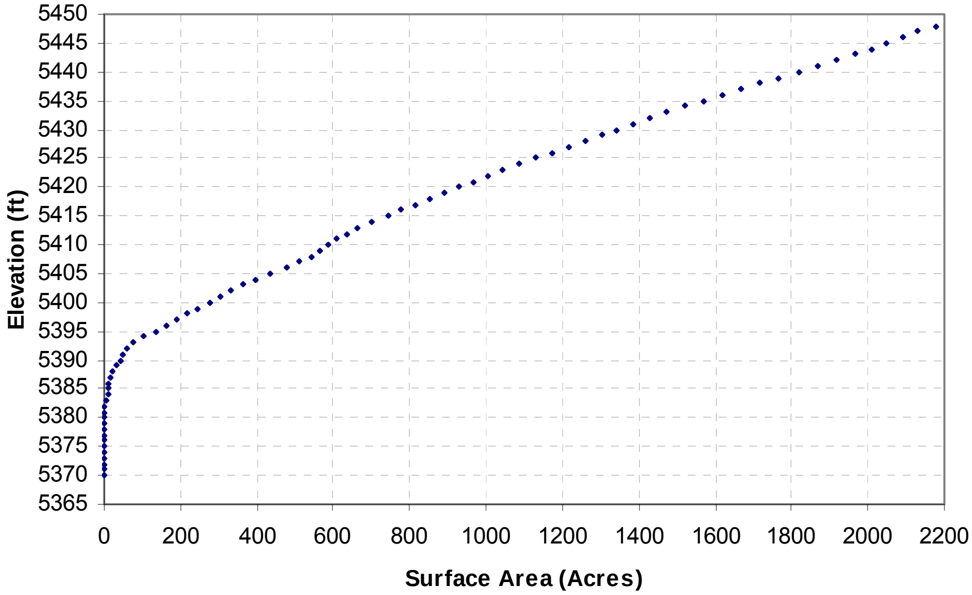


Figure 2-2. Elevation vs. Reservoir Surface Area (1998 Survey) (Source: USACE, 2001).

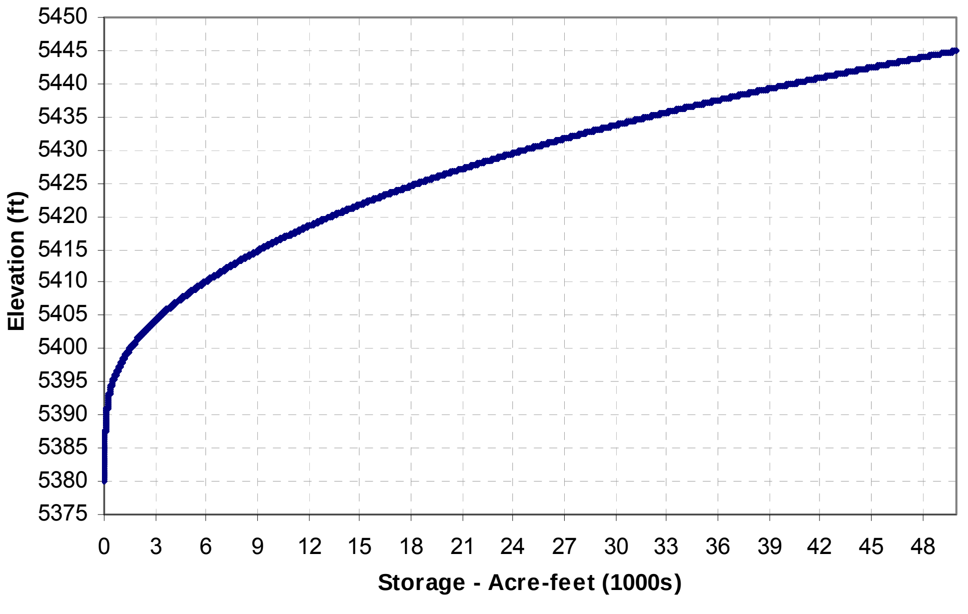


Figure 2-3. Elevation vs. Reservoir Capacity (1998 Survey) (Source: USACE, 2001).

It can be seen from Figures 2-2 and 2-3 that at the conservation pool elevation of 5432 ft msl the surface area and volume are 1,429 acres and 27,428 acre-feet, respectively. The maximum proposed increase in the pool elevation is 12 ft (i.e., 5444 ft msl) and it corresponds to a surface area of 2,009 acres and a volume of 48,066 acre-feet. Daily water surface elevations for both the existing and maximum proposed project conditions were also obtained from the USACE (2006) to support the water quality analysis (Figure 2-4). Figure 2-4 shows the daily inter year variability between the baseline and maximum proposed condition from 1942 to 2000. Based on USACE's modeled pool elevations for the maximum proposed condition, it was found that the 5444 ft msl elevation (greater than or equal to) occurs approximately 18 percent of the time (based on the daily values shown below from 1942 to 2000). The average increase in elevation during the summer period for the entire period of record was estimated to be 9.3 ft. This was computed based on an average value for the mean summer months (June, July and August) elevations for the period of 1942 to 2000. Hence, the water surface elevation data seem to suggest that the average summer increase of 9.3 ft is a more typical and likely case that can be expected during the critical summer period. In this report both the 12 ft and 9.3 ft increase scenarios were evaluated.

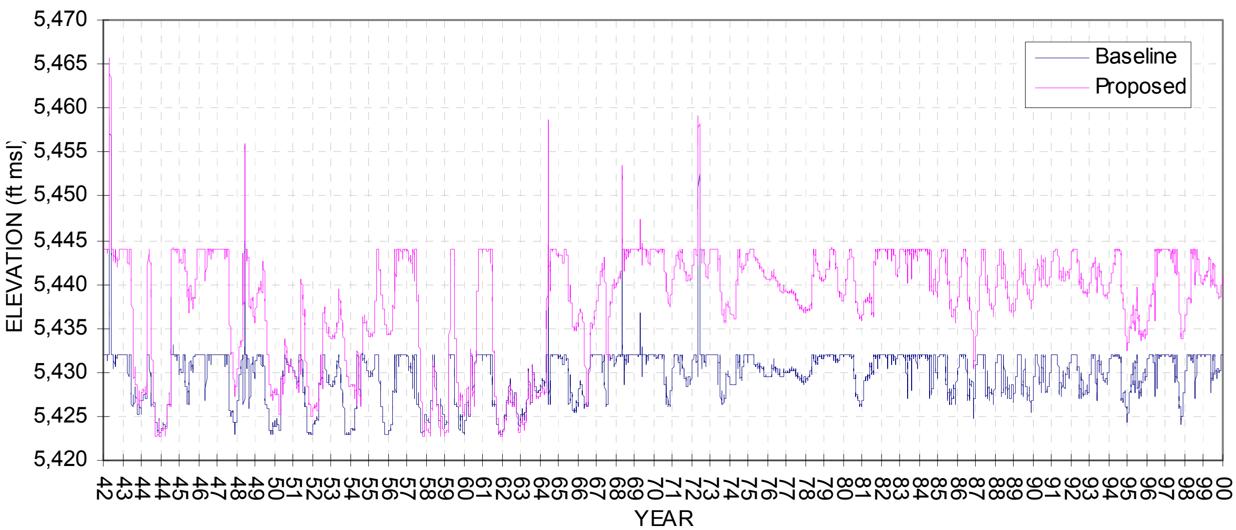


Figure 2-4. Chatfield Reservoir Daily Water Surface Elevations (1942 – 2000) (Source: USACE, 2006).

2.2. *Hydraulic Residence Time*

In addition to an assessment of proposed volumetric and surface area changes, potential changes in reservoir residence time were also evaluated. This analysis consisted of computing historic residence time information and estimating residence times under the proposed operational regime to qualitatively assess impacts on water quality. Significantly longer or shorter residence times can have a significant impact upon the water quality of the reservoir in terms of hypolimnetic oxygen depletion, nutrient cycling and other parameters (Horne and Goldman, 1994).

The hydraulic residence time (HRT) is basically the amount of time that would be required for the outflow to replace the quantity of water in the reservoir. If the volume is large and the flow is small, the reservoir would have a large HRT (i.e., it would take longer for the reservoir to flush out). Alternatively, if the reservoir has a small volume and a high flow, it is considered a "fast flusher" (Chapra, 1997). It should be noted that the retention time of a nutrient is somewhat different from the hydraulic residence time, since sedimentation and recycling take place within a reservoir (Horne and Goldman, 1994).

The HRT can be determined as follows:

$$\text{HRT} = \frac{V}{Q_{outflow} \times CF} \quad [1]$$

where:

HRT = the hydraulic residence time (days)
V = the volume of the reservoir (acre-ft)
$Q_{outflow}$ = mean outflow (cfs)
CF = conversion factor = 1.983, if V is in acre-ft and $Q_{outflow}$ is in cfs

Daily baseline and proposed elevation data were available from the USACE (2006) for the period of 1942 to 2000. Annual average elevations were computed and their corresponding volume was estimated using the stage-storage relationship for the reservoir (as shown in Figure 2-3). Daily outflow data for the existing and proposed conditions were also available for the years 1942 to 2000 from the USACE (2006). Annual average outflows were computed for each year and the HRT was calculated for both the baseline and proposed conditions (using equation [1]). Figure 2-5 shows the annual HRT for 1942 to 2000. Figure 2-5 and Table 2-1 present the annual HRT for the baseline and proposed condition for each year based on annual average outflows and annual average volumes estimated using annual average elevations.

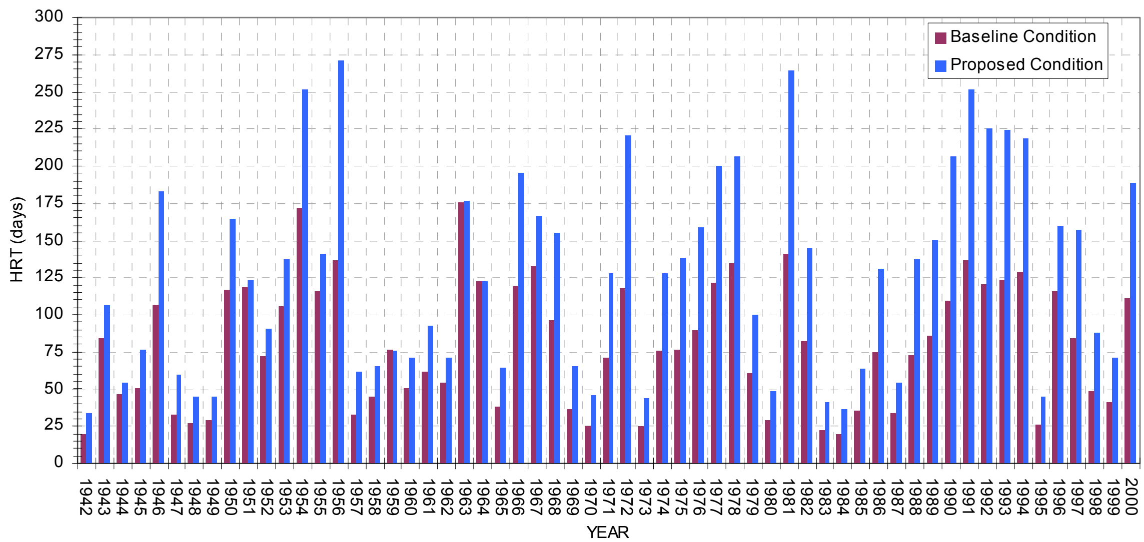


Figure 2- 5. Baseline and Proposed Annual HRT from 1942 to 2000 for the Chatfield Reservoir.

Table 2-1. Baseline and Proposed Annual HRT from 1942 to 2000 for the Chatfield Reservoir.

Year	Average Baseline Conditions Outflow (cfs)	HRT – Baseline Conditions (days)	Average Proposed Conditions Outflow (cfs)	HRT – Proposed Conditions (days)
1942	780	20	759	34
1943	140	84	163	106
1944	223	47	219	54
1945	219	50	186	76
1946	119	106	115	183
1947	425	32	406	59
1948	437	27	439	45
1949	431	29	404	45
1950	96	117	98	165
1951	94	119	97	123
1952	151	72	143	91
1953	104	106	93	138
1954	62	172	60	252
1955	96	115	93	141
1956	82	137	67	271
1957	370	32	343	62
1958	248	45	264	66
1959	132	77	126	75
1960	203	51	188	71
1961	190	62	157	92
1962	207	54	229	71
1963	56	175	54	177
1964	87	123	84	122
1965	334	38	285	65
1966	99	120	104	195

Year	Average Baseline Conditions Outflow (cfs)	HRT – Baseline Conditions (days)	Average Proposed Conditions Outflow (cfs)	HRT – Proposed Conditions (days)
1967	89	132	91	166
1968	135	96	125	155
1969	383	36	354	66
1970	553	25	528	46
1971	175	71	172	128
1972	108	118	100	221
1973	580	25	551	44
1974	163	76	164	128
1975	166	77	148	139
1976	146	89	143	159
1977	102	121	102	200
1978	91	134	91	206
1979	215	61	203	100
1980	465	29	448	48
1981	87	141	77	264
1982	155	82	140	145
1983	610	22	577	41
1984	679	20	649	37
1985	367	36	352	64
1986	161	75	157	131
1987	369	33	356	54
1988	167	73	144	137
1989	139	86	135	151
1990	107	109	98	207
1991	91	136	85	252
1992	104	120	99	225
1993	99	123	96	225
1994	98	129	95	219
1995	471	26	454	45
1996	101	116	102	160
1997	160	84	135	157
1998	248	49	237	88
1999	325	41	296	71
2000	118	111	110	189
Average for Period of Record	227	80	217	126

It can be seen that the outflow varies depending on the hydrologic regime for each year and that there is an increase in retention time irrespective of whether it is a dry year or a wet year (except for two years 1959 and 1964 which had a slight decrease in retention time). The HRT generally increases because the proposed project outflow does not increase proportionally with the increase in reservoir volume (the proposed project outflow actually decreases). However, it should be noted that HRT values could vary "daily" as significant inflow and outflow events occur. Hence, the results shown in the table above do not take into account the short term variations in HRT that can be expected due to changes in volume and outflow conditions. This could lead to an increase or decrease in HRT which could result in a decrease or increase in water quality respectively.

3. Nutrient Analysis

Two types of nutrient analysis were conducted for the baseline and proposed project conditions. A simplistic but conservative, regional analysis was followed by a more detailed analysis which was pursued to address some of the shortcoming of the regional analysis.

3.1. Conditions based on Regional Statistical Models

This analysis focused on estimating mean concentrations across the entire reservoir for several years. This assessment uses a regional statistical model to evaluate historical incoming total phosphorus loads, hydraulic residence time, and change in volume information to predict reservoir eutrophication potential and chlorophyll-a for the baseline and reservoir storage reallocation condition. In this analysis the internal loading is inferred from algorithms based on relationships derived from regionalized lakes.

3.1.1. Total Phosphorus and Chlorophyll-a Analysis using EUTROMOD Model

The EUTROMOD water quality model (Reckhow et al., 1992) was chosen for this analysis. EUTROMOD is a spreadsheet-based model that is used for the prediction of lake eutrophication for individual lakes in the U.S. Lake eutrophication is predicted based on a set of regional statistical models. Response variables include: total phosphorus concentration, chlorophyll-a, secchi disk depth and Carlson's trophic state index. The model algorithms predict lake-wide, growing season (defined as the period from June through September in EUTROMOD) average conditions as a function of annual nutrient input or loading. The Chatfield Reservoir phosphorus standard is based upon attaining the chlorophyll-a goal in Chatfield Reservoir for July through September (Chatfield Watershed Report, 2007). This study assumes that the predicted growing season results would still be comparable to the criteria.

The model also provides an estimate of uncertainty (estimated 5th percentile and 95th percentile output) for the mean estimated values. As with any simplified approach, this model also has a high level of uncertainty, and the model cannot be used to evaluate a short term and dynamic response. Year-to-year variability is addressed using the precipitation coefficient of variation to account for hydrologic variability in the output. Precipitation data from a nearby NCDC (National Climatic Data Center) precipitation station (Kassler – CO4452) were used to estimate the coefficient of variation in this study. The hydrologic variability is propagated using first-order error analysis (Reckhow et al., 1992).

The model has six regional models coded in the spreadsheet. The closest regional model applicable to Chatfield Reservoir is from the Midwest region. The EUTROMOD model equations for the Midwest region are presented below.

Total Phosphorus (mg/L)

$$\log_{10}(TP) = \log_{10}\left[\frac{TP_{in}}{1+k\tau}\right] \qquad [2]$$

Chlorophyll-a (μg/L)

$$\log_{10}(Chla) = 1.99 + 0.51 \cdot \log_{10}(TP) + 0.23\log_{10}(\tau) - 0.35\log_{10}(z) \qquad [3]$$

Secchi Disk Depth (m)

$$\log_{10}(SD) = -1.32 - 0.66 \cdot \log_{10}(TP) + 0.47\log_{10}(z) \qquad [4]$$

Trophic State Index

$$\left[TSI = [(60 - 14.41 \cdot \log_{10}(SD)) + (30.6 + 9.81 \cdot \log_{10}(Chla)) + (4.15 + 14.42 \cdot \log_{10}(1000 \cdot TP))]/3\right] \qquad [5]$$

Where,

k is the trapping parameter or loss rate defined as $k = 10.77\tau^{-0.61}z^{0.01}TP_{in}^{\ 0.82}$ [6]

TP = predicted total phosphorus concentration (mg/L)

TP_{in} = average influent total phosphorus concentration (mg/L)

z = lake mean depth (meters), computed as the volume divided by the surface area

τ = hydraulic residence time (years)

As can be seen in the above equations the predicted TP concentration is directly related to the incoming TP concentration and inversely related to the loss rate and hydraulic residence time. Any increase in the loss rate or hydraulic residence time would result in a decrease in the TP concentration and vice versa. The predicted chlorophyll-a concentration is directly dependent on the predicted TP concentration, hydraulic residence time and mean depth. Similarly the secchi depth is also related to the predicted TP concentration and mean depth and generally increases with decreasing TP concentration. The TSI is computed based on the predicted secchi depth, predicted chlorophyll-a, and predicted TP concentration.

3.1.2. Inputs to the EUTROMOD Model

The input data requirements for the EUTROMOD model are minimal. They include incoming total phosphorus loading, inflow, mean depth and hydraulic residence time. Each of these items is discussed below.

3.1.2.1. Total Phosphorus Loading and Total Inflow

Historical total phosphorus loading and inflow data for the years 1986 to 2007 were provided by the Chatfield Watershed Authority at the time that the models presented in this technical report were run. More recent data from the Chatfield Watershed Authority (collected in 2008, 2009, and 2010) are discussed at the end of Section 3. The same loading was used for both the baseline and proposed condition analyses. Table 3-1 shows the total inflow and external total phosphorus load to Chatfield Reservoir. The percentile distribution of the total incoming inflow is also presented in Table 3-1 to allow for identifying low water years versus high water years. For example, 1987 corresponds to the high water year at the 90th percentile and the year 2003 can be considered as a low water year being the 10th percentile year. Years 2000 and 2006 are considered as median years. The average incoming total phosphorus concentration for a particular year was computed by dividing the external TP load by the total inflow.

Table 3-1. Total Phosphorus Load and total inflow used in the EUTROMOD model

Year	Total Inflow (ac-ft/yr)	External TP Load (lbs/yr)	Percentile Distribution of Total Volume	Estimated External TP (TP_{in}) concentration (mg/L)
1986	116,996	15,900	67%	0.050
1987	270,468	50,201	90%	0.068
1988	122,351	26,693	76%	0.080
1989	100,690	12,342	57%	0.045
1990	80,666	11,181	38%	0.051
1991	74,113	10,848	24%	0.054
1992	78,306	14,169	33%	0.067
1993	70,621	9,832	19%	0.051
1994	74,847	11,544	29%	0.057
1995	336,345	52,471	100%	0.057
1996	82,408	9,511	43%	0.042
1997	120,653	16,596	71%	0.051
1998	177,849	39,586	81%	0.082
1999	242,221	46,691	86%	0.071
2000	88,223	13,886	48%	0.058
2001	67,072	10,360	5%	0.057
2002	36,464	3,506	0%	0.035
2003	68,742	13,778	10%	0.074
2004	69,339	12,527	14%	0.066
2005	107,785	25,202	62%	0.086
2006	89,786	13,540	52%	0.055
2007	288,680	56,077	95%	0.071

Source: Total Inflow and External TP Load provided by Chatfield Watershed Authority.
Note: More recent data are discussed at the end of Section 3.

3.1.2.2. Mean Depth

Daily baseline and proposed elevation data from USACE (2006) for the period of 1942 to 2000 were used. Annual average elevations were computed and their corresponding volume and surface area were estimated using the stage-storage relationship for the reservoir. The mean depth was then calculated as the lake volume divided by the surface area.

3.1.2.3. Hydraulic Residence Time

The hydraulic residence time for baseline and proposed condition were based on the USACE (2006) water surface elevation and outflow data for the period of 1942 to 2000. The HRT values used are presented in Table 2-1 and a discussion on how the HRT values were computed is presented in section 2.2.

Table 3-2 shows the mean depth and hydraulic residence time for the baseline and proposed condition. Note that the data extend past 2000 (up to 2007). In order to make use of the seven years of recent total phosphorus input data provided by the Chatfield Watershed Authority when this analysis was completed, mean hydraulic residence time and mean depth were estimated based on the data from 1942 to 2000. Although the model incorporates the inter-year variability from 2001 to 2007 in terms of total phosphorus loading, there is some uncertainty with the model results from 2001 to 2007 because the HRT and mean depth are assumed to be the same for that period, when in reality they would also vary from year to year.

Table 3-2. Mean Depth and Hydraulic Residence Time used in the EUTROMOD model

	Baseline				Proposed Conditions			
Year	Volume (Ac-ft)	Surface Area (ac)	Mean Depth (m)	HRT (yr)	Volume (Ac-ft)	Surface Area (ac)	Mean Depth (m)	HRT (yr)
1986	23,901	1,320	5.52	0.21	40,742	1,828	6.79	0.36
1987	24,404	1,336	5.57	0.09	37,991	1,749	6.62	0.15
1988	24,259	1,331	5.55	0.20	39,281	1,786	6.70	0.38
1989	23,689	1,313	5.50	0.24	40,249	1,814	6.76	0.41
1990	23,217	1,298	5.45	0.30	40,141	1,811	6.76	0.57
1991	24,616	1,343	5.59	0.37	42,426	1,875	6.90	0.69
1992	24,943	1,353	5.62	0.33	44,151	1,921	7.01	0.62
1993	24,047	1,325	5.53	0.34	42,577	1,879	6.91	0.62
1994	25,025	1,355	5.63	0.35	41,277	1,843	6.83	0.60
1995	24,457	1,338	5.57	0.07	40,798	1,830	6.80	0.12
1996	23,255	1,299	5.45	0.32	32,468	1,588	6.23	0.44
1997	26,710	1,407	5.79	0.23	42,088	1,866	6.87	0.43
1998	24,087	1,326	5.54	0.13	41,351	1,845	6.83	0.24
1999	26,682	1,406	5.78	0.11	41,554	1,851	6.84	0.19
2000	25,980	1,385	5.72	0.30	41,240	1,842	6.82	0.52
2001	24,193	1,330	5.55	0.15	36,946	1,720	6.55	0.24
2002	24,193	1,330	5.55	0.15	36,946	1,720	6.55	0.24
2003	24,193	1,330	5.55	0.15	36,946	1,720	6.55	0.24
2004	24,193	1,330	5.55	0.15	36,946	1,720	6.55	0.24
2005	24,193	1,330	5.55	0.15	36,946	1,720	6.55	0.24
2006	24,193	1,330	5.55	0.15	36,946	1,720	6.55	0.24
2007	24,193	1,330	5.55	0.15	36,946	1,720	6.55	0.24

Note: The years 2001 to 2007 represent average conditions based on data from 1942 to 2000

3.1.3. EUTROMOD Modeling Results

The incoming average total phosphorus concentration, mean depth and hydraulic residence time were specified as input into the spreadsheet, and the resulting in-lake growing season average total phosphorus concentrations for the baseline condition were estimated using the EUTROMOD model. The predicted baseline total phosphorus and chlorophyll-a results were then verified with observed data.

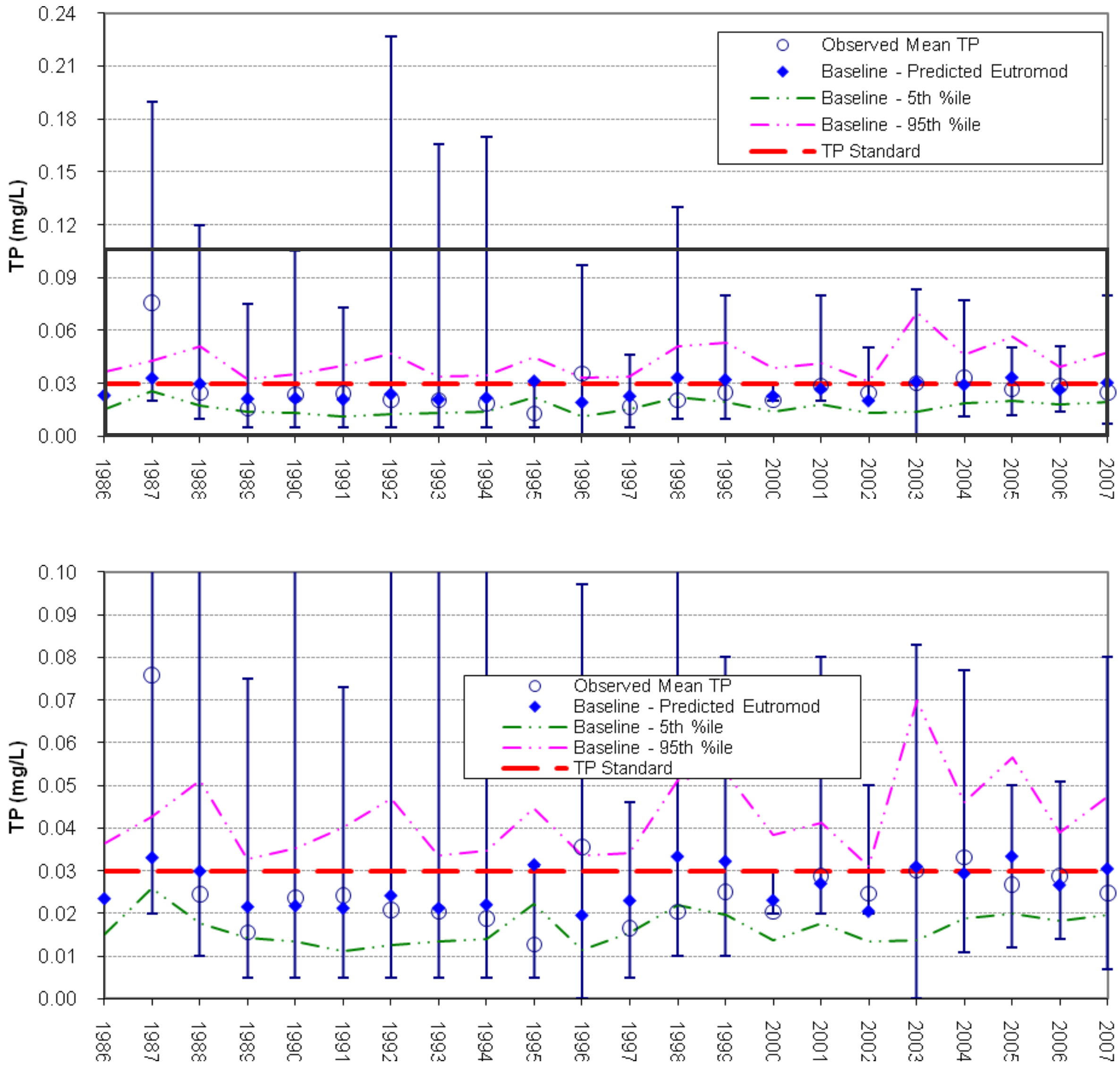
3.1.3.1. <u>Baseline Model Verification</u>

Observed total phosphorus and chlorophyll-a data provided by the Chatfield Watershed Authority were used to compare with the model results. For comparison purposes mean total phosphorus and chlorophyll-a concentration for the period from June through September were computed. The mean was based on the samples observed throughout the depth and across the reservoir. In addition the minimum and maximum values were also computed to provide a range of observed data for that time period. Table 3-3 shows the observed data values and counts associated with them. The overall loss rate (k) was adjusted to better match the predicted mean total phosphorus concentrations with the mean of the observed total phosphorus data (equation [2]). This ensured that the model predictions were within a reasonable range compared to the observed conditions and that the model could be then used for scenario evaluation and testing. Adjusting the loss rate indirectly also adjusted the chlorophyll-a, secchi depth and TSI index which are dependent on the predicted TP concentrations (equation [3], [4], and [5]). As stated in the previous section the results from 2001 to 2007 are based on average water surface elevation conditions based on data from 1942 to 2000 due to lack of appropriate data for that time period. However, those years represent the appropriate temporal variability in terms of the TP loading into the Chatfield Reservoir.

Figures 3-1 and 3-2 present the model response for total phosphorus and chlorophyll-a compared to the observed data. The model does a fair job in matching the mean observed data. The model attempts to predict the mean observed concentrations but is unable to match the observed trend very well. This can be due to several reasons. There is a wide range in the observed data which is possibly due to the instantaneous minimums and maximums that can occur due to dynamic eutrophication processes in the reservoir (e.g., bottom nutrient release or highly dynamic short term variations of chlorophyll-a). However, most of the data tend to be more towards the lower end of the range as reflected by the mean values where the majority of the data are observed. This model, like any other simple model, cannot be used to predict short-term (e.g., monthly or daily) lake response to inputs, spatial patterns (e.g., localized response) in nutrient concentration, or dynamic response (e.g., changes over time) to changes in nutrient inputs.

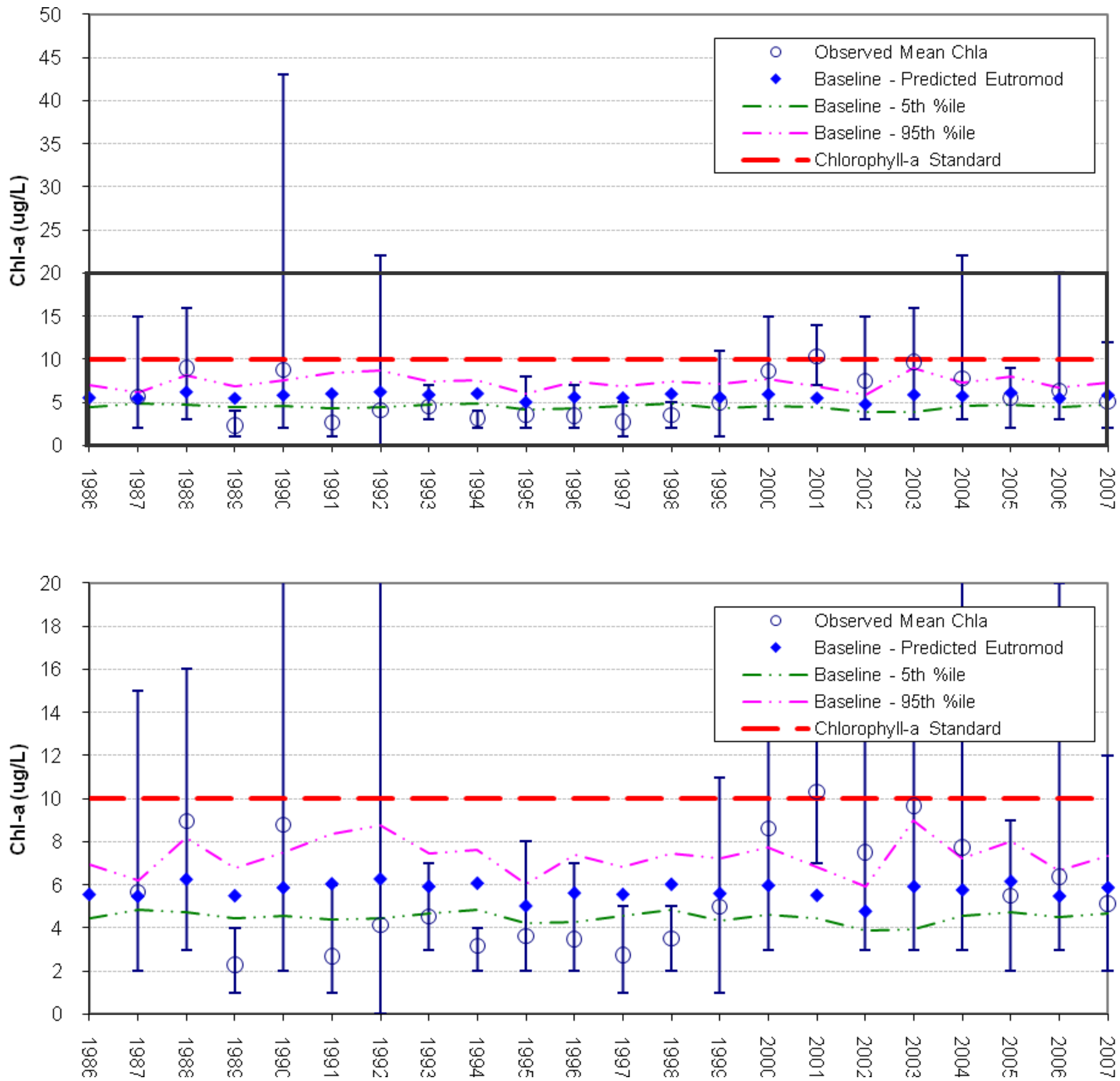
Table 3-3. Growing Season (June through September) Mean and Range of TP and Chlorophyll-a Based on Observed Data

Year	Mean Observed TP (mg/L) for Growing Season	Observed TP Range (mg/L) for Growing Season	TP Count for Growing Season	Mean Observed Chlorophyll-a (µg/L) for Growing Season	Observed Chlorophyll-a Range (µg/L) for Growing Season	Chlorophyll-a Count for Growing Season
1987	0.076	0.17	12	5.67	13	6
1988	0.025	0.11	47	8.96	13	24
1989	0.016	0.07	44	2.30	3	21
1990	0.024	0.10	46	8.79	41	23
1991	0.024	0.07	42	2.68	5	20
1992	0.021	0.22	36	4.13	22	21
1993	0.020	0.16	40	4.55	4	20
1994	0.019	0.17	44	3.17	2	21
1995	0.013	0.03	42	3.63	6	21
1996	0.036	0.10	42	3.49	5	21
1997	0.017	0.04	21	2.75	4	7
1998	0.020	0.12	21	3.50	3	7
1999	0.025	0.07	21	5.00	10	7
2000	0.020	0.01	24	8.63	12	8
2001	0.029	0.06	21	10.33	7	6
2002	0.025	0.03	21	7.50	12	7
2003	0.030	0.08	26	9.67	13	6
2004	0.033	0.07	21	7.75	19	7
2005	0.027	0.04	21	5.50	7	7
2006	0.029	0.04	21	6.38	17	6
2007	0.025	0.07	21	5.13	10	7



Note: Range of the observed data (open circle) are provided as error bars, and the 5th and 95th percentile values (dashed lines) represent variability for the mean estimated value.

Figure 3-1. Predicted Baseline TP concentration and Observed TP Data (top figure shows the overall range of observed data and model results, while the bottom plot shows the boxed area zoomed in)

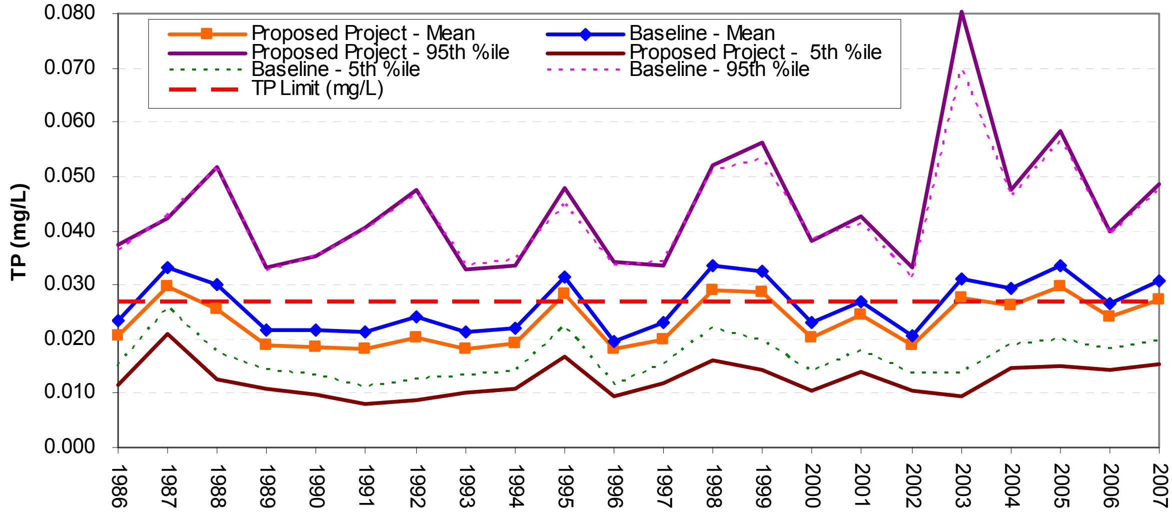


Note: Range of the observed data (open circle) are provided as error bars, and the 5th and 95th percentile values (dashed lines) represent variability for the mean estimated value.

Figure 3-2. Predicted Baseline Chlorophyll-a concentration and Observed Chlorophyll-a Data (top figure shows the overall range of observed data and modeled results, while the bottom plot shows the boxed area zoomed in)

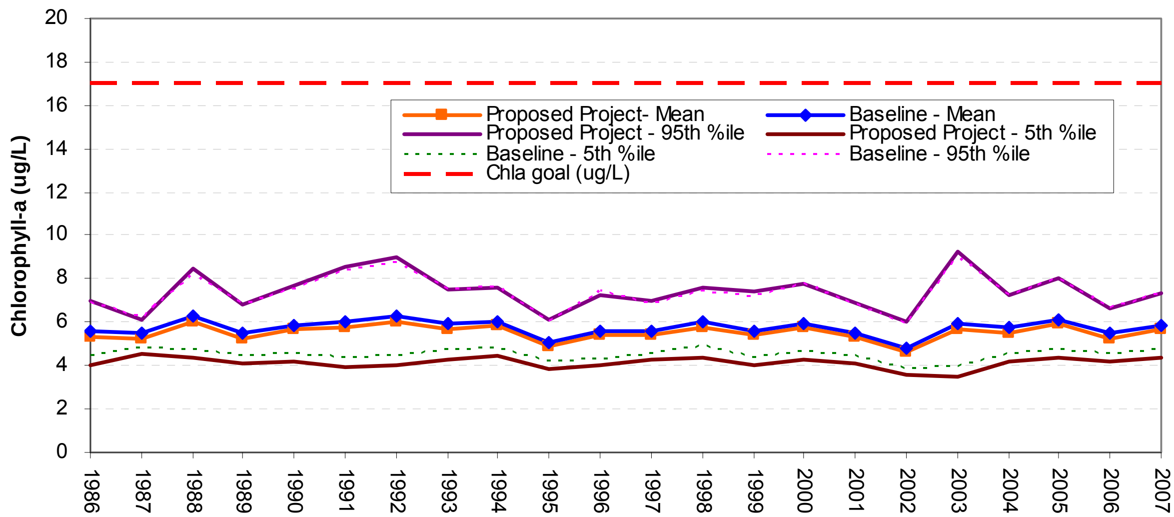
3.1.3.2. Baseline and Proposed Project Scenario Analysis

The baseline model was then used to run the proposed project conditions using the incoming TP concentration (Table 3-1) and the mean depth and hydraulic residence time for the proposed condition (Table 3-2). Figures 3-3 through 3-6 show the mean baseline and proposed results along with the variability associated with the mean values in terms of the 5th percentile and 95th percentile values.



Note: Effective March 30, 2009, the total phosphorus standard is 0.030 mg/L.

Figure 3-3. Predicted TP Concentrations for Baseline and Proposed Conditions



Note: Effective March 30, 2009, the chlorophyll-a standard is 10 µg/L.

Figure 3-4. Predicted Chlorophyll-a Concentration for Baseline and Proposed Conditions

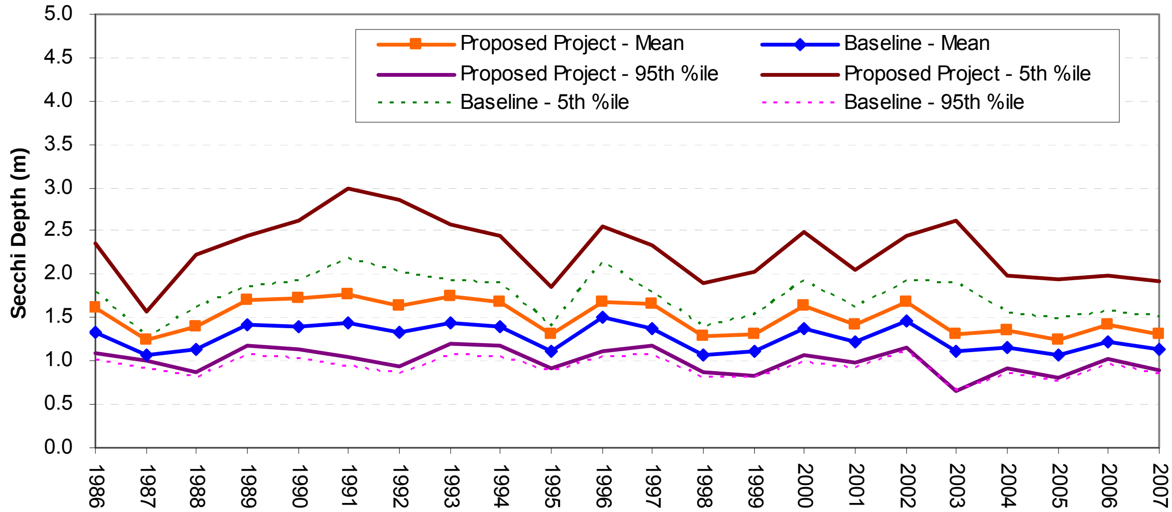


Figure 3-5. Predicted Secchi Depth for Baseline and Proposed Conditions

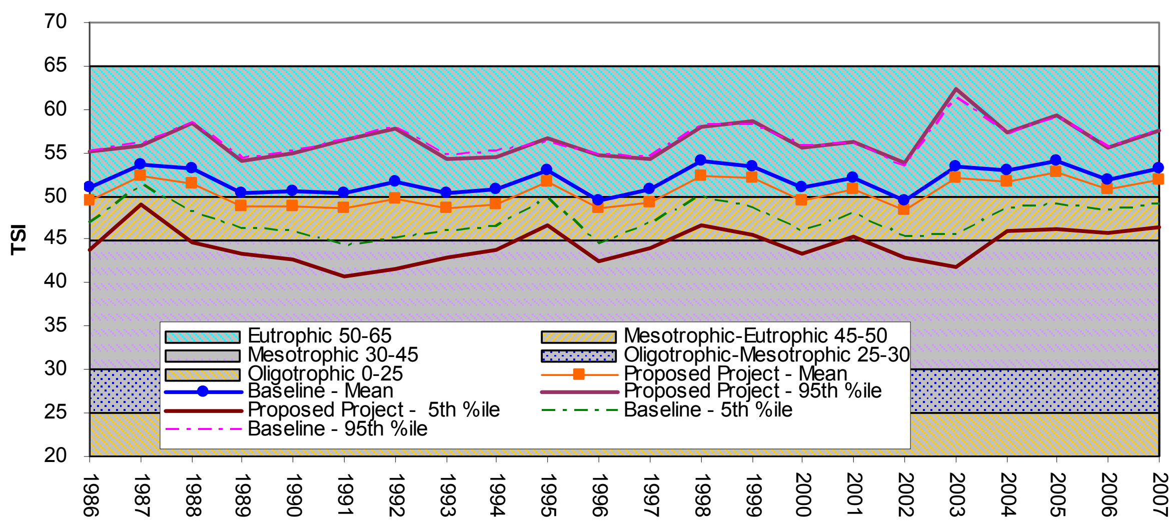


Figure 3-6. Predicted Carlson's Trophic State Index for Baseline and Proposed Conditions

There was an overall decrease in all the parameters estimated (except for secchi depth which increased). The current and previous mean TP standards (30 and 27 µg/L, respectively) for the growing season were equaled or exceeded for a few years in both the baseline and proposed project condition (Figure 3-3). For example, the high water year (90 percentile inflow - 1987) showed a mean TP concentration of 33 µg/L in the baseline and 30 µg/L for the proposed project condition, higher than the previous TP standard of 27 µg/L and greater than or equal to the current TP standard of 30 µg/L for the growing season. Whereas the low water year (10 percentile year - 2003) showed TP concentration of 31 μg/L in the baseline, also higher than the current and previous TP standards, and 28 μg/L in the proposed project condition, higher than the previous TP standard. Overall if we consider all the years, the mean TP for the growing season under the proposed project results in an overall decrease of approximately 3 μg/L from the baseline.

The chlorophyll-a concentrations showed a minimal change (decrease) for the proposed project condition and were never greater than the previous goal of 17 μg/L or the current standard of 10 μg/L for the growing season. The decrease in the mean TP concentration occurs due to an increase in hydraulic residence time and mean depth in the proposed project condition (see equation [2] and [6]). Neither the current chlorophyll-a standard nor the previous chlorophyll-a goal were exceeded in the baseline condition and continue to be similar in the proposed project condition. For both TP and chlorophyll-a, even though the mean values were not exceeded, the observed range of data indicates that the prescribed limits were exceeded during different times of the year (Figures 3-1 and 3-2). The mean secchi depth always remains higher than 1 meter. The overall increase in volume and depth results in higher mean secchi depth results for the proposed project condition (Figure 3-5). The model results indicate a minimal change in the trophic state index (Figure 3-6). The TSI predictions indicate that the reservoir would remain in the mesotrophic to eutrophic range tending to be towards the lower bounds of the eutrophic range (approximately 47 to 53).

3.1.3.3. Sensitivity Analysis of Hydraulic Residence Time

The hydraulic residence time is an important parameter which has an impact on the water quality of the reservoir. A sensitivity analysis of the hydraulic residence time was conducted using the baseline model to evaluate the water quality effects in the reservoir due to varying hydraulic residence time. The hydraulic residence time (and mean depth) of the baseline condition was increased and decreased by 50 percent to evaluate the effects on TP, chlorophyll-a, and TSI index. The results of the sensitivity analysis are shown below in Figures 3-7 through 3-9.

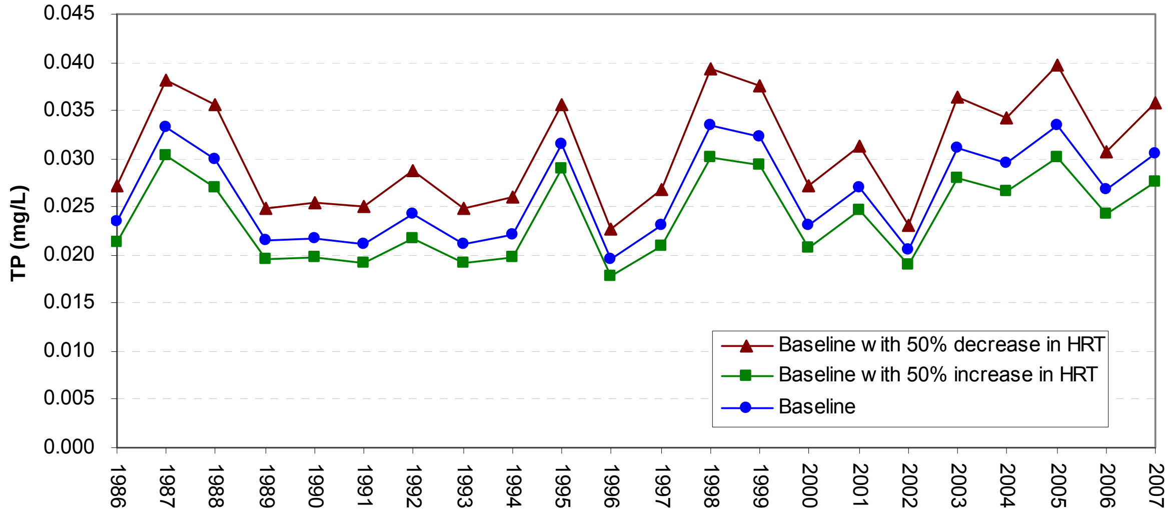


Figure 3-7. HRT Sensitivity to Predicted Mean TP concentrations in Chatfield Reservoir

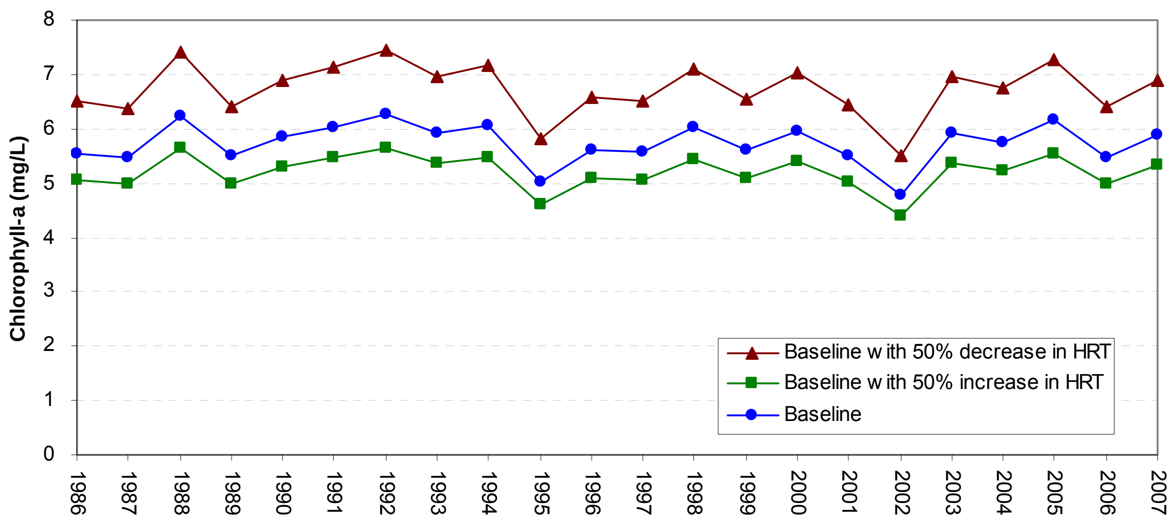


Figure 3-8. HRT Sensitivity to Predicted Mean Chlorophyll-a concentrations in Chatfield Reservoir

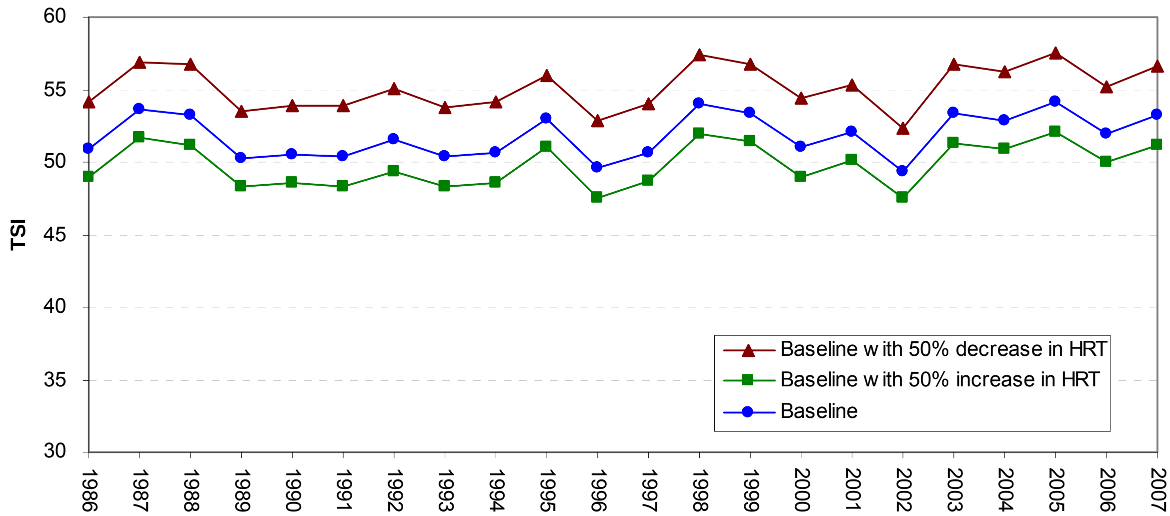


Figure 3-9. Hydraulic Residence Time Sensitivity to Predicted Carlson's Trophic State Index in Chatfield Reservoir

As can be seen in Figures 3-7 through 3-9 the increase in hydraulic residence time results in an overall decrease in concentrations due to more loss from the system and vice versa. The results indicate that the key eutrophication parameters are sensitive to the hydraulic residence time and by proper management of the volumes and outflow from the reservoir the desired goals can be reasonably achieved.

3.1.4. Limitations of EUTROMOD Analysis

The overall decrease in concentrations using the EUTROMOD model is expected since the volume and the hydraulic residence time increased in the proposed conditions, which results in more dilution for the same TP concentration coming into the reservoir. For the proposed conditions the EUTROMOD model does not include any additional increase in TP loading from the baseline condition (e.g., possible increase in internal loading due to increased stratification is not considered). In addition the model does not take into account the dynamic effect and processes taking place across the reservoir. As can be seen from the observed data (Figures 3-1 and 3-2) the reservoir shows a wide range of results spatially and temporally across the depth of the reservoir, which are much higher than even the range of model error bounds estimated by the model in terms of the 5th and 95th percentile for the mean concentrations. Short term variations (e.g., anoxic releases from the sediment or fluctuation of nutrient and chlorophyll-a result due to respiration and photosynthesis) can cause a wide range of results and can only be evaluated using a costly hydrodynamic model which includes detailed eutrophication processes. The water quality workgroup, including representatives from the Chatfield Watershed Authority, Colorado State Parks, Colorado Division of Wildlife, the water providers, the Corps, and Tetra Tech, evaluated the use a hydrodynamic model to estimate potential impacts for the proposed project and determined such a model was not needed. Instead, the nutrient analysis described in the next section (Section 3.2) was conducted to address some of the uncertainty with regards to the possible increases in anaerobic and inundated vegetation nutrient fluxes. The workgroup determined that, in combination, the nutrient models described in this report adequately assess potential water quality impacts.

3.2. Conditions based on a Localized Loading Model

Section 3.1 provided a simplistic view of the nutrient analysis from which the internal loading is inferred from algorithms based on relationships derived from regionalized lakes. The analysis described in this section provides a more detailed localized analysis to address the uncertainty regarding possible increases in anaerobic and inundated vegetation nutrient fluxes due to orthophosphorus and ammonia.

An evaluation of nutrient enrichment potential for Chatfield Reservoir was done by estimating orthophosphorus and ammonia loading within and to the reservoir for existing conditions and for the proposed increase in pool elevation. Nutrient sources that were quantified include release from lake bottom sediments in both the aerobic and anaerobic zones, contributions from inundated plants and soil/sediment (for only the proposed increase case), watershed contributions, and atmospheric deposition. These sources were quantified on a loading basis, and then a mass balance was calculated for the reservoir to estimate the overall reservoir concentrations (for the existing and proposed scenarios). Figure 3-10 below shows a schematic of phosphorus sources to the reservoir. It is assumed that the plants do not contribute ammonia-N and it is assumed that the total nitrogen release from these areas would not likely alter the role of phosphorus as the primary limiting nutrient in the reservoir. For ammonia-N, aerobic release was assumed to extend to the inundated areas.

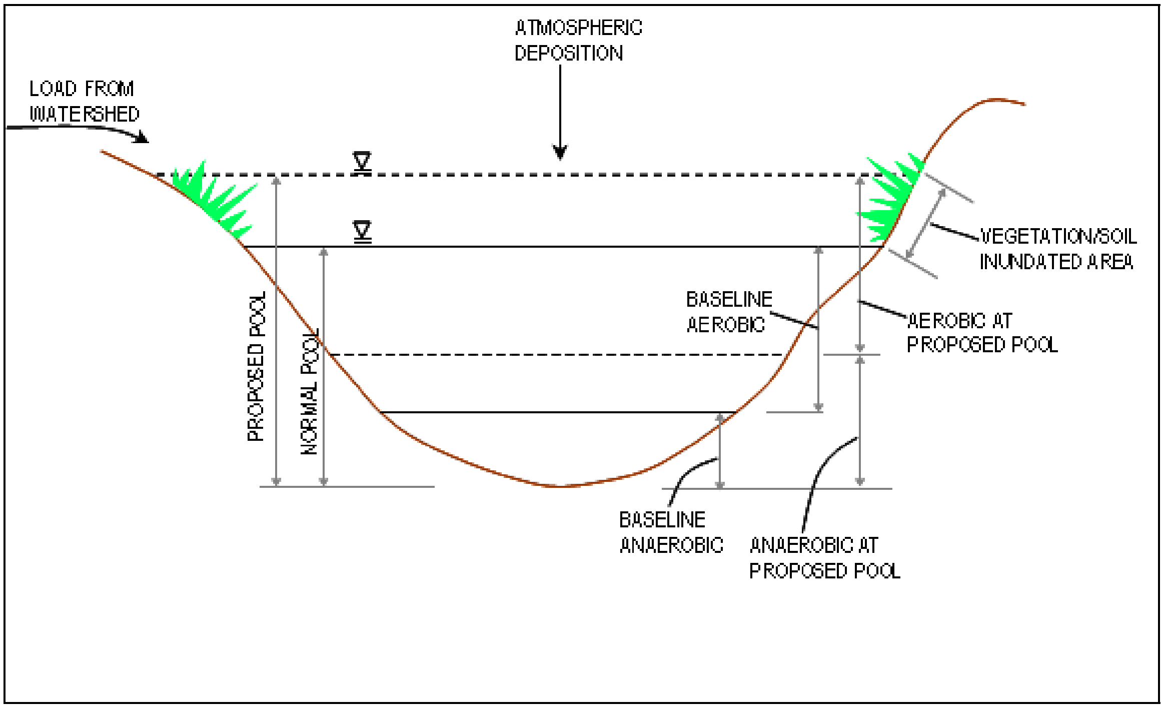


Figure 3-10. Phosphorus Sources to the Reservoir Represented in the Nutrient Analysis.

This assessment is intended to be a conservative analysis that brackets the minimum, typical and maximum impact cases possible. All calculations were performed for the critical summer period (minimum lake volume and maximum hypolimnetic volume) of a dry year (2004). To account for uncertainty in the change in hypolimnetic depth and to provide upper and lower bounds to the estimated loads, the reservoir was evaluated for the different scenarios with varying depth conditions (under and including the 12 ft increase in pool elevation) (Table 3-5).

- *Baseline Case*: Two baseline cases were evaluated at the normal pool, one with a hypolimnion and another hypothetical case without a hypolimnion. For the case where there was a hypolimnion the hypolimnetic anaerobic depth was assumed to be at 5402 ft msl (1 meter depth hypolimnion) for this baseline condition, where release from the anaerobic zone was estimated. It is possible that the hypolimnion/anoxic zone is at a greater or lower depth, however based on observed data this was considered the best assumption.

- *Maximum Case – 12 ft increase in hypolimnetic depth*: Increased reservoir volume was assumed to lead to an increased anaerobic hypolimnetic volume, and the reservoir depth is sufficient for thermal stratification to be maintained throughout the summer. It was assumed that the anaerobic hypolimnetic depth would increase by the same amount as the increase in pool elevation (12 ft). The assumption that the anaerobic hypolimnetic depth would increase by the same amount as the increase in pool elevation cannot be fully evaluated without implementing a hydrodynamic and water quality model, however it provides a conservative basis for evaluating potential impacts on reservoir nutrient levels (and the potential for eutrophication). For the proposed conditions, it was found that the 12 ft increase (which corresponds to 5444 ft msl) occurs approximately 18 percent of the time (based on the entire time period of the daily reservoir modeling results from 1942 to 2000) (Figure 2-4). Hence, the 12 ft increase in pool elevation provides a conservative estimate of the maximum increase in pool depth for the summer condition.

- *Typical Case – 9.3 ft increase*: This scenario represents the most likely typical summer condition. The USACE (2006) modeled and proposed water surface elevation data were used to derive average monthly water surface elevation data for the period 1942 to 2000. The mean monthly increase in elevation was computed for the baseline, and "with project" elevation was computed to estimate the increase in depth for each month. The estimated mean monthly increase in depth was always less than 12 ft (between the baseline and proposed conditions). The mean increase in depth during the summer period (June, July, and August) was estimated to be 9.3 ft (Table 3-4). Thus, for the typical case, it was assumed that the anaerobic hypolimnetic depth would increase by 9.3 ft.

Table 3-4. Average monthly water surface elevation (based on USACE 1942 to 2000 data).

Month	Baseline Conditions - Average Elevation (ft)	Proposed Conditions - Average Elevation (ft)	Increase in Depth (ft)
Jan	5429	5437	7.7
Feb	5430	5438	7.8
Mar	5430	5438	8.1
Apr	5430	5439	8.4
May	5431	5440	9.0
Jun	5431	5440	9.6
Jul	5429	5439	9.3
Aug	5430	5438	8.9
Sep	5429	5437	8.5
Oct	5429	5437	8.0
Nov	5429	5437	7.8
Dec	5429	5437	7.7

- *Minimum Case – No hypolimnetic depth*: For this scenario it was assumed that the anaerobic hypolimnetic depth does not exist and only aerobic fluxes exist. This represents the case with minimal impacts possible, with no hypoxic or anoxic zone. This case assumes a 12 ft increase to the normal pool baseline which does not include any hypolimnion.

The contributions from the submerged vegetation are expected to decrease substantially with time as the "trophic upsurge" subsides (Soballe, 2006). As the contributions due to the inundated vegetation subside, it is expected that the aerobic zone contributions would take over. A scenario after the pool increase, but without the contribution of the vegetation, was also evaluated for each of the three cases discussed above. For this case aerobic fluxes take over when no contribution from vegetation is present in the long-term. Table 3-5 shows the various nutrient scenarios evaluated.

Table 3-5. Nutrient Scenarios Matrix

Scenario	Description
BASELINE – Normal Pool	
BASE1	Assumes 1-meter hypolimnion
BASE2	Assumes no hypolimnion
MAXIMUM CASE – Assumes 12 ft increase (maximum proposed pool) in hypolimnetic depth from BASE1	
MAXST	Considers contribution of phosphorus from inundated soil and vegetation (short-term impact)
MAXLT	Considers no nitrogen nor phosphorus contribution from inundated soil and vegetation (long-term impact)
TYPICAL CASE – Assumes 9.3 ft increase (typical summer pool under proposed condition) in hypolimnetic depth from BASE1	
AVGST	Considers contribution of phosphorus from inundated soil and vegetation (short-term impact)
AVGLT	Considers no nitrogen nor phosphorus contribution from inundated soil and vegetation (long-term impact)
MINIMUM CASE – Assumes 12 ft increase in the normal pool, but no hypolimnion present (i.e., 12 ft increase from BASE2, with only aerobic release)	
MINST	Considers contribution of phosphorus from inundated soil and vegetation (short-term impact)
MINLT	Considers no nitrogen nor phosphorus contribution from inundated soil and vegetation (long-term impact)

3.2.1. Determination of Anoxic Volume and Surface Area

The bathymetry data were analyzed in conjunction with available water quality monitoring data to determine the anoxic depth and compute the corresponding reservoir bottom surface area and anoxic volume (referred to as “anaerobic” in the report). Dissolved oxygen (DO) depth profile data for the years 2003, 2004, and 2005 at the Chatfield reservoir dam location were used to determine if the reservoir was becoming anoxic, and at what depth in the water column the anoxic conditions were occurring in the reservoir. These data were downloaded from the Chatfield Watershed Authority website: http://www.chatfieldwatershedauthority.org/ (Chatfield Watershed Report, 2004) when the analysis was completed. In general, the reservoir begins to stratify in mid-March and remains stratified until the end of August (after which the fall turnover occurs).

Based on the observed data, the DO in the hypolimnion seldom falls below 2.0 mg/L; in fact, the concentration was below 2.0 mg/L only once. This indicates hypoxic conditions (low DO <2 mg/L), which are tending toward anoxic conditions (0 mg/L) (ESA, 2005). Anoxic and hypoxic events are caused by the decomposition of organic matter by oxygen-utilizing bacteria. In many cases anoxia and hypoxia result from eutrophication (e.g., enhanced sedimentation of particulate matter to the bottom waters) and reflect the underlying problem of excessive nutrient loads. Depth profile observations in August 2004 at the Chatfield reservoir dam station showed the lowest observed DO concentration of 1.45 mg/L in the bottom 1-meter of the water column. Though this was the only measured value below 2.0 mg/L, it is likely that other hypoxic and anoxic pockets exist throughout the bottom layers of the lake at other times. A more in-depth data collection effort would be necessary to accurately identify all these locations, occurrences, and corresponding oxygen levels.

Based on the hypoxic DO observation identified above, it was assumed that the anoxic volume occupies the bottom 1-meter of the water column at the Chatfield Reservoir dam station. Based on the available observed DO data this was considered as a conservative estimate for this analysis. This depth corresponds to an elevation of 5402 ft msl. The bottom surface area below 5402 ft msl was then derived from the bathymetry data. To determine this bottom surface area, the GIS was used to compute a 3-D surface area. The bottom surface area estimated from the bathymetry in the GIS (i.e., surface area below the elevation 5402 ft msl) was 325 acres.

In this analysis it was assumed that increasing the reservoir volume can lead to an increased anaerobic hypolimnetic volume and that the reservoir depth is sufficient for thermal stratification to be maintained throughout the summer. It was assumed that the anaerobic depth would increase by the same amount as the increase in pool elevation (12 ft). The resulting anaerobic bottom surface area after the proposed 12 ft increase in pool elevation was estimated from the bathymetry to be 880 acres (i.e., based on an increase in the hypolimnetic depth from 5402 to 5414 ft msl). This is an approximately 170 percent increase in anaerobic surface area from the baseline condition to the proposed pool condition.

The actual change in hypolimnetic depth can only be rigorously evaluated with a hydrodynamic model. To account for this uncertainty, anaerobic depths other than the conservative, 12 ft increase in the anaerobic depth were also evaluated to provide a range of conditions.

3.2.2. Estimating Nutrient Loads

Sources of loading to the Chatfield Reservoir were estimated to evaluate each of the scenarios mentioned in the previous section. Nutrient loads for orthophosphorus and ammonia nitrogen were estimated from anaerobic and aerobic internal loading from the reservoir bottom, loading from inundated sediment and vegetation, watershed loading, and due to atmospheric deposition. Each of these sources is discussed in the following sections.

3.2.2.1. Loading from Reservoir Bottom Sediments

Estimates of orthophosphorus and ammonia loading during anoxic/hypoxic (anaerobic conditions) and aerobic conditions were computed. Fluxes of these nutrients were calculated from the anaerobic zone using observed data. Observed nutrient data at the bottom of the reservoir at the "Chatfield In-Reservoir Near Dam" station were available and were used in this analysis. Because 2004 exhibited the worst conditions in terms of DO during the critical summer condition and had a fairly good coverage of monitoring data all throughout the year, data from this year were used to estimate the nutrient fluxes in the anaerobic zone. Using observed data reduces uncertainty and increases confidence because site-specific nutrient fluxes are calculated.

Sediment nutrient fluxes and sediment oxygen demand (SOD) were computed based on a sediment flux model developed by Di Toro (Chapra and Pelletier, 2003; Di Toro et al., 1991; Di Toro, 2001). The approach allows oxygen and nutrient sediment-water fluxes to be computed based on the downward flux of particulate organic matter from the overlying water. The sediments are divided into 2 layers: a thin ($\cong$ 1 mm) surface aerobic layer underlain by a thicker (10 cm) lower anaerobic layer (default values specified in the model). Organic carbon, nitrogen and phosphorus are delivered to the anaerobic sediments via the settling of particulate organic matter (i.e., phytoplankton and detritus). There they are transformed by mineralization reactions into dissolved methane, ammonium and inorganic phosphorus. These constituents are then transported to the aerobic layer where some of the methane and ammonium are oxidized. Oxidation reactions in the model become zero at low oxygen levels and denitrification becomes pronounced at low oxygen concentrations. The flux of oxygen from the water required for these oxidation reactions is the SOD predicted by the model.

The sediment flux model computes sediment nutrient fluxes using specified fluxes for carbon (C), nitrogen (N), and phosphorus (P) (J_{Cin}, J_{Nin}, and J_{Pin}, respectively) and overlying nutrient, DO and temperature concentrations in the water column. The model computes the SOD based on the input fluxes, and the resulting fluxes are calculated using the product of the concentration gradient between the sediment and the overlying water column and the mass transfer coefficient between water and the anaerobic sediments. The sediment flux model is a spreadsheet model and has the same algorithms (Di Toro, 2001) as the Qual2K model. For more details about the algorithms the reader is referred to Di Toro, 2001 and the Qual2K manual (Chapra and Pelletier, 2003).

The particulate carbon flux into the sediments (J_{Cin} $gO_2/m^2/d$) from settling organic carbon, includes phytoplankton and detritus in oxygen equivalent units, and was computed using the observed TOC (Total Organic Carbon) data collected at the bottom layer of the reservoir ($gO_2/m^2/d$ L = $gC/m^2/d$ * 2.67 gO_2/gC*0.1 m/day *0.8). It was assumed that 80 percent of the TOC is particulate, and the other 20 percent is the fast-reacting dissolved organic carbon and $CBOD_u$ (Carbonaceous Biochemical Oxygen Demand ultimate). The fluxes J_{Nin}, and J_{Pin} were estimated based on stoichiometry using a redfield ratio (molecular ratio of carbon, nitrogen and phosphorus in phytoplankton) of

C:N and C:P of 5.68 and 41.1, respectively (Di. Toro, 2001). Other inputs specified for the water overlying the sediment were the DO, temperature, ammonia N, nitrate N, and soluble reactive P. The model also requires input of the total water depth overlying the sediment to compute the in-situ pressure when calculating the methane saturation concentration. The input data along with the computed nutrient fluxes using the Sedflux model in the anaerobic zone of the reservoir are given below in Table 3-6. Note that the DO was set at the summer time low DO concentration of 1.45 mg/L along with varying observed nutrient fluxes and nutrient concentrations. During the summer period nitrification is usually limited to almost close to zero at the bottom due to low DO conditions. Since the analysis focused on the critical summer period, high DO values would lead to more nitrification and hence lead to lower of ammonia nitrogen fluxes (and higher nitrate fluxes) during the summer low DO period. Hence a constant low DO value along with varying observed particulate nutrient fluxes and nutrient values were used to determine a range of possible nutrient fluxes.

The range of nutrient fluxes and the median value presented in Table 3-6 come from the variability in the monitoring data in 2004. A nutrient flux value was estimated for each day a measurement of water quality was recorded at the bottom of the reservoir near the "Chatfield In-Reservoir Near Dam" station. Then the minimum, maximum and median of the estimated flux values were estimated. Positive values indicate a source of the nutrient to the water column. Negative values indicate a transfer of nutrients to the sediment. The PO_4 and NH_4 fluxes range from 0.0062 to 0.0129 and 0.0445 and 0.0972 g/m2/d respectively. Median flux values were used in this study. The SOD in the Chatfield reservoir ranges from 0.84 to 1.47 $gO_2/m^2/d$. The computed nitrate fluxes for the reservoir was minimal and assumed to be a net sink (negative) into the sediment.

Table 3-6. Required Input Data to the SedFlux Model and Computed Nutrient Flux Output.

INPUT									
Date	Particulate carbon flux (Jcin) (gO2/m^2/d)	Particulate nitrogen flux (Jnin) (gN/m^2/d)	Particulate phosphorus flux (Jpin) (gP/m^2/d)	Dissolved oxygen in water overlying the sediment (O20) (mgO2/L)	Temperature in water overlying the sediment (Tw) (deg C)	Ammonia N in water overlying the sediment (NH30) (mgN/L)	Nitrate N in water overlying the sediment (NO30) (mgN/L)	Soluble reactive P in water overlying the sediment (PO40) (mgP/L)	Dissolved Organic Carbon in the water overlying the sediment (CH40) (mgO2/L)
1/27/2004	0.854	0.056	0.008	1.45	3.30	0.60	0.150	0.004	2.136
2/10/2004	1.068	0.070	0.010	1.45	3.40	0.60	0.150	0.004	2.670
3/24/2004	1.282	0.085	0.012	1.45	7.60	0.60	0.150	0.004	3.204
4/27/2004	0.854	0.056	0.008	1.45	11.30	0.60	0.150	0.004	2.136
5/11/2004	1.709	0.113	0.016	1.45	11.20	0.60	0.150	0.004	4.272
8/24/2004	0.833	0.055	0.008	1.45	18.00	0.60	0.150	0.032	2.083
9/30/2004	1.068	0.070	0.010	1.45	15.30	0.60	0.150	0.007	2.670
10/25/2004	1.068	0.070	0.010	1.45	11.60	0.60	0.150	0.007	2.670
11/22/2004	1.068	0.070	0.010	1.45	5.80	0.60	0.150	0.003	2.670
12/17/2004	1.068	0.070	0.010	1.45	2.80	0.60	0.150	0.003	2.670
	OUTPUT								

Date	SOD (gO2/m^2/d)	Jnh4 (gN/m^2/d)	Jno3 (gN/m^2/d)	Jpo4 (gP/m^2/d)
1/27/2004	0.841	0.046	0.000	0.006
2/10/2004	0.973	0.058	-0.001	0.008
3/24/2004	1.167	0.072	-0.001	0.010
4/27/2004	0.955	0.047	0.000	0.006
5/11/2004	1.469	0.097	-0.001	0.013
8/24/2004	1.042	0.045	0.000	0.006
9/30/2004	1.182	0.060	0.000	0.008
10/25/2004	1.113	0.060	-0.001	0.008
11/22/2004	1.013	0.059	-0.001	0.008
12/17/2004	0.964	0.058	-0.001	0.008
Min	**0.84**	**0.0445**	**-0.0007**	**0.0062**
Max	**1.47**	**0.0972**	**0.0002**	**0.0129**
Median	**1.03**	**0.0586**	**-0.0005**	**0.0078**

The flux from the aerobic zone, though small in comparison to the anaerobic zone (Thomann and Mueller, 1997), was also estimated. A flux of 0.0015 gP/m^2/day was used for orthophosphorus. Nitrogen (ammonia) flux from the aerobic zone was assumed to be 0.005 gN/m^2/day. Note that these values are considerably lower than those calculated for the anaerobic zone.

The nutrient fluxes for each zone were multiplied by corresponding reservoir bottom surface areas to compute the amount of nutrients released from the sediment. Table 3-7 shows the load for each nutrient from the anaerobic zone based on different anaerobic depth conditions. The aerobic load of orthophosphorus was computed to be 7.36 lb/day.

$$\text{Mass of nutrients released per day (lb / day)} = A_c \cdot J \cdot cf \qquad [7]$$

where:

A_c is the area of the interface between the two sides, i.e., the reservoir bottom surface area assumed to be anoxic (m^2)

J = nutrient flux (g/m^2/day)

Cf = conversion factor for g to lbs (2.204/1000)

Table 3-7. Mass of Nutrients Released Per Day from the Bottom Sediments in the Anaerobic Zone.

	BASE1	**Maximum Impact Case (12 ft proposed maximum increase)**	**Typical Impact Case (9.3 ft increase, based on summer average data)**
Orthophosphorus (PO4) (lb/day)			
Minimum	17.94	48.58	40.93

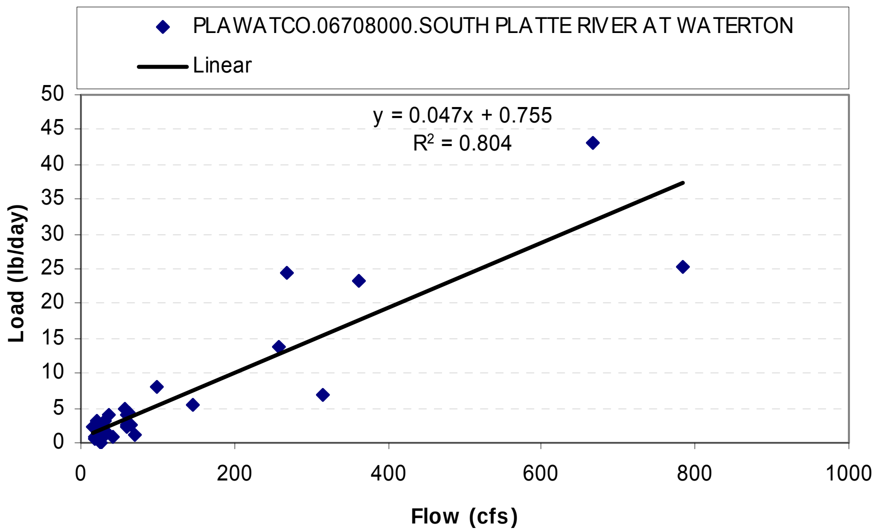
	BASE1	Maximum Impact Case (12 ft proposed maximum increase)	Typical Impact Case (9.3 ft increase, based on summer average data)
Maximum	37.34	101.10	85.17
Median	23.17	62.74	52.86
Ammonia N (NH4) (lb/day)			
Minimum	128.94	349.15	294.17
Maximum	281.56	762.40	642.33
Median	169.76	459.68	387.29

3.2.2.2. Loading from Inundated Sediment and Vegetation

Soballe (2006) from the ERDC Environmental Laboratory provided estimates of the magnitude of internal phosphorus loading from the inundated vegetation and soil/sediments due to the increase in pool elevation of Chatfield Reservoir. The report concludes that combining the vegetation and sediment releases results in an annual total increase in phosphorus (assumed to be orthophosphorus) up to 8,000 lbs (3,000 lbs from vegetation plus 5,000 lbs from inundated soil) (Soballe, 2006). The estimates were for an estimated inundated area of 230 ha (568 acres) flooded for 197 days. Since no information on a likely range of values at Chatfield is currently available, this value (8,000 lbs) was used in the analysis as a conservative assumption. This value can be refined if actual vegetation and soil data from the areas to be inundated are collected in the future.

3.2.2.3. Watershed Loading

Watershed nutrient loads were estimated from the observed nutrient data from Plum Creek and the South Platte River. Monthly observation data from both streams were available for the year 2004. These monthly nutrient data were used to compute an instantaneous load and then regressed with instantaneous flow. R^2 values ranged from 0.611 to 0.924 and were deemed acceptable for the gross load nature of the calculations. The resulting relationship was used to generate a time-series of loading using daily flow data. Flow time series from the USGS station 06709530 – Plum Creek at Titan Road and South Platte River at Waterton 0670800 (from the Colorado Division of Water Resources) were then used to compute a loading time-series based on the relationships developed for flow and load. The total annual watershed load (Plum Creek and South Platte) for orthophosphorus and ammonia was computed to be 2,832 lbs and 7,480 lbs, respectively. The relationships between phosphorus and ammonia loading and instantaneous flow are shown in Figures 3-11 and 3-12, respectively.



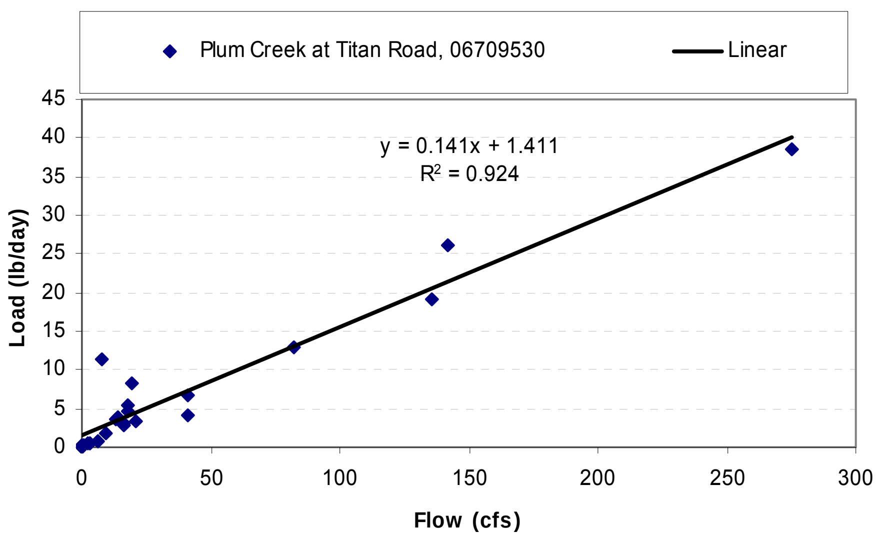
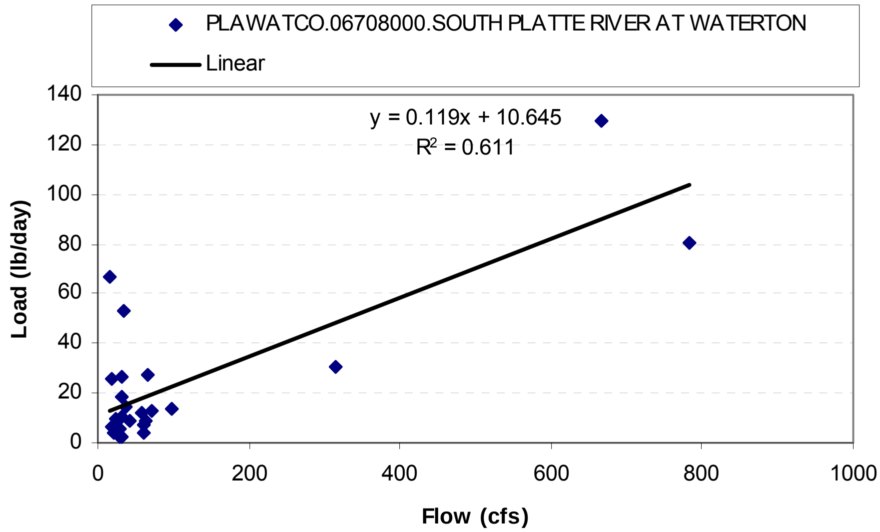


Figure 3-11. Orthophosphorus (PO4) Load vs. Flow Relationship for 2004.



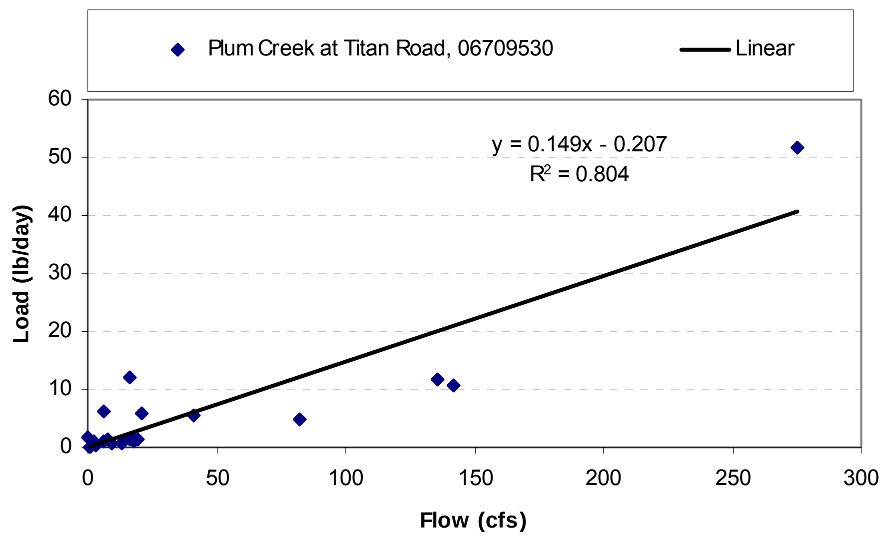


Figure 3-12. Ammonia nitrogen (NH3-N) Load vs. Flow Relationship for 2004.

3.2.2.4. Atmospheric Deposition

Loading due to atmospheric deposition was also considered. The National Atmospheric Deposition (NADP) network was queried for nitrogen and phosphorus deposition rates for stations in the vicinity of the Chatfield Reservoir. The closest station, Manitou Springs, is located in Teller County, Colorado. This station reported an annual wet deposition rate of 1.44 kg/ha for NH4. No PO4 observations were available from any of the NADP network stations in Colorado. There are no good records of atmospherically deposited P, because soluble PO4 is rarely above detection limits (NADP, 1999), and total P is not measured (Baron et al., 2000). For this analysis PO4 from atmospheric deposition was assumed to be zero, however if site-specific data become available they could be incorporated into the analysis. The atmospheric deposition for ammonia was multiplied by the reservoir surface area for baseline and the proposed 5444 ft msl pool elevation to compute a loading.

3.3. Nutrient Mass Balance Analysis

This section presents the estimated nutrient loads and presents nutrient concentrations for each scenario.

3.3.1. Nutrient Load Summary

After estimating the source loads, the loads were compared for existing conditions and the proposed reallocation. Figure 3-13 shows the orthophosphorus and ammonia loading from all sources feeding into the reservoir for the baseline and proposed conditions (typical case). The typical case condition is presented merely for information purposes to show the relative magnitude of loading coming from different sources. The analysis was conducted for all the scenarios shown under Table 3-5. Note the ranges shown in the figures are based on the minimum, maximum and median fluxes shown in Table 3-6.

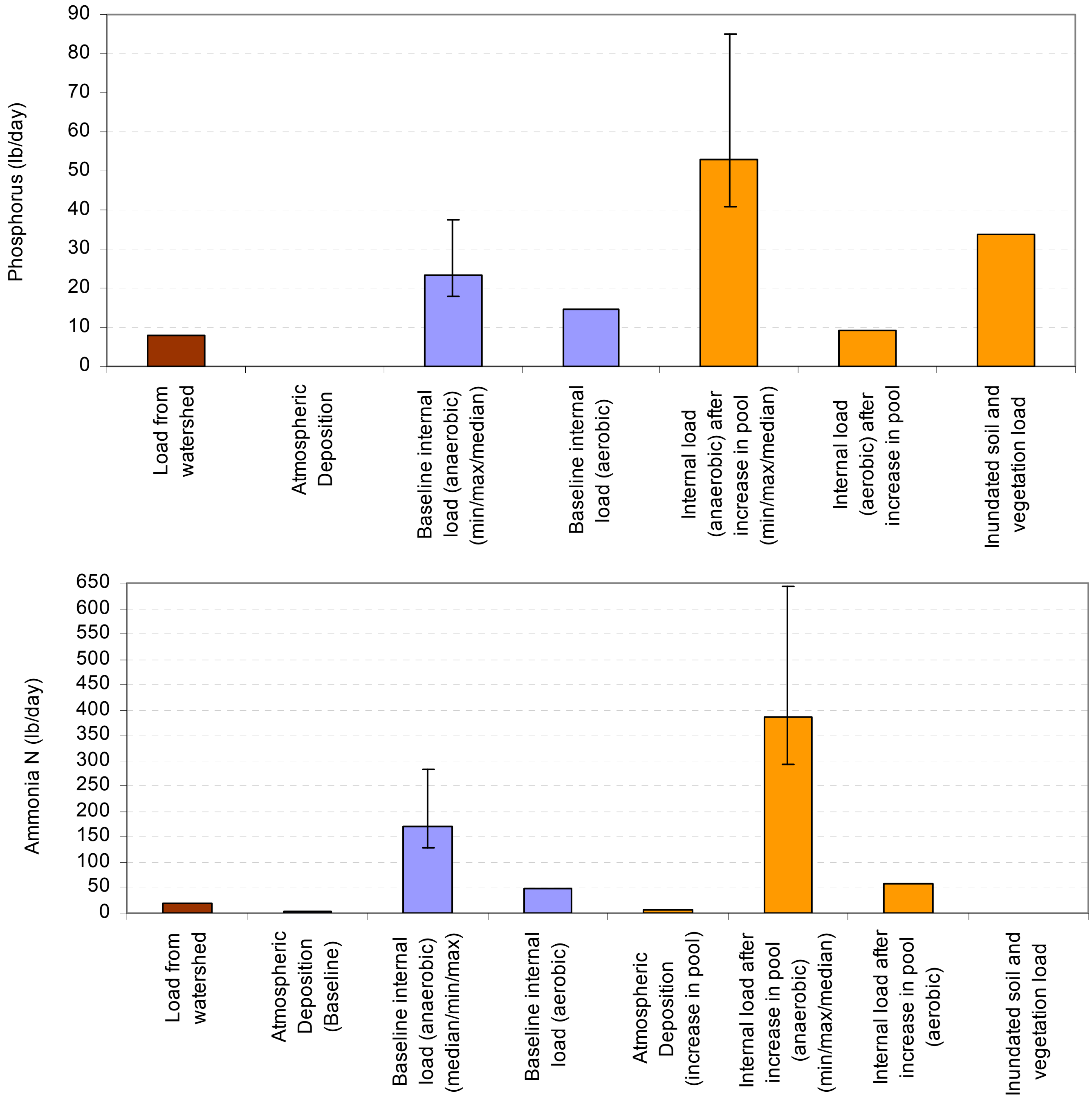


Figure 3-13. Orthophosphorus and Ammonia N Loading from Different Sources Feeding into the Reservoir baseline and proposed conditions (Typical Case).

Figure 3-14 shows loads computed for the different increases in anaerobic depth (refer to Table 3-5 for scenario descriptions). The internal loading presented for the anaerobic zone is based on median computed fluxes. Note that with a decrease in anaerobic depth the phosphorus loading decreases considerably. These depth increase scenarios show the sensitivity to the loading for the anaerobic depth used in the analysis. Since the aerobic depth decreases with an increase in anaerobic depth, there is a corresponding decrease in internal load from aerobic areas. Note that no short term analysis was done for ammonia nitrogen since it was assumed that the newly inundated areas with a net sink for nitrogen. For ammonia nitrogen, aerobic release was assumed to extend to the inundated areas and was addressed in the long-term analysis.

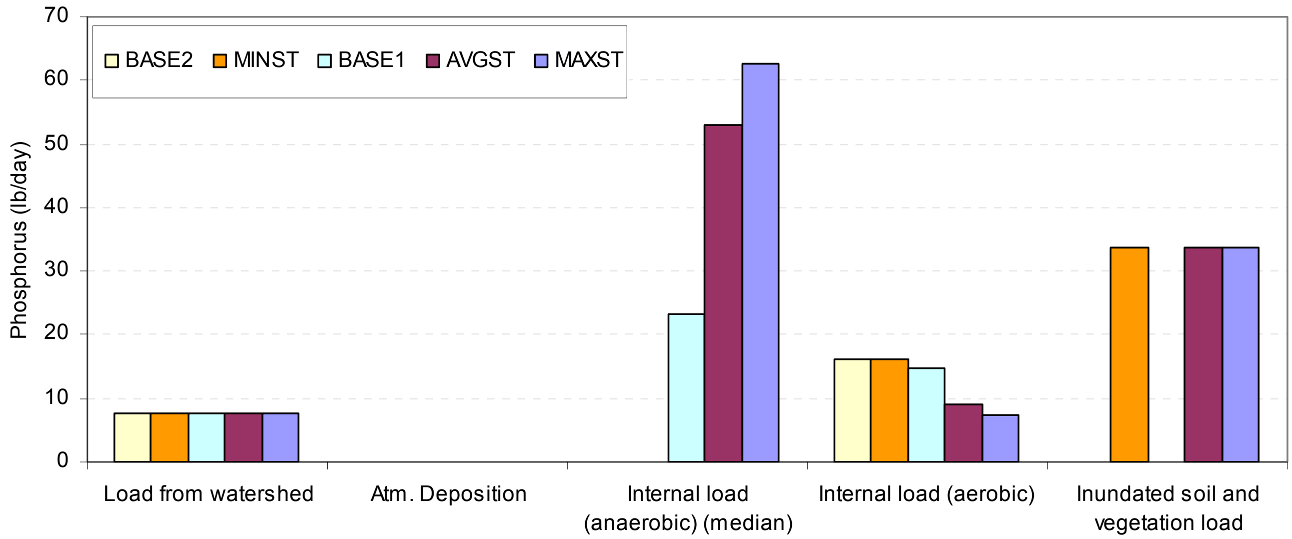
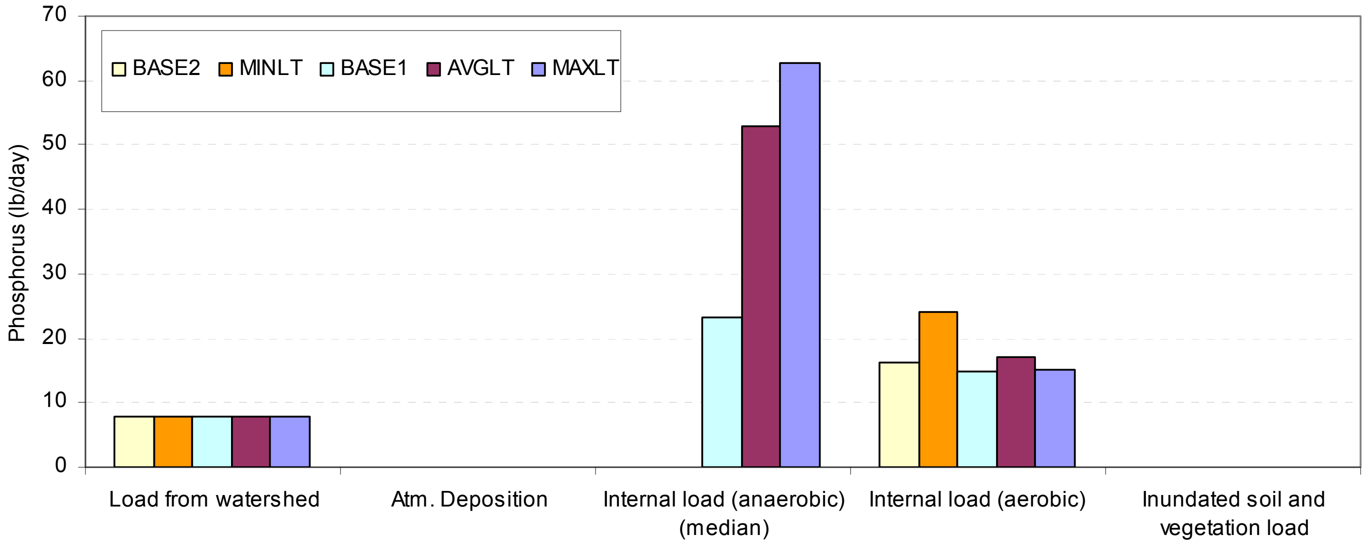


Figure 3-14. Phosphorus Loading for Different Increase in Depth Conditions.

As the phosphorus contributions due to the inundated vegetation and soil subside over time, it is expected that aerobic conditions would ultimately apply to the inundated zone. Therefore, a scenario without the contribution of the vegetation and soil was also evaluated. This is likely more representative of long-term conditions in the reservoir. For this scenario, the aerobic release was assumed to extend into the inundated areas. Figure 3-15 shows the phosphorus and ammonia loading for the no vegetation contribution case. As can be seen from the figure (and as compared to Figure 3-14), the aerobic load increases after the increase in pool elevation and the vegetation contribution becomes zero.



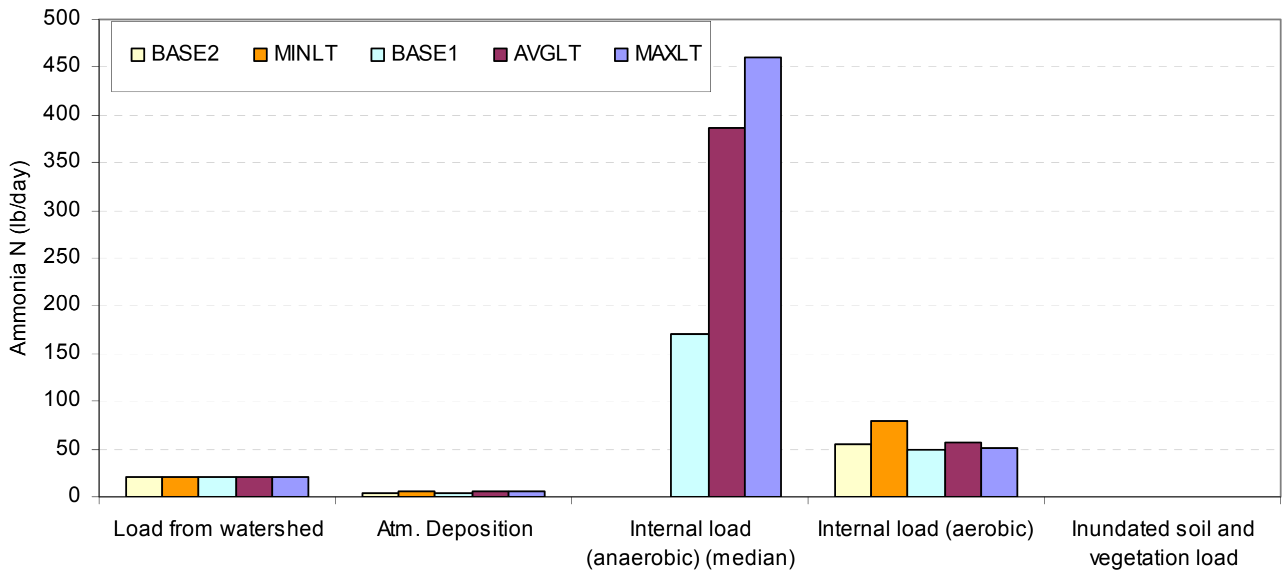


Figure 3-15. Phosphorus and Ammonia N Loading (no contribution from vegetation case).

3.3.2. Nutrient Concentration Estimation

A simple mass balance calculation was made to estimate a gross average reservoir concentration for all scenarios. This gross concentration assumes a completely-mixed reservoir, at a steady-state condition, even though the calculations focus on the critical summer period exhibiting stratification. It essentially represents conditions at the onset of the reservoir's de-stratification or fall turnover.

To determine the gross reservoir concentration, the following steady-state equation was used (Chapra, 1997):

$$c = \frac{\sum W}{(Q + K_s \cdot V)} \qquad [8]$$

where:
c = steady state nutrient concentration
$\sum$ W = sum of all the loading into the system,
Q = outflow during the summer critical period. Data from 1942 to 2000 (provided by USACE, 2006) were used to estimate the outflow during the critical summer period (June, July and August). The mean outflow was computed to be 439 cfs and 434 cfs for the baseline and proposed conditions respectively. Note the outflow decreased slightly for the proposed conditions, which would mean less flushing.
K_s = overall loss rate of the nutrient (Chapra, 1997).
V = reservoir volume. Baseline volume is 27,428 ac-ft (at 5432 ft msl), proposed maximum volume (12 ft increase) is 48,066 ac-ft (at 5444 ft msl), and 42,729 ac-ft (at 5441.3 ft msl) for the 9.3 ft increase from baseline typical case scenario.

The resulting phosphorus and ammonia concentrations are shown below in Table 3-8. Table 3-8 provides a range of estimated steady-state concentrations due to varying loading conditions in the reservoir for the summer. Note that the anaerobic internal load is based on the median anaerobic nutrient flux that was estimated.

Table 3-8. Orthophosphorus (PO4) and Ammonia-N (NH3-N) Concentrations for Baseline and Increased Depth Conditions.

Scenario	**Description**	**Orthophosphorus (µg/L)**	**Ammonia-N (mg/L)**
BASELINE – Normal Pool			
BASE1	Assumes 1-meter hypolimnion	14.4	0.077
BASE2	Assumes no hypolimnion	7.5	0.020
MAXIMUM CASE – Assumes 12 ft increase (maximum proposed pool) in hypolimnetic depth from BASE1			
MAXST	Considers contribution of phosphorus from inundated soil and vegetation (short-term impact)	29.6	—
MAXLT	Considers no nitrogen nor phosphorus contribution from inundated soil and	22.8	0.143

Scenario	Description	Orthophosphorus (µg/L)	Ammonia-N (mg/L)
	vegetation (long-term impact)		
TYPICAL CASE – Assumes 9.3 ft increase (typical summer pool under proposed condition) in hypolimnetic depth from BASE1			
AVGST	Considers contribution of phosphorus from inundated soil and vegetation (short-term impact)	28.7	—
AVGLT	Considers no nitrogen nor phosphorus contribution from inundated soil and vegetation (long-term impact)	21.5	0.131
MINIMUM CASE – Assumes 12 ft increase in the normal pool, but no hypolimnion present (i.e., 12 ft increase from BASE2, with only aerobic release)			
MINST	Considers contribution of phosphorus from inundated soil and vegetation (short-term impact)	15.3	—
MINLT	Considers no nitrogen nor phosphorus contribution from inundated soil and vegetation (long-term impact)	8.4	0.028

The observed orthophosphorus ranged from 9 to 32 µg/L, and observed ammonia ranged from 0.057 to 0.11 mg/L during 2004. Note that the estimated baseline concentrations (BASE1) are within the range of those observed in the reservoir. BASE2 is a hypothetical baseline with no hypolimnion. This was used to put the minimum impact case (MINST and MINLT) condition results in perspective. In general, the amount of increased loading to the reservoir is not offset by the increase in volume (dilution effect). This results in an increase in concentration in the reservoir compared to the baseline condition. The anaerobic depth has a significant impact on the concentration.
The short term cases (MAXST, AVGST, and MINST) also contribute significantly, though this is expected to have an impact in the near-term (most of the phosphorus release is expected to occur in the first year after inundation (Soballe, 2006)) as opposed to the long-term. It can be seen that the long-term "no contribution from inundated soil and vegetation case" (MAXLT, AVGLT, and MINLT) result in a lower concentration in phosphorus (by almost 7 µg/L) compared to the with the soil and vegetation (short-term) case. Thus, a range of scenarios representing different anaerobic depths were evaluated.

A sensitivity analysis was done to evaluate the response due to varying outflow rates. However, it should be noted that the steady state assumption of outflow equals inflow is not valid and this is purely hypothetical. The typical case and minimum case were used to illustrate the sensitivity of the system to varying outflow. Four cases were evaluated for each of these two cases to evaluate the sensitivity of orthophosphorus (short term and long term): the outflow rates were increased by 50 percent, decreased by 50 percent, increased by 60 percent, and increased by 100 percent. The estimated concentrations decreased for the cases where the outflows were increased and the concentrations increased for the case where the outflow was decreased (Table 3-9).

Table 3-9. Outflow Sensitivity Analysis

Scenario	Proposed	50% Decrease in Outflow from Baseline	50% Increase in Outflow from Baseline	60% Increase in Outflow from Baseline	100% Increase in Outflow from Baseline
Outflow (cfs)	434	220	659	702	878
AVGST (orthophosphorus µg/L)	28.7	42.3	21.5	20.4	17.3
AVGLT (orthophosphorus µg/L)	21.5	31.7	16.1	15.3	12.9
MINST (orthophosphorus µg/L)	15.3	22.1	11.6	11.1	9.4
MINLT (orthophosphorus µg/L)	8.4	12.2	6.4	6.1	5.2

Note: Baseline Condition for orthophosphorus was calculated to be 14.4 µg/L (BASE1) and 7.5 µg/L (BASE2)
Baseline outflow = 439 cfs

The above sensitivity analysis shows the impact of the outflow when all other parameters, (e.g., volume and overall loading) are held constant. In reality the volume would potentially also change when the outflows are varied. Varying the outflow (i.e., managing the outflow) can help arrive at approximately similar concentrations as the baseline case when compared to the long-term case (e.g., 60 percent increase in outflow results in a concentration of 15.3 µg/L for AVGLT and 6.1 µg/L for MINLT). However, this is not possible since equation [8] is based on a steady state assumption (inflow equals outflow), when increasing the outflow the inflow and the corresponding loading would also change. This is a purely hypothetical estimation and not necessarily feasible from an operational point of view and just shows the sensitivity due to outflow. Only a more detailed analysis using a hydrodynamic model could fully predict the effects of managing the outflows. More practical than running a costly model is to use adaptive management to address this uncertainty should the proposed Chatfield Reallocation Project be implemented. Closely monitored changes in inflows and outflows from Chatfield Reservoir could be used to manage flushing and the HRT of the reservoir, with the goal of reducing potential impacts to water quality.

Thomman and Mueller, 1987 suggests that the trophic status of a lake can be defined as: oligotrophic (clear low productivity lake) if the TP (Total Phosphorus) is <10 µg/L, mesotrophic (intermediate productivity lake) if the TP is between 10 to 20 µg/L and eutrophic (high productivity lake relative to a basic natural level) if the TP is >20 µg/L. The trophic status values reported in literature are based on long-term averages of lakes based on data.

The values presented in Table 3-8 are instantaneous maximums for worst-case summer conditions that can be expected in the reservoir, however the trophic status value classifications are normally based on a longer-term average of monitoring data. The mean observed TP concentration for the entire year of 2004 was approximately 31 µg/L suggesting that the reservoir was tending to be eutrophic. The mean was based on forty six observations taken throughout the depth of the reservoir at the Chatfield In-Reservoir near Dam site. If the PO4 concentrations in Table 3-8 (estimated instantaneous maximum values) are converted to TP concentrations, based on the ratio of PO4 to TP (PO4/TP = 0.416) derived from monitoring data for Chatfield Reservoir, the baseline and proposed conditions both suggest that the reservoir to be eutrophic, with estimated instantaneous maximum TP concentration ranging from 35 µg/L at the baseline (BASE1) to 71 µg/L for the maximum case (MAXST).

3.4. Recent Phosphorus and Chlorophyll Water Quality Trends

This section presents phosphorus and chlorophyll-a monitoring data collected since the models presented in this technical report were completed. These data, collected in 2008, 2009, and 2010, were obtained from the Chatfield Watershed Authority (Chatfield Watershed Authority, 2008, 2009, 2011a).

In 2008, the total phosphorus standard and chlorophyll goal were attained, and the phosphorus TMAL was met. The growing season (June through September) total phosphorus concentration of 19 µg/L was less than the 27 µg/L reservoir standard and the chlorophyll-a concentration of 4.9 µg/L was much less than the 17 µg/L goal to meet beneficial uses. The TMAL was met at 14,566 pounds with 117,631 acre feet (ac-ft) of flow.

The following year, Control Regulation No. 73 changed substantially, as discussed in the introductory section of this report. In 2009, the growing season (July through September) phosphorus concentration of 18.3 µg/L was less than the 30 µg/L reservoir standard. The TMAL was met at 11,049 pounds with 135,032 acre feet (ac-ft) of flow. The growing season chlorophyll-a concentration of 13.1 µg/L exceeded both the new 10 µg/L standard and the 11.2 µg/L attainment threshold, an increase from prior years. However, the one-in-five year exceedance criterion was attained.

Preliminary 2010 data include a phosphorus outlier of 1,100 µg/L from September 9, 2010. Including that value results in an average growing season phosphorus concentration of 198.2 µg/L. Excluding the outlier, the average appears to meet the phosphorus standard (Chatfield Watershed Authority 2011b). The growing season average chlorophyll-a concentration of 26.3 µg/L exceeds the standard. In meeting notes from November 16, 2010, the Chatfield Watershed Authority suggests the possibility that a regional environmental issue may be affecting Chatfield Reservoir, noting that three nearby reservoirs recently have exceeded their phosphorus and chlorophyll-a standards. The Chatfield Watershed Authority is considering increasing 2011 sampling to weekly during the growing season and is planning to conduct a limnological study to better identify indicators and metrics to understand the reservoir water quality dynamics.

The models in this technical report are based on phosphorus data collected from 1986 to 2007. As described in Regulation No. 38, typical summertime concentrations of phosphorus in Chatfield Reservoir have been about 0.020 mg/L, with no trend for increasing concentrations. Summer median concentrations have exceeded 0.030 mg/L in only 3 of 24 years. Typical summer average chlorophyll-a is about 6 μg/L, with no trend for increasing concentrations. Concentrations vary from year to year, but have exceeded 10 μg/l only 5 times in 24 years, and only twice since 1990. Despite the increase in chlorophyll-a during 2010, more recent data (October 2010 through January 2011) appear to fall within the historical range of variability of the 1986-2007 data modeled in this technical report.

4. Metals Analysis

The potential for metals to be mobilized under anoxic conditions was assessed for the baseline and proposed conditions. The concern with metals mobilization is the development of anoxic conditions under summer thermal lake stratification. The mobilization and bioavailability of metals is a complex process and can be influenced by changes in pH, redox conditions, and organic complexation (Shipley, 2004). In anoxic sediments, sulfides are often believed to be the major solid phase regulating the mobility and bioavailability of metals (USEPA, 2000a; Shipley, 2004; Goossens and Zwolsman, 1996). This analysis does not simulate any of the complex interactions in the sediments but uses the flux of metals to estimate the loadings. For this analysis the following metals of concern were selected based on available sediment data – Copper (Cu), Lead (Pb), Mercury (Hg), Cadmium (Cd), Selenium (Se), and Arsenic (As).

Based on a literature review, it was found that fluxes of sediment-based metals to and from the water column exhibit a wide range of variability. They are dependent on the environmental setting of the waterbody and the type of the waterbody, vary by orders of magnitude, and can be both positive and negative (from and to the sediment). Of interest in this study are their characteristics under both anaerobic and aerobic conditions. Unfortunately, the literature reviewed was not definitive in identifying anaerobic versus aerobic flux rates.

For this analysis, it was assumed that flux rates are the same between the anaerobic and aerobic zones. Hence, evaluation of multiple scenarios for the anaerobic hypolimnion was not performed as was done in the nutrients analysis. The diffusive metal flux was calculated based on observed metals data from the sediment and water column and evaluated for the baseline and increase in pool conditions (maximum case of 12 ft and typical case of 9.3 ft). The estimation of the metal fluxes may be updated in the future as additional literature is identified or sediment core sampling is conducted to estimate site-specific metal fluxes.

4.1. Estimation of Metals Flux from Sediment

For this study, observed metals data in the sediment and water column were used to estimate the diffusive flux of the metals. This method affords a way to quantify the internal loading using observed data for the relative comparison of the metals' internal loading at normal pool elevation and after the proposed elevation increase. It was assumed that the computed diffusive fluxes apply to the entire reservoir surface area (both aerobic and anaerobic zones). The exchange of metals between interstitial pore-water and overlying water was determined using Fick's first law. This method calculates the flux of an element by molecular diffusion. The model is defined as follows:

$$J_z = -D\left(\frac{dc}{dz}\right) \qquad [9]$$

where J_z is the mass flux in the z direction, D is the molecular diffusion coefficient for the element in the sediment, and dc/dz is the concentration gradient of the element across the sediment-water interface (Chapra, 1997; Naes et al., 2001; Balistrieri, 1995). Equation 9 can be used to determine the mass of metal released per day and is written as follows:

$$A_c \cdot J_z = A_c \cdot v_d \cdot (c_2 - c_1) \qquad [10]$$

where:
c_2 is the metal concentration in the pore water of the sediment; c_1 is the observed concentration of the metal in the water overlying the sediment; A_c is the area of the interface between the two sides, i.e., the reservoir bottom surface area; and v_d is called a diffusion mass-transfer coefficient (D/z) and can be estimated from the empirically derived formula (Di Toro et al., 1981 as cited in Thomann and Mueller, 1987; Chapra, 1997):

$$v_d = 69.35 \cdot \phi \cdot M^{-2/3} \qquad [11]$$

v_d has units of m/yr, M = molecular weight of the compound, and ϕ is the sediment porosity (assumed to be 0.9).

The pore-water concentration of the metal in the sediment (c_2) in equation [10] was calculated using the observed sediment associated concentration (υ) and the sediment partition coefficient for the particular metal (K_d). This is given as follows (Chapra, 1997):

$$c_2 = \upsilon / K_d \qquad [12]$$

For the metals of concern, sediment data were collected for Cu, Hg, Pb, Cd, Se, and As. Therefore, these were the only metals evaluated. One value of sediment-associated metals fraction (mg/kg) was measured for each year from 1999 to the current year (n = 6). Arsenic was the only exception, and it had data starting in 2001. For this analysis a median value for each metal was estimated and used. Table 4-1 shows observed concentrations of the metals sorbed to the sediment for each year and the median metals concentration. The sediment associated metals were measured during the month of August for each year.

Table 4-1 Concentration of Metal on Sediment in the Chatfield In-Reservoir Near Dam Station

Year	Total Copper mg/kg)	Total Mercury mg/kg)	Total Lead mg/kg)	Total Cadmium (mg/kg)	Total Selenium (mg/kg)	Total Arsenic (mg/kg)
1999	25.00	0.06	30.00	0.50	2.00	
2000	11.00	0.02	12.00	0.25	0.80	
2001	14.90	0.02	22.00	0.50	0.77	2.00
2002	14.90	0.05	22.00	1.00	3.10	79.00
2003	33.60	0.08	42.40	0.82	2.25	8.95
2004	27.20	0	36.20	0.99	2.00	4.30

Year	Total Copper mg/kg)	Total Mercury mg/kg)	Total Lead mg/kg)	Total Cadmium (mg/kg)	Total Selenium (mg/kg)	Total Arsenic (mg/kg)
Median	**19.95**	**0.04**	**26.00**	**0.66**	**2.00**	**6.63**

(Source: Chatfield Watershed Report, 2004)

The K_d values for each metal were determined from the literature (Allison et al., 2005). Allison et al. provides mean, minimum and maximum values of K_d for soil/soil water collected from various literature sources with a relative confidence flag for the K_d value for each metal. Table 4-2 shows all the observed data, coefficients and intermediate calculation values leading to the computation of the mass of metal released per day for normal pool elevation and the proposed 12 ft maximum and 9.3 ft mean increase in depth. It should be noted that the 12 ft increase is the maximum possible case but occurs infrequently (approximately 18 percent of the time based on daily data from 1942 to 2000) and that the mean case of 9.3 ft is the most likely typical condition that may occur under summer conditions.

Table 4-2. Calculations for the Mass of Metals Released Per Day:

Calculation	Cu	Hg	Pb	Cd	Se	As
Total Sediment Concentration *v* (mg/kg)	19.95	0.04	26.00	0.66	2.00	6.63
Dissolved Concentration (mg/L) *c1*	0.0027	0.00016	0.0011	0.0001	0.00000	0.0008
Molecular Weights	63.546	200.59	207.2	112.41	78.96	74.9216
Diffusion Mass-transfer Coefficient *vd* (m/yr)	4.20	1.82	1.78	2.68	3.39	3.51
Mean Values from Literature - Partition Coefficient [logKd] (L/kg)	2.70	2.30	4.10	3.25	5.70	3.50
Kd (L/kg)	501	200	12589	1778	501187	3162
Dissolved Metal Concentration (mg/L) *c2=v/kd*	0.040	0.00020	0.002	0.000	0.00000	0.002
Estimated Metal Flux Using Fick's First Law ($\mu g/cm^2/yr$)	15.60	0.008	0.172	0.073	0.001	0.442
At Conservation Pool Elevation (5432 ft)						
Mass of Metal Released per Day (lb/day) = *vd.Ac.(c2-c1)*	5.44	0.0027	0.060	0.025	0.0005	0.154
At 9.3ft increase (5441.3 ft)						
Mass of Metal Released per Day (lb/day) = *vd.Ac.(c2-c1)*	7.13	0.0035	0.079	0.033	0.0006	0.202
At 12ft increase (5444 ft)						
Mass of Metal Released per Day (lb/day) = *vd.Ac.(c2-c1)*	7.65	0.0038	0.084	0.036	0.0007	0.217

It can be seen from Table 4-2 that the estimated flux values are positive i.e., there is a positive flux or net source to the water column.

4.2. Metals Source Comparison and Concentration Estimation

Watershed loads for Cu, Hg, Pb, Cd, Se, and As were estimated from the observed 2004 metals data from Plum Creek and South Platte (Chatfield Watershed Report, 2004). Of the monthly data collected, no metals concentration was observed for Plum Creek, however observed data from South Platte showed the presence of metals during certain sampling events.

A flow-weighted approach was used to estimate the loads from the watershed, since the regression between instantaneous load and flow did not show a good relationship for any of the metals as it did for nutrients. A flow-weighted concentration was computed for each observed value and the resulting concentration was multiplied by the average summer flow for 2004 to obtain a load. The relative contribution of the watershed loads, along with the internal loads for the two pool level conditions, are shown below in Table 4-3.

Table 4-3. Metal Loading from Different Sources.

Loading Condition	Cu (lb/day)	Hg (lb/day)	Pb (lb/day)	Cd (lb/day)	Se (lb/day)	As (lb/day)
Watershed Loading	16.0	2.0	0.4	0.04	0.00	0.24
Internal Loading Normal Pool Elevation (5432 ft)	5.44	0.003	0.060	0.025	0.000	0.154
Internal Loading After 9.3 ft increase (5441.3 ft)	7.13	0.0035	0.079	0.033	0.0006	0.202
Internal Loading After 12 ft increase (5444 ft)	7.65	0.0038	0.084	0.036	0.0007	0.217

A simple mass balance calculation was also made to provide a relative comparison between overall reservoir impact for the current and proposed conditions. A gross average reservoir concentration was thus calculated based on only the watershed and internal sources. As for the nutrient calculation, this gross concentration assumes a completely-mixed reservoir, at steady-state, even though the calculations focus on the critical summer period exhibiting stratification. These values should only be used for relative comparison purposes as they only represent the diffusive fluxes from the sediment and do not represent detailed processes, such as the pH condition, redox conditions, organic complexation and complex metal speciation dynamics in the sediment.

To estimate the gross reservoir concentration, the following steady-state equation was used (Chapra 1997):

$$c = \frac{\sum W}{(Q + K_s \cdot V)} \quad [13]$$

where:
c = steady state metal concentration
$\sum$ W = sum of all the loading into the system (sum of the estimated watershed load and the internal load),
Q = outflow during the summer critical period. Data from 1942 to 2000 (provided by USACE) were used to estimate the outflow during the critical summer period (June, July and August). The outflow was computed to be 439 cfs and 434 cfs for the baseline and proposed conditions. Note the outflow decreases for the proposed conditions, which would mean less flushing.
K_s = overall loss rate of the metal
V = reservoir volume. A baseline volume of 27,428 ac-ft at an elevation of 5432 ft msl;, and proposed volumes of 48,066 ac-ft at an elevation of 5444 ft (12 ft increase from baseline) and 42,729 ac-ft at an elevation of 5441.3 ft msl (9.3 ft increase from baseline).

The resulting estimates of metals concentrations are shown in Table 4-4. In general, the increase in volume is expected to provide sufficient dilution to offset the decreased outflow and amount of increased loading from the newly inundated areas. This results in an estimated decrease in metals concentrations in the reservoir for the increase in pool elevations.

Table 4-4. Estimated Steady State Metals Concentrations.

Scenario	Cu	Hg	Pb	Cd	Se	As
Assessed Water Quality Standard (in ug/L) based on a hardness value of 111 mg/L (Chatfield Watershed Authority 2005).	15.3	1.4	75	4.96	18.4	50
Range of Observed Data (µg/L)	0–10	0–0.9	0–2	0–0.1	0	0–1.7
Estimated Concentration at Conservation Pool (µg/L)	6.75	0.63	0.15	0.022	0.0005	0.123
Estimated Concentration (9.3 ft increase in Pool) (µg/L)	6.42	0.55	0.14	0.021	0.0004	0.121
Estimated Concentration (12 ft increase in Pool) (µg/L)	6.29	0.53	0.13	0.021	0.0004	0.120

Table 4-4 shows the estimated steady-state metal concentrations. None of the metals exceeded the water quality standards in the baseline and proposed condition. Hg is estimated to have the greatest percent decrease followed by Pb, Cu, Se, Cd, and As. The small increase in loading is offset by the increase in volume and results in a decrease in steady-state metal concentrations in the proposed alternative. It should be noted that this analysis only considers the diffusive flux due to the observed concentration gradient between the water and the sediment. It is possible that the metal concentrations might be higher in the hypolimnion due to the increased seasonal stratification and changes in the site-specific chemistry due to the increase in volume (resulting in increased stratification) for the proposed condition, resulting in greater internal loading due to release of metals. Site-specific metal release rates or a more detailed model would be necessary to confirm this hypothesis. In addition the partition coefficients used in the analysis are based on mean values from literature and are also subject to uncertainty. Literature shows a wide range in the partition coefficients for the metals (Allison, 2005). The partition coefficient of a metal has the effect of increasing or decreasing the pore-water concentration of the metal in the sediment (c_2) (equation [12]). Based on sensitivity analysis (increasing and decreasing the partition coefficient by 1 L/Kg), a lower partition coefficient value could result in higher dissolved metal concentration from the sediment and potentially result in an increase in the estimated concentration for some metals. This is mainly due to an increased internal loading that would be predicted due to the higher dissolved metal concentration from the sediment. However, sensitivity analysis of the partition coefficients showed that the water quality standard (based on the specified hardness of 111 mg/L) would not be exceeded in any of the scenarios.

5. Bacteria Analysis

The water quality workgroup for the Chatfield project noted that if increasing the water surface elevation in Chatfield Reservoir increased the littoral area of the reservoir, it could attract more birds (e.g., waterfowl, shorebirds) to the lake and its shoreline areas. Increased usage by birds would result in a net increase in bacteria loading. The primary concern with this potential increase in bacteria loading is that conditions at the Chatfield swim beach could be detrimentally affected. Conversely, if the proposed recreation modifications do not increase the littoral area of the reservoir near the swim beach, then more birds would not be expected in this area and impacts to bacteria would not be anticipated.

The Chatfield State Park routinely monitors the swimming beach for E-coli bacteria during the swimming season from Memorial Day weekend through Labor Day weekend. The maximum observed E-coli concentrations at the swim beach based on data from the 2004 and 2005 swimming seasons ranged from 14 to 446 counts/100mL (Table 5-1) (Colorado State Parks, 2006a).

Table 5-1. Monthly Maximum Observed E-coli concentration (2004 to 2005) from the North and South sampling locations at the Chatfield Swim Beach (Source: Colorado State Parks, 2006a).

Month	North Station (Counts/100 mL)	South Station (Count/100 mL)
May	164	70
June	104	168
July	446	394
August	106	194
September	52	14

Based on stream classification and water quality standards for the Upper South Platte River, an E-coli concentration of 126 counts/100mL and a fecal coliform concentration of 200 counts/100mL have been set as targets for Chatfield Reservoir. In general, all months except September had maximum E-coli concentrations greater than 126 counts/100mL.

Under the proposed condition, the swim beach and nearby areas would be modified as described in the FR/EIS Appendix M. To meet the goal of replacing affected facilities and use areas "in-kind", the relocation plan is based on maintaining current walking distances at the swim beach. Under this conceptual design, the beach area would be graded to minimize the distance between swim beach facilities and the water's edge at low water conditions. As a result, the configuration of the shoreline near the beach area and the overall dimensions of the swim beach would be similar to current conditions. Given this proposed modification to the swim beach, changes in E. coli concentrations are not expected under the proposed condition.

6. Assumptions and Limitations

The following section provides the major assumptions and limitations that were used in the analysis of the different pollutants. These assumptions and limitations were considered and documented during model development as part of the process of evaluating the predicted water quality impacts under each alternative. Where possible, conservative, worst-case assumptions were modeled to avoid underestimating any potential detrimental impacts to water quality.

- The load quantification process and concentration predictions do not consider the complex interactions among evaluated parameters and those not explicitly considered. It is a gross quantification of impacts. Even with this limitation, the model does a fair job in matching the mean observed data. This model, like any other simple model, cannot be used to predict short-term (e.g., monthly or daily) lake response to inputs, spatial patterns (e.g., localized response) in nutrient concentration, or dynamic response (e.g., changes over time) to changes in nutrient inputs.
- The HRT results are annualized and do not take into account the short term variations in HRT that can be expected due to changes in volume and outflow conditions.
- None of the analyses take into account transport.
- For this study, the watershed outflow/operations were assumed to remain the same for both the normal pool and increase in pool elevation condition.
- South Platte and Plum Creek, which are the dominant inflows to the reservoir, were assumed to contribute the entire watershed loading to the reservoir.
- It was assumed that 2004, which was a dry year and exhibited low DO levels, provided the worst-case conditions for the reservoir.
- It was assumed that increasing the lake volume would lead to an increased hypolimnetic volume by the same amount (i.e., 12 ft and 9.3 ft), and that the lake depth is sufficient for thermal stratification to be maintained throughout the summer.
- The anaerobic layer elevation was determined by using a cutoff value of <2.0 mg/L based on observed data at the Chatfield Reservoir dam location.
- In determining the sediment flux, the TOC was assumed to be 80 percent particulate and 20 percent fast reacting dissolved. The nitrogen and phosphorus were derived based on the red-fields ratio.
- The nutrient mass balance assumes a steady-state, completely-mixed condition for the worst case loadings that would occur during the summer stratified period. This was done to estimate a worst-case concentration based on the quantified sources for varying levels of hypolimnion.
- For the metals analysis diffusive fluxes were assumed to apply, and the flux rates were assumed to be same between the anaerobic and aerobic zones.
- The vegetation/plants were assumed to not contribute ammonia-N in the inundated areas. It is assumed that the total nitrogen release from these areas would not likely alter the role of phosphorus as the primary limiting nutrient in the reservoir. For ammonia-N, aerobic release was assumed to extend to the inundated areas.

- Diffusive fluxes were computed to estimate the amount of metals contributed by the reservoir sediment. Changes in the aquatic conditions and exposing the anoxic sediment to an oxic environment can cause sulfide to be re-oxidized and metals to be released. These diffusive fluxes do not represent the processes such as the overlying pH conditions, redox conditions, organic complexation, bioturbidation and complex metal speciation dynamics in the sediment. In order to predict a more accurate metals flux, additional sediment core sampling is required.
- The EUTROMOD model algorithms allow prediction of lake-wide, growing season (June-September) average conditions in a lake, as a function of annual nutrient input or loading. Hence, short-term trophic state (e.g., weekly or monthly concentrations) and dynamic response (e.g., continuous changes in trophic state over time) cannot be predicted with this model.

7. Summary

The potential water quality impacts due to the proposed reallocation of flood control storage from 5432 ft msl to 5444 ft msl in Chatfield Reservoir, Littleton, Colorado were evaluated using a number of spreadsheet-based techniques. Gross water quality impacts were assessed for nutrients, metals, and bacteria. The load quantification process and concentration predictions do not consider the complex interactions among evaluated parameters and those not explicitly considered. This limitation was considered during model development as part of the process of evaluating the predicted water quality impacts under each alternative. Where possible, conservative, worst-case assumptions were modeled to avoid underestimating any potential detrimental impacts to water quality.

Two types of nutrient analysis were conducted for the baseline and proposed project conditions – first a simple but conservative analysis (using the EUTROMOD model) was conducted to evaluate historical TP loadings and estimate TP, chlorophyll-a, secchi depth, and Carlson's Trophic State Index; and a second more detailed localized analysis was conducted to address the uncertainty regarding possible increases in anaerobic and inundated vegetation nutrient fluxes due to orthophosphorus and ammonia.

The EUTROMOD model predicts lake eutrophication response based on a set of regional statistical models. This analysis focused on estimating mean concentrations across the entire reservoir for several years. Historical incoming total phosphorus loadings along with the corresponding hydraulic residence time and change in volume for the baseline and reservoir storage reallocation condition were used to predict reservoir eutrophication potential and chlorophyll-a to evaluate possible occurrence and magnitude of water quality impacts to the Chatfield Reservoir.

Under the proposed reallocation, the EUTROMOD model predicted an overall decrease in concentration for all estimated parameters (except secchi depth which increased) from the baseline condition. This is expected since for the proposed condition the hydraulic residence time and mean depth are higher than the baseline, and the influent TP was set to be the same as the baseline, thus resulting in a greater loss from the system (the internal loading being inferred from the model algorithms based on relationships derived from regional lakes). Chlorophyll-a concentrations were also estimated. Proposed condition results indicate a minimal change (slight decrease) in chlorophyll-a concentrations from the baseline. In addition the model results indicate a very small change in the trophic state index. The TSI estimates indicate that the reservoir would remain in the mesotrophic to eutrophic range tending towards the lower bounds of the eutrophic range (approximately 47 to 53).

A sensitivity analysis of the hydraulic residence time was also conducted by increasing and decreasing the baseline hydraulic residence time (including the reservoir depth) by 50 percent. The results indicate that the key eutrophication parameters are sensitive to the hydraulic residence time. An increase in residence time results in a corresponding decrease in concentration and vice versa. This illustrates that by proper management of the volumes and outflow (i.e., the hydraulic residence time) for the reservoir the desired goals can be reasonably achieved.

An additional nutrient analysis was conducted to address the shortcomings of the simplistic analysis. This analysis assumed that increased depth and reduced outflow under increased storage promoted stronger summer thermal stratification and results in possible anoxic conditions in the hypolimnion that would increase internal phosphorus loading from bottom sediments. Nutrient loads for orthophosphorus (PO_4) and ammonia nitrogen (NH_3-N) from the watershed, atmospheric deposition, inundated soil and vegetation (for PO_4 only) and internal load were evaluated for baseline and a series of hypothetical scenarios. The internal loading from the reservoir was estimated based on the increase in anaerobic hypolimnetic depth and sediment nutrient fluxes. Several scenarios were evaluated – a minimum impact case condition which includes no hypolimnetic depth, a typical condition which includes an increase in hypolimnetic depth based on mean summer increase in depth of 9.3 ft (estimated from the modeled baseline and the proposed increase water surface elevation data (USACE, 2006)), and a maximum impact condition which includes a 12 ft increase in hypolimnetic depth based on the proposed increase in pool. A complete list of scenarios can be found in Section 3 under Table 3-5. The 12 ft increase in anaerobic hypolimnetic depth condition provides an upper bound for the concentrations that can be expected, while the 9.3 ft scenario provides an average typical summer condition case.

Sediment nutrient fluxes were estimated using a sediment flux model (SedFlux) developed by Di Toro (Chapra and Pelletier, 2003; Di Toro et al., 1991; Di Toro, 2001). Since the amount of increase in the hypolimnetic depth for the proposed conditions is unknown, for the internal load analysis it was assumed that increasing the lake volume would lead to an increased anaerobic hypolimnetic volume by the same amount (i.e., 12 ft and 9.3 ft). This conservative assumption was made because the actual change in hypolimnetic depth can only be rigorously evaluated with a hydrodynamic model.

The steady-state nutrient concentrations in the reservoir for the critical summer period indicated that it is likely that the reservoir might experience an increase in PO_4 and NH_3-N concentrations from the baseline to the maximum possible increase condition (Table 3-5). For the instantaneous maximum condition case the estimated PO_4 concentrations increased from 14.4 µg/L to 22.8 µg/L, while the NH_3-N concentrations increased from 0.08 mg/L to 0.14 mg/L. Nutrient concentrations for the typical and minimum case condition were also evaluated. When compared to the typical case the PO_4 concentrations increased from 14.4 µg/L to 21.5 µg/L for PO_4 and 0.08 mg/L to 0.13 mg/L for NH_3-N. The minimum case condition showed that there would be a very marginal increase in concentrations (7.5 µg/L to 8.4 µg/L), with a possible decrease in concentration in orthophosphorus when evaluating the long term effects compared to the baseline condition which included the effects due to a 1 meter hypolimnetic depth at normal pool.

Increasing the outflow in the proposed condition can improve the nutrient concentration. However, this is a purely hypothetical condition based on the same volume arrived at based on sensitivity analysis and the operation of which probably cannot be implemented due to the steady state assumption of the model used. The anaerobic depth has a significant impact on this concentration and may alter water quality in the reservoir for several years. An increase in concentration occurs irrespective of whether the contribution due to the internal loading from the hypolimnetic depth is considered or if no contribution from the hypolimnion is considered, i.e., in the minimum case condition when aerobic fluxes dominate (although the increase is minimal in the latter case). The contribution of PO_4 from inundated vegetation and soil also has an impact in the near-term, however this is expected to decrease substantially with time.

The nutrient analysis showed that there is uncertainty in the data available and the models used. Although the proposed project may actually improve water quality conditions (as modeled using EUTROMOD), the simplistic analysis has limitations and uncertainty when applied to a localized situation (i.e., Chatfield Reservoir). In the EUTROMOD model the internal loading is inferred from the algorithms based on relationships derived from regionalized lakes. The more detailed second analysis, based on "Chatfield-derived" loading models, provides further insight into the possible water quality impacts of the proposed project. The detailed analysis shows that there may be uncertainty regarding internal loading from increased anaerobic conditions due to increases in reservoir pool levels and inundated vegetation.

Adaptive management could address this uncertainty should the proposed Chatfield Reallocation Project be implemented. In addition it is suggested that water quality monitoring be conducted on an on-going basis to identify any water quality impacts and evaluate their level of significance. Potential adaptive management measures that could be implemented to "mitigate" problems potentially caused by increased internal nutrient loading include:

- Removing terrestrial vegetation prior to inundation.
- "Aeration/mixing" of Chatfield reservoir to limit stratification and development of anaerobic conditions. Similar to measures recently installed at other local Corps reservoirs (i.e., Cherry Creek Reservoir and Bear Creek Reservoir).
- Altered management of inflows and outflows from Chatfield Reservoirs to manage flushing and the Hydraulic Residence Time of the reservoir.

Metal loads for Cu, Pb Hg, Cd, Se and As from the watershed and internal load were also evaluated. Diffusive fluxes were computed to estimate the amount of metals contributed by the reservoir sediment to the water column. These diffusive fluxes do not represent all processes such as the overlying pH conditions, redox conditions, organic complexation, bioturbidation and complex metal speciation dynamics in the sediment. In order to predict a more accurate metals flux, additional flux measurements from sediment core sampling is required.

The metals steady-state analysis under the worst-case loading condition in the reservoir resulted in an estimated decrease in metals concentrations in the reservoir for the proposed pool condition. The increase in volume provides sufficient dilution to offset the decreased outflow and amount of increased loading from the newly inundated areas. The analysis showed that the estimated concentrations of Cu, Hg, Pb, Cd, Se and As decreased from the baseline condition to the 12 ft and 9.3 ft increase in pool depth conditions. For the proposed condition, Hg had the greatest reduction in concentration, followed by Pb, Cu, Se, Cd, and As (Table 4-4). It should be noted that there is a level of uncertainty associated with these predictions. The estimated concentrations are estimates based on diffusive fluxes and could change if additional sediment core sampling is performed to more precisely estimate the site-specific sediment metal fluxes. An additional area of uncertainty can possibly occur due to the wide range of partition coefficients observed in the literature. However, results indicate that in all scenarios the concentrations never exceeded the metals' standard and were within the range of observed data.

The potential for increased bird (e.g., waterfowl, shorebirds) populations in the vicinity of the swim beach was evaluated to assess potential impacts on bacteria concentrations. The analysis focused on the shallow volume of water near the swim beach. Impacts due to an increased hypolimnetic volume were assumed to be negligible. To meet the goal of replacing affected facilities and use areas "in-kind" under the proposed condition, the configuration of the shoreline near the beach area and the overall dimensions of the swim beach would be similar to current conditions. Given this proposed modification to the swim beach, changes in E. coli concentrations are not expected.

Finally for all the parameters of concern the reservoir water quality can potentially be enhanced for given loadings, by timely managing water in storage and flushing times through the reservoir (residence time). Adaptive management could be used to test reasonable changes in reservoir operations to mitigate any water quality concerns that may arise through the increased storage of water in Chatfield Reservoir.

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