BIG BEAR LAKE ANALYSIS: REPLENISH BIG BEAR

FINAL REPORT

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EXECUTIVE SUMMARY

Big Bear Lake is an important natural resource that provides extensive recreational, economic, ecological, and aesthetic benefits for the local community as well as the larger inland Southern California region. As with all other natural and man-made lakes in Southern California, the lake is subject to dramatic variability in water surface elevation; surface elevations reached as low as -48.5 feet (ft) relative to dam crest (72.33 ft maximum depth) in November 1961, corresponding to a volume of less than 1,000 acre-feet (af) and a lake surface area on the order of 200-300 acres during the extended drought in the late 1950's and early 1960's. Big Bear Municipal Water District (BBMWD) was subsequently formed in 1964 to manage and help stabilize the water level in Big Bear Lake. The region's natural hydrology includes severe protracted droughts and is influenced by the Pacific Decadal Oscillation (PDO) and El Nino-La Nina climate systems, which makes lake level stabilization a tremendous challenge. This wide variability in lake level, in turn, can have significant impacts on beneficial uses of the lake. Monitoring data collected primarily by the Big Bear City Community Services District (BBCCSD), BBMWD, and the Big Bear Lake Nutrient Total Maximum Daily Load (TMDL) group over the past decade underscore both the variability in regional hydrology and lake levels, and the consequences of extended periods of low runoff on water quality conditions. To minimize the impacts of frequent droughts, Replenish Big Bear was developed to recover and use a water resource currently discharged outside of the watershed.

This study assessed the overall conditions, ecological health and water quality in Big Bear Lake, and evaluated the potential influence on lake health of Replenish Big Bear. Three treatment alternative strategies (Treatment Alternatives), composed of advanced nutrient removal and reverse osmosis (RO) technologies, were evaluated:

(i) Alternative 1: TIN & TP Removal
(ii) Alternative 2: 70% RO (in addition to TIN & TP Removal)
(iii) Alternative 3: 100% RO (in addition to TIN & TP Removal)

This study included an analysis of available water quality data, development of a 2-D hydrodynamic-water quality model (CE-QUAL-W2), and application of the model to evaluate lake conditions with Replenish Big Bear that focused on the period from 2009-2019. This period was selected based upon a number of factors, including the wide range of hydrologic and water quality conditions in the lake, and availability of extensive lake monitoring and meteorological data, as well as some watershed monitoring data. Model simulations from 2020-2050 were also conducted to assess possible future conditions in Big Bear Lake under different hydrologic scenarios and Replenish Big Bear discharge alternatives. The routing of Replenish Big Bear water through Stanfield Marsh was also explored in greater detail to provide better understanding of the possible role of the marsh in nutrient attenuation.

Analysis of Water Quality Data

To augment the water quality information provided in the TMDL annual reports, additional conventional statistical and advanced machine learning analyses were conducted. Analyses focused on chlorophyll-a as the key response variable. The ratio of total nitrogen (total N) to total phosphorus (total P), often used to identify nutrient limitation, confirm P-limitation principally in place regulating algal production. Correlations developed between total P, total N, total inorganic N (TIN) and chlorophyll-a for each of the 4 TMDL sampling stations (n=150 for each station) indicate relatively weak correlations with nutrient concentrations (e.g., R^2-values of 0.08, 0.19, 0.21 and 0.31 between chlorophyll-a and total P for TMDL stations #1, 2, 6 and 9, respectively). R^2 values quantify the variance in dependent variable (chlorophyll-a) captured with the independent variable (e.g. total P), so it is clear that phytoplankton levels are a more complex function of conditions in the lake. Slightly higher R^2 values were in fact noted with total N (R^2=0.22-0.53), while chlorophyll-a was uncorrelated with TIN. Concentration of chlorophyll-a was also relatively weakly correlated with TDS and lake level; multiple linear regression (MLR) using all these variables yielded R^2-values of 0.31-0.55 depending upon TMDL sampling station.

Since significant portions of variance in observed chlorophyll-a concentrations remained uncaptured using MLR, machine learning was also evaluated. Machine learning, which is starting to be used in water quality applications, is often able to more effectively elucidate trends in complex datasets. Random forest and gradient-boosted regressor algorithms applied to TMDL station #1 data using day of year, lake level, TDS concentration and windspeed were able to capture most (0.92-0.96) of the observed variance in chlorophyll-a for the 10-yr 2009-2018 training set, notably without considering concentrations of total N or total P. For comparison, MLR using this same set of independent variables captured 0.43 of variance in observed chlorophyll-a concentrations. The gradient-boosted regressor model also demonstrated strong forecasting power, capturing 0.73 of variance in predicted chlorophyll-a concentrations of the 2019 data set (compared with 0.36 for the equivalent MLR model). Statistical analyses highlighted that multiple factors regulate chlorophyll-a concentrations in complex ways; machine learning was able to identify relationships and develop regressor models that reproduced and forecasted concentrations of chlorophyll-a with considerable accuracy.

Water column profile data were also used to quantify rates of internal nutrient recycling and areal hypolimnetic oxygen demand (AHOD). Internal nutrient recycling rates have been measured on a limited number of dates since 2002 using the laboratory core-flux method, while AHOD has not previously been measured at the lake. The *in situ* hypolimnetic mass balance approach using measured water column concentrations of ammonium as N (NH_4-N) and orthophosphate as P (PO_4-P) yielded recycling rates for 2010-2011 and 2015-2017 that were similar to previously measured values confirming the importance of nutrient recycling in lake biogeochemistry and nutrient budgets, and establishing the reliability of alum treatments in suppressing PO_4-P release. The analysis also yielded *in situ* estimates of early summer AHOD rates at TMDL station #1 of approximately 0.5 $g/m^2/d$.

Development of 2-D Hydrodynamic-Water Quality Model

A 2-D (longitudinal-vertical) hydrodynamic -water quality model for Big Bear Lake was developed using CE-QUAL-W2. The model quantifies heat and water budgets, 2-D hydrodynamics, and predicts concentrations of nutrients, dissolved oxygen (DO), chlorophyll-a and other parameters. The 2-D (longitudinal-vertical) representation assumes the primary gradients in water column properties and water quality are in the vertical and longitudinal directions, and well-mixed in the lateral direction; model branches were added for embayments that allow a quasi-3-D representation of the lake. The model requires extensive bathymetric, hydrologic, meteorological, water quality, and other data. The 2-D laterally-averaged model grid was developed from the bathymetric survey data collected by Fugro Pelagos Inc. (2006). Hydrologic data defining inflows, outflows, and withdrawals were developed from annual Big Bear Water Master reports. Hourly meteorological conditions were taken from Big Bear Airport and California Irrigation Management Information System (CIMIS) Station #199 located at the golf course. Data included solar shortwave radiation, air temperature, dewpoint temperature, windspeed, wind direction and cloud cover. Cloud cover was determined from sky cover conditions reported in METAR data for the airport. The model was calibrated against measured lake level, *in situ* profiles of temperature and DO, and laboratory analyses of water samples collected at the lake for 2009-2019. The model was first developed and calibrated for lake level, water column temperature profiles and TDS, where generally very good agreement was achieved (mean absolute errors of 3.6 cm, 0.79-0.89 °C, and 11.9 mg/L, respectively).

Following this, model calibration to water quality data was conducted. The model included external nutrient loading from the watershed, atmospheric deposition, internal nutrient recycling, and nutrient uptake and release associated with macrophyte and epiphyton growth, senescence and death. Two algal groups were simulated, included one representing cyanobacteria capable of N_2-fixation. The 1st-order dynamic sediment model was combined with the 0th-order SOD model to simulate nutrient recycling and DO uptake in the surficial bottom sediments. Relative root mean square error was 17.7% for total P, 18.0% for total N, 29.5% for TIN, and 24.0 % for chlorophyll-a. Mean absolute errors for DO ranged from 1.02 – 1.40 mg/L for the 4 TMDL sampling stations.

Application of Model to Evaluate Conditions with Replenish Big Bear

The model was then used to predict conditions in Big Bear Lake from 2009-2019 that would reasonably be expected with water from Replenish Big Bear delivered to the lake. Supplementation of natural flows with 1,920 af/yr of Replenish Big Bear water adds about 0.2 meter (m) annually to the lake relative to levels observed in 2009-2019 (baseline), and which accrues over time such that the lake was predicted to be 1.7 m higher in late 2018 compared to the level present at that time. Supplementation also increased predicted lake volumes and surface areas, with lake area about 300 acres (16%) larger in late 2018 compared with actual area (approximately 2,200 acres vs 1,900 acres, respectively). TDS levels in the lake were strongly influenced by level of treatment and TDS concentrations in the Replenish Big Bear water; Alternative 1 water with TIN and total P removal was projected to have a TDS of 450 mg/L, while addition of RO to further treat 70% and 100% of the water (Alternatives 2 and 3) was assumed to reduce effluent TDS to 150 and 50 mg/L, respectively. Addition of 1,920 af/yr of Alternative 1 water significantly increased TDS levels in the lake, increasing average predicted TDS from 251 mg/L for the baseline (natural) condition for 2009-2019 to 300 mg/L, while Alternatives 2 and 3 were predicted to yield lower average TDS concentrations of 244 and 226 mg/L, respectively. Exceedance of the TDS water quality objective of 175 mg/L was predicted to occur 97.6% of the time for both the baseline condition and for Alternative 2, while exceedance frequency increased to 100% for Alternative 1 and was reduced to 93.3% for Alternative 3.

Nutrient concentrations in the Replenish Big Bear water also varied markedly with treatment, with total N and total P concentrations in Alternative 1 effluent being about 6-9 times higher than median watershed concentrations, while effluent concentrations in Alternative 2 were projected to be 1.8-2.3 times larger and Alternative 3 being about 0.4-0.8 times that of median watershed values. The increased nutrient loading from Alternative 1 had a strongly detrimental effect on water quality, increasing average concentrations over 2009-2019 baseline of total N by about 50%, total P by 70%, and chlorophyll-a by 300%. In comparison, further treatment of effluent with RO yielded average concentrations comparable to (Alternative 2) or slightly improved (Alternative 3) relative to the baseline (natural no-project) condition.

Predicted Long-Term Future Conditions with Replenish Big Bear

Simulations for 2009-2019 were extended to 2050 to evaluate possible long-term conditions in the lake under natural hydrologic variability with and without supplemental water from Replenish Big Bear. Since detailed meteorological and hydrological conditions for the future are not known *a priori*, existing meteorological and flow data for 2009-2019 were used as the basis for forecasts. 2009-2019 included extreme ranges in rainfall, runoff and air temperatures; assuming this range is broadly representative of likely future meteorological and hydrologic conditions, Monte Carlo techniques were used to randomly select 100 different 30 year annual records from this set of data. From these 100 different hydrologic scenarios, the 5th-, 50th- and 95th-percentile 30 year average annual flow records and corresponding meteorological conditions were used as temporal boundary conditions for predictions of future conditions in the lake. The 5th-percentile corresponds to an average inflow rate of 8,646 af/yr and represents extended drought, while the 50th-percentile (median) corresponds to intervals of high runoff and drought (average annual inflow of 10,595 af/yr) comparable to 2009-2019, and the 95th-percentile represents a period of protracted above average rainfall and runoff (average annual inflow of 12,225 af/yr). (Note that since precipitation and runoff are log-normally distributed, the above arithmetic mean values understate the range in runoff within the simulation intervals; that is, a single high runoff year can significantly skew upward average values during a period of protracted drought.)

Supplementation with Replenish Big Bear was also predicted to increase average long-term (2009-2050) conditions in the lake that varied under the 3 hydrologic scenarios. Under the 50th-percentile hydrologic scenario, Replenish Big Bear was predicted to increase average lake level by 1.5 m, lake volume by nearly 13,000 af, and lake area by 260 acres relative to the predicted long-term baseline (no-project) condition. Water quality varied with level of treatment, with Alternative 1 nearly doubling predicted long-term average concentrations of TDS, total P and total N and quadrupling average predicted chlorophyll-a levels. Long-term simulations indicate slight increases in average TDS, total P and total N and modest increase in chlorophyll-a for Alternative 2, and generally slight reductions or no significant change in concentrations with Alternative 3. Supplementation was predicted to have more substantial effects under the 5th-percentile runoff scenario, with increased average lake level of 3.4 m, increased volume of 16,104 af, and an additional average 638 surface acres (about 40% increase) relative to baseline. As with the median runoff scenario, supplementation with Alternative 1 effluent substantially degraded water quality, while further treatment (Alternatives 2 and 3) was predicted to result in comparable or slightly improved water quality in the lake. Effects of Replenish Big Bear were more muted at the 95th-percentile runoff scenario, when supplementation is less important, owing to the lower overall contributions of water and TDS and nutrients relative to the watershed.

Routing of Supplemental Water Through Stanfield Marsh

Simulations with Replenish Big Bear involved routing of effluent through Stanfield Marsh, where some nutrient uptake could be expected. Simulations indicate net removal of total P through the Marsh with Alternative 1 and Alternative 2 effluent, while simulations predicted that the Marsh would be a modest source of total P to Alternative 3 water with very low influent concentrations. Interestingly, the Marsh was predicted to be a source of total N across all levels of treatment, due to sediment decay, and some N_2-fixation and subsequent decay in response high PO_4-P concentrations and high TN:TP ratios in the effluent. Further work is needed, however, to better understand the role of the Marsh as a net sink and/or source for nutrients.

Summary

Lake conditions and water quality in Big Bear Lake varied significantly over 2009-2019, with wide variations in lake level, volume and surface area, as well as concentrations of TDS, nutrients and chlorophyll-a. Statistical, machine learning and hypolimnetic mass balance analyses provided valuable new information about water quality in Big Bear Lake, while CE-QUAL-W2 was able to reproduce observed trends in lake conditions. Supplementation of natural runoff with Replenish Big Bear water significantly increased lake levels, volumes and surface areas, especially during periods of drought, with resulting recreational, aesthetic, community and related benefits. The level of treatment had dramatic effects on water quality, however. Nutrient removal (Alternative 1) was not sufficient to protect water quality, although nutrient removal with further treatment (Alternatives 2 and 3) was predicted to yield water quality comparable to or slightly improved relative to baseline conditions.

I. INTRODUCTION AND STUDY OBJECTIVES

The Replenish Big Bear Team, a collaborative regional water resources program being implemented by Big Bear Area Regional Wastewater Agency (BBARWA), Big Bear City Community Services District (BBCCSD), Big Bear Lake Department of Water and Power (BBLDWP), Big Bear Municipal Water District (BBMWD) and the Bear Valley Basin Groundwater Sustainability Agency (BVBGSA), engaged Professor Emeritus Michael A. Anderson (Dr. Anderson), who has in-depth knowledge of the Big Bear Lake (Lake), to evaluate the Lake water quality conditions and assess the potential impacts of the Replenish Big Bear project. This study was prepared in response to the Santa Ana Regional Water Quality Control Board (Santa Ana Water Board) staff's need to have a better understanding of the Lake's health to consider approving a discharge above current Basin Plan water quality objectives (WQOs) or the Nutrient Total Maximum Daily Load (Nutrient TMDL) for Dry Hydrologic Conditions.

This study assesses the overall conditions, ecological health, and water quality in Lake, and evaluates the potential influence on lake health of three treatment alternative strategies (Treatment Alternatives) to supplement the natural water supply to the lake. These Treatment Alternatives are composed of advanced nutrient removal and reverse osmosis (RO) technologies:

(i) Alternative 1: TIN & TP Removal
(ii) Alternative 2: 70% RO(70% RO + 30% TIN & TP Removal)
(iii) Alternative 3: 100% RO

A. Project Background

Replenish Big Bear was developed in an effort to help protect Big Bear Valley (Valley) and the Santa Ana Watershed from the impacts of drought and variable precipitation by recovering a water resource currently discharged outside of the watershed. Replenish Big Bear is comprised of three independent projects, which will be implemented separately in the following progression, as practicable:

- Effluent discharge to Stanfield Marsh (and subsequently to the Lake) and Shay Pond;
- Use of Lake water for landscape irrigation of the local golf course; and
- Use of Lake water for groundwater recharge in Sand Canyon.

The first project, and primary regulatory driver, includes treatment upgrades at the BBARWA wastewater treatment plant (WWTP) to produce highly treated effluent for discharge to Shay Pond and Stanfield Marsh, which flows into the lake. This study evaluates the water quality in the lake and assesses impacts of discharge through Stanfield Marsh. For redundancy purposes, BBARWA is also seeking to maintain its current discharge location in Lucerne Valley, where undisinfected secondary effluent is currently conveyed to irrigate crops used for livestock feed. These new discharge points will allow BBARWA to minimize discharge of treated effluent outside of the watershed, which will increase Lake levels to better support beneficial uses including recreation and habitat, particularly in times of drought. Additionally, discharge to Shay Pond will replace potable water currently discharged to maintain the water flow through the pond. Figure

1 shows the project components for this first project, which is referred to as the effluent discharge project.

The other two projects will utilize lake water for (i) landscape irrigation at the local golf course to achieve in lieu recharge of the groundwater basin and (ii) direct groundwater recharge in Sand Canyon. These projects are not planned for any time soon.

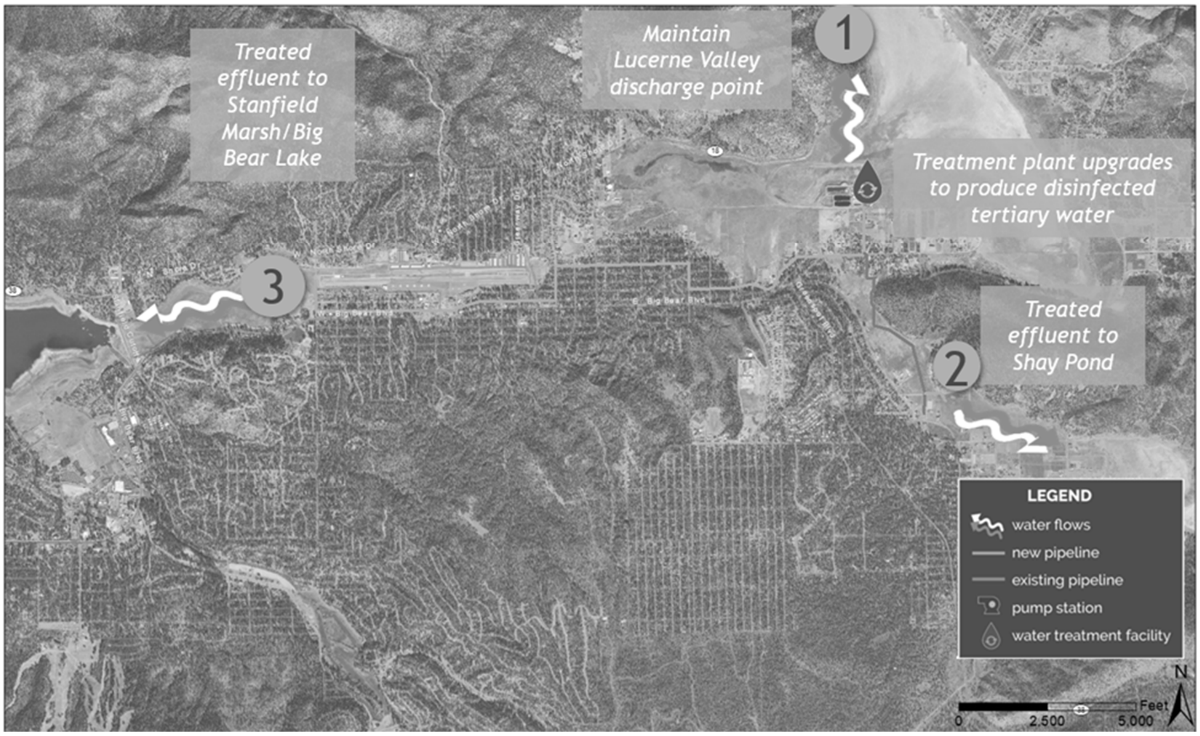

Figure 1. Effluent discharge project components and overview of discharge locations

B. Lake Background

Big Bear Lake is an important resource that provides extensive recreational, economic, ecological, and aesthetic benefits for the local community as well as the larger inland southern California region. Together, Stanfield Marsh and the Lake have a surface area of nearly 3,000 acres, a storage capacity of 73,320 af, and an average depth of 32 feet (ft). Stanfield Marsh and the Lake are both waters of the State of California (State) and United States (U.S.), which have several designated beneficial uses. For reference, Table 1 shows the designated beneficial uses of the Lake and Stanfield Marsh per the 1995 Water Quality Control Plan for the Santa Ana Basin Plan (Basin Plan), as amended in 2008, 2011, 2016, and 2019. In addition, the Nutrient TMDL was adopted to address concerns with phosphorus and nitrogen impacts on the lake. Table 2 presents the Lake regulatory limits set to protect the Lake benefits.

Table 1. Beneficial uses of Big Bear Lake and Stanfield Marsh

Beneficial Uses	**Big Bear Lake**	**Stanfield Marsh**
AGR - Agricultural Supply	✓	
COLD - Cold Freshwater Habitat	✓	✓
GWR - Groundwater Recharge	✓	
MUN - Municipal and Domestic Supply	✓	✓
RARE - Rare, Threatened, or Endangered Species	✓	✓
REC1 - Water Contact Recreation	✓	✓
REC2 - Non-Contact Water Recreation	✓	✓
SPWN - Spawning, Reproduction, and/or Early Development	✓	
WARM - Warm Freshwater Habitat	✓	
WILD - Wildlife Habitat	✓	✓

Table 2. Lake Regulatory Limits for Constituents of Interest

Constituent	**Basin Plan WQO (mg/L)**	**Nutrient TMDL (mg/L)**
Total Dissolved Solids (TDS)	**175**	
Hardness	125	
Sodium	20	
Chloride	10	
Total Inorganic Nitrogen (TIN) (mg/L-N)	**0.15**	
Sulfate	10	
Total Phosphorus (TP) (mg/L-P)	**0.15**	**0.035**
Total Nitrogen (TN) (mg/L-N)		1
Chlorophyll-a (µg/L)		14

Note: **Bolded** constituents were identified as priority in previous regulatory meetings and are specifically evaluated in this study.

The Lake is located about 6,743 ft (2,055 m) above mean sea level (MSL) in the San Bernardino Mountains in San Bernardino County. The Lake was formed following construction of the Bear Valley Dam in 1883-1884 to serve as an irrigation supply for the citrus industry in the downstream Redlands-San Bernardino communities. Since that time, the Lake has served as a vital engine for economic growth in the Valley, and the region has developed into a year-round destination with extensive recreational and commercial activities, primary and secondary residences, vacation properties and hospitality, and other services.

As with all other natural and man-made lakes in Southern California, the Lake is subject to dramatic variability in water surface elevation; surface elevations reached as low as -48.5 ft relative to dam crest (72.33 ft maximum depth) in November 1961, corresponding to a volume of less than 1,000 af and a lake surface area on the order of 200-300 acres during the extended drought in the late 1950’s and early 1960’s. BBMWD was subsequently formed in 1964 to manage and help stabilize the water level in the Lake. The region's natural hydrology includes severe protracted droughts and is influenced by the Pacific Decadal Oscillation (PDO) and El Nino-La Nina climate systems (Kirby, 2010), which makes lake level stabilization a tremendous challenge.

This wide variability in Lake level, in turn, can have dramatic impacts on recreational, economic, and aesthetic values of the Lake, as well as ecological conditions and Lake water quality.

Monitoring data collected over the past decade underscore both the variability in regional hydrology and Lake levels, and the consequences of extended periods of low runoff for water quality conditions in the Lake.

C. Objectives

This study (i) analyzed available historical data on Lake conditions to improve quantitative understanding of water quality in the Lake and the interactions and relationships of key causal and response parameters through statistical and advanced machine learning approaches; (ii) developed and calibrated a 2-D hydrodynamic-water quality model using available historical data to develop an improved process-level understanding of water quality; (iii) assessed conditions in the Lake under natural variable hydrology and climate change through the application of the 2-D hydrodynamic water quality model; and (iv) evaluated, through model simulations, Lake conditions with different treatment alternatives for the proposed Replenish Big Bear project. Phosphorus, nitrogen and total dissolved solids (TDS) are the primary constituents of interest with respect to impacts to the Lake and its beneficial uses.

II. ANALYSIS OF AVAILABLE WATER QUALITY DATA

As illustrated in the Baseline Assessment Tech Memo (WSC, 2020), the Lake is subject to widely varying lake volumes and wide ranges in nutrient, TDS, and chlorophyll-a concentrations. Extension of the analysis provided in the Baseline Assessment Tech Memo (WSC, 2020) was conducted to include additional calculations, regressions, and machine learning to better understand the factors, relationships, and interactions governing water quality. Field and laboratory data for TMDL stations #1 (Dam), #2 (Gilner Point), #6 (Mid-lake) and #9 (Stanfield) over the 2009-2019 time period formed the basis for the analyses. These monitoring stations are shown in Figure 2.

Linear regressions and other statistical analyses are commonly used to identify factors affecting water quality in lakes. Machine learning is now starting to be used for water quality assessments (Chou et al., 2018; Ahmed et al., 2019), including short-term forecasting of algal blooms (Park et al., 2015), owing its ability to often elucidate relationships within complex datasets. Supervised machine learning requires a robust dataset on which to train and validate models. BBMWD has developed and maintained a high quality Lake monitoring program, and has an excellent dataset that was used to train and test different supervised machine learning models. This dataset provides an empirical, data-based approach to identifying and understanding relationships between causal and response variables and predicting water quality in the Lake.

Data were also used where possible to quantify rates of important processes operating within the Lake. For example, increases in total P and total inorganic nitrogen (TIN) concentrations are routinely recorded in late summer/early fall that are thought to be associated with lake mixing (WSC, 2020). Hypolimnetic and/or water column mass balance calculations often allow calculation of internal nutrient recycling rates from bottom sediments (Cooke et al., 2005). Such calculations also provide comparisons with previous laboratory core-flux measurements (Anderson and Dyal, 2003), and allow evaluation of effects of runoff, lake level, and other factors on internal nutrient loading, which is recognized as an important source of nutrients to the Lake (contributing, for example, an estimated 52% of total nitrogen and total P loading under a dry scenario) (Santa Ana Water Board, 2005).

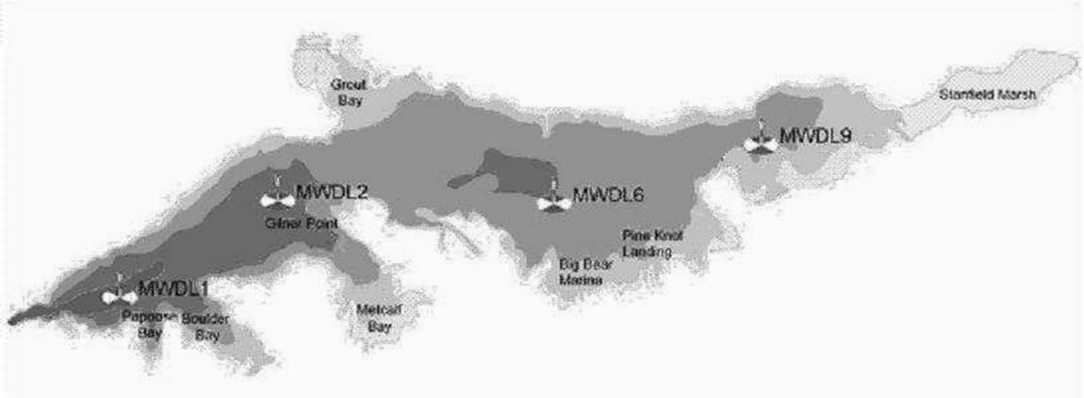

Figure 2. Big Bear Lake TMDL sampling station.

A. Factors Regulating Algal Productivity in Big Bear Lake

1. Statistical Analysis

The TMDL annual water quality reports provide water quality reports, time-series data, and summary statistics, so this section focuses on select statistical analyses of TMDL water quality data. The Lake is generally considered to be P-limited; the ratio of TN to TP concentrations (TN:TP ratio) is reflective of the elemental composition of phytoplankton, with P-limitation generally recognized at TN:TP ratios >20, and N-limitation at TN:TP ratio <5 (Thomann and Mueller, 1998). Photic zone TN and TP concentrations for the 2009-2019 time period were used to calculate TN:TP ratios at the four stations to confirm that P-limitation typically exists in the Lake. Median TN:TP ratios were 27-28 at the Dam, Gilner Point, and Mid-lake stations, but somewhat lower (21.1) at the Stanfield station (Table 3). The TN:TP ratios exhibited considerable variability, so values have been plotted as cumulative distribution functions (Figure 3). Based on these data, the Lake can be considered to be P-limited about 70% of the time and co-limited about 30% of the time. By this measure, N-limitation was present only 1-2% of the time, thus supporting efforts to constrain external loading and internal recycling of P in the Lake.

Table 3. Summary statistics for total nutrients and chlorophyll-a concentrations at the four TMDL sampling stations for 2009-2019 (photic zone).

Parameter	**Value**	**Dam**	**Gilner Point**	**Mid-Lake**	**Stanfield**
Total P	Median	0.036	0.040	0.040	0.051
	25-75%	0.024 – 0.050	0.024 – 0.060	0.026 – 0.068	0.033 – 0.088
	Min-Max	0.005 – 0.150	0.005 – 0.210	0.005 – 0.200	0.008 – 0.400
Total N	Median	1.12	1.10	1.16	1.22
	25-75%	0.92 – 1.26	0.93 – 1.27	0.94 – 1.33	0.96 – 1.53
	Min-Max	0.028 – 2.14	0.19 – 3.25	0.17 – 2.43	0.28 – 2.89
Chlorophyll-a	Median	9.4	10.9	11.7	15.1
	25-75%	6.1 – 14.6	6.7 – 16.0	7.5 – 16.5	8.8 – 27.0
	Min-Max	0.9 – 51	0.5 – 205	2.0 – 106	1.8 – 150
TN:TP	Median	28.2	27.3	27.2	21.2
	25-75%	19.1 – 40.4	18.9 – 38.2	17.4 – 39.0	14.8 – 30.8
	Min-Max	7.3 – 162	3.4 – 244	4.0 – 284	3.5 – 147

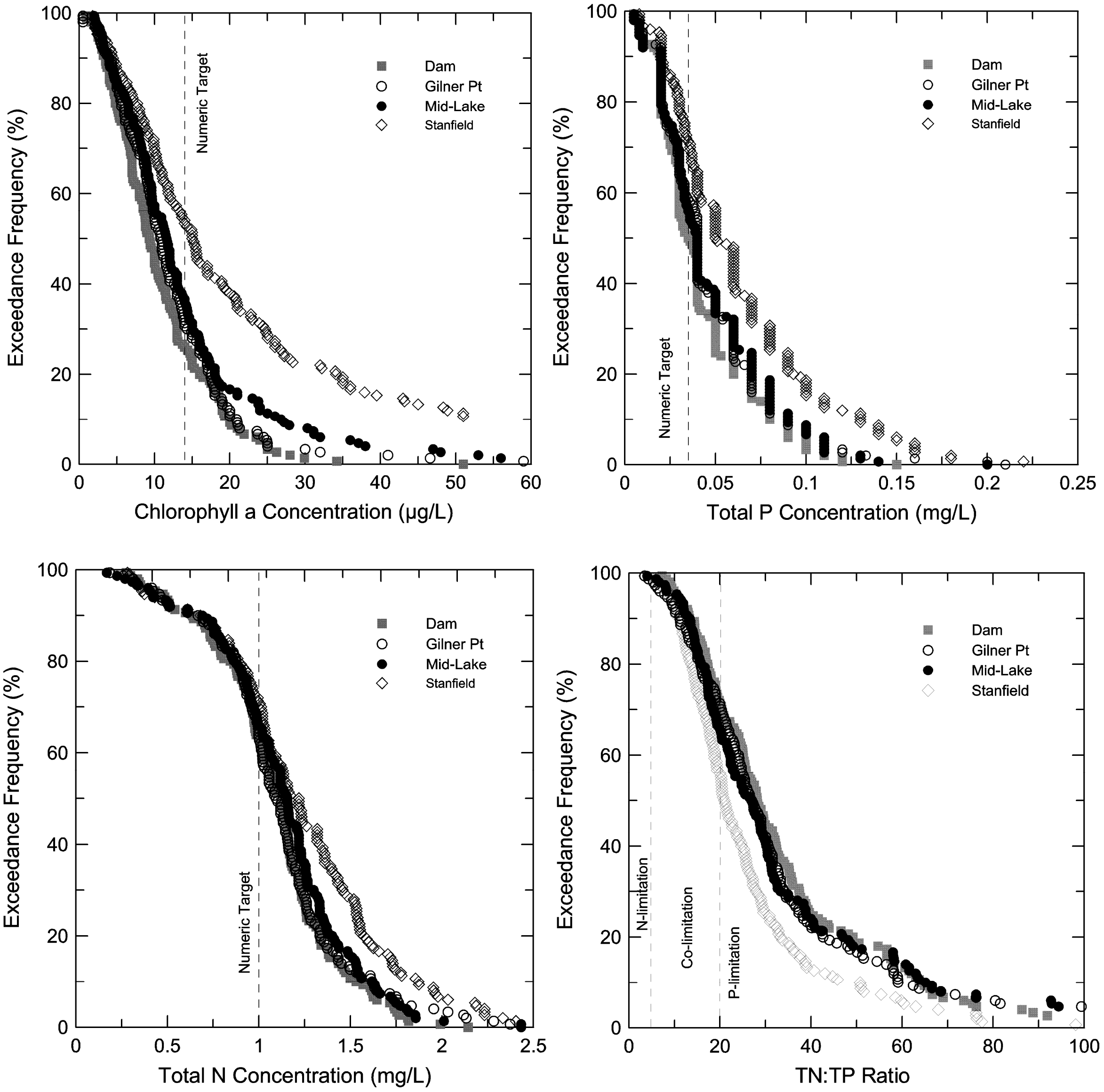

Figure 3. Cumulative distribution functions for a) chlorophyll-a, b) total P, c) total N and d) TN:TP ratios for the 4 TMDL sampling stations.

Correlations between chlorophyll-a concentrations and selected water column properties indicate that no single property captures a substantial amount of the variance in observed chlorophyll-a concentration for all four sampling stations, although the Stanfield station was somewhat more responsive to nutrient concentrations than the other stations (Table 4). Interestingly, TP concentration captured a smaller fraction of observed chlorophyll-a variance than TN (0.08-0.31 vs 0.22-0.53, respectively). Depth below full pool appears to be a useful attribute that integrates across a number of lake conditions and captured, on average, slightly more of the variance (larger R^2) in chlorophyll-a concentrations across all sites (R^2 = 0.22) compared with TP (R^2=0.21) (Table 4). Multiple linear regression using all of these parameters yielded limited improvements in R^2 values compared with single values, indicating that a substantial amount of variance in chlorophyll-a concentration is unaccounted for using basic water quality (and lake level) information (Table 4). Results are very similar when considering only summer months (Jun-Sep) (data not shown). In general, there was no strong correlation between chlorophyll-a and the parameters evaluated.

Table 4. R^2-values for correlations between selected water column properties and chlorophyll-a concentrations (Zrel full represents depth below full pool) (n=150).

Station	**TN**	**TP**	**TIN**	**TDS**	**$Z_{rel\ full}$**	**All**
Dam	0.22	0.08	0.05	0.17	0.29	0.31
Gilner Pt	0.31	0.19	0.00	0.25	0.32	0.43
Mid-Lake	0.34	0.21	0.00	0.19	0.25	0.40
Stanfield	0.53	0.31	0.04	0.18	0.22	0.55

Plots for Gilner Point highlight the variability in chlorophyll-a concentrations as a function of TP, TN, and TDS concentrations and depth below full pool ($Z_{ref\ full}$) across the wide ranging conditions present in the Lake over the 2009-2019 period (Figure 4).

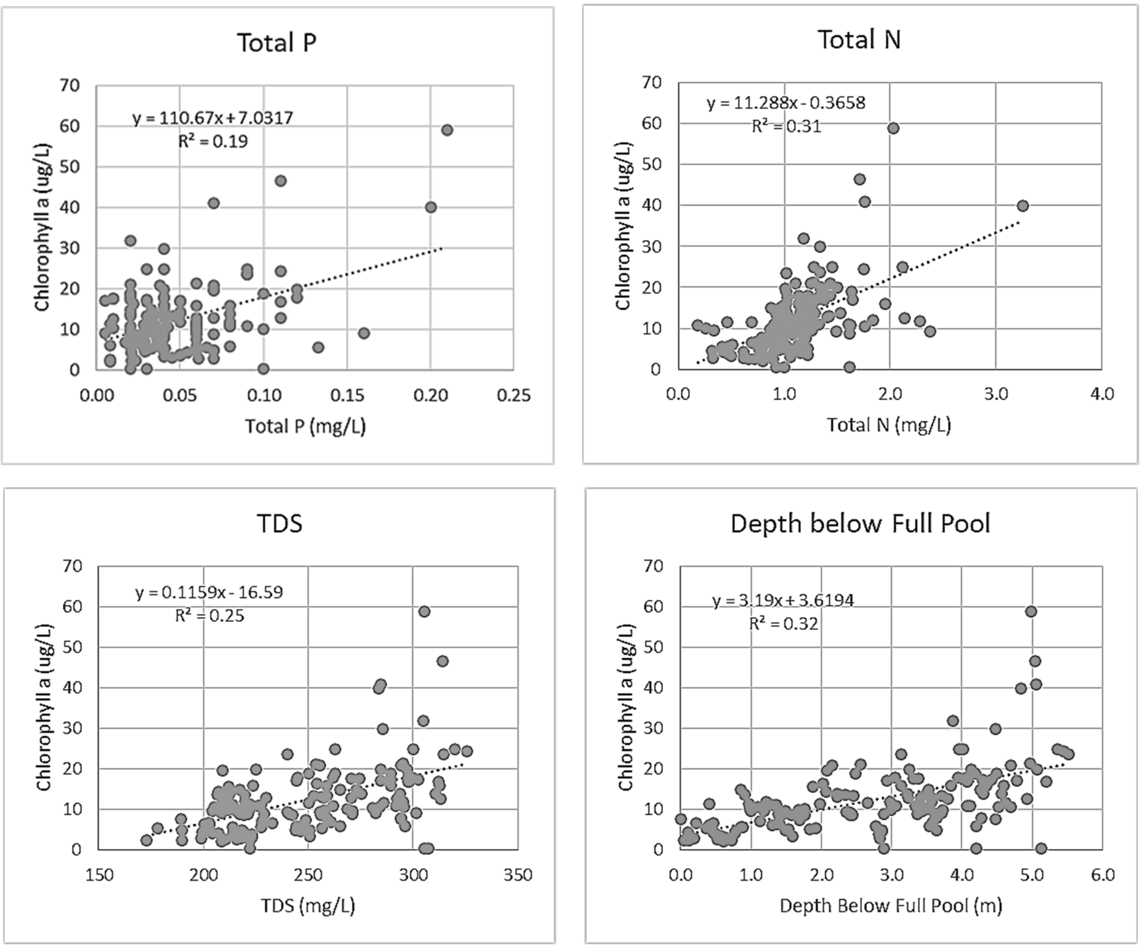

Figure 4. Plots and regression lines between chlorophyll-a and a) total P, b) total N, c) TDS and d) depth below full pool (TMDL station #2, Gilner Point).

2. Machine Learning

Linear regression equations reflected general trends indicating increases in chlorophyll-a in response to increased concentrations of nutrients, TDS, and decreasing lake level, but only captured a relatively small proportion of the variability in measured chlorophyll-a concentrations. Machine learning is often able to more effectively elucidate trends in complex datasets. Random forest and gradient boosted regression trees, k-nearest neighbor, and neural net models were developed using Python 3.7 scikit-learn (e.g., Mueller and Guido, 2017). The machine learning algorithms were trained on the 10-yr record from 2009-2018 (inclusive) and then used to predict water quality for 2019 for comparison with observed conditions.

Chlorophyll-a was the target variable in the machine learning analysis since it represents the key response variable for water quality in the Lake. Independent variables ("features") evaluated included total and dissolved N and P concentrations, water temperature, day of year, lake level (depth below full pool), TDS concentration, and wind speed (U_w). Model goodness-of-fit was determined based on mean absolute error (MAE) and variance captured. Interestingly, nutrient concentrations and water temperature contained less value in predicting chlorophyll-a concentrations than day of year, lake level, TDS, and average wind speed. The relationships between these features and chlorophyll-a concentration at TMDL Station #1 (dam) in the training data are graphically represented in Figure 5.

The lowest set of panels in the following matrix diagram are scatter plots of chlorophyll-a (Chl) as a function of day of the year (Day), lake level below full pool (Level), TDS, and average windspeed (Uw). Visually one notes that chlorophyll-a exhibits trends of increased concentrations with increasing depth below full pool and increased TDS, although extremely large variability in chlorophyll-a concentrations exists at any given value of lake level or TDS. The final panel on the lower right side of the figure represents a frequency histogram, illustrating that most chlorophyll-a values were around 5-10 µg/L (*i.e.*, below the TMDL target of 14 µg/L), with very few observations at this station >25 µg/L (Figure 5).

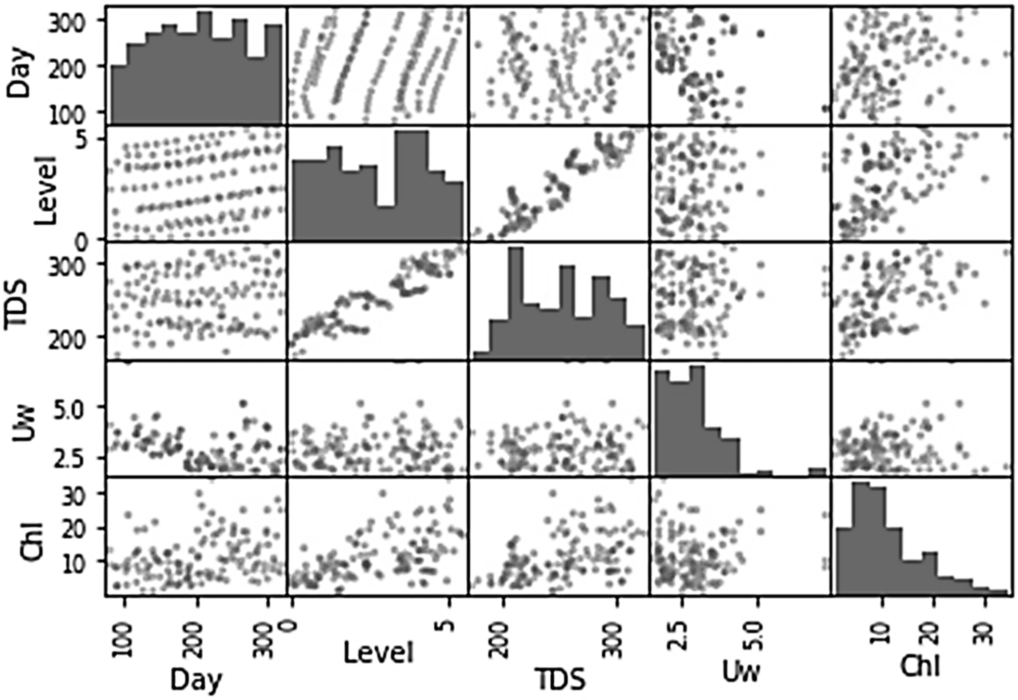

Figure 5. Matrix diagram showing scatter plots between selected parameters at TMDL station #1 (dam).

Application of the random forest regressor (RFR) and gradient-boosted regressor (GBR) using Day-Level-TDS-Windspeed as features yielded models that much more accurately reproduced observed chlorophyll-a concentrations and captured more than 90% of the variance (Figure 6, Table 5). Multiple linear regression using an expanded parameter set yielded a model that was only better than the multi-layer perceptron (MLP) model, which actually generated excess variance.

Table 5. Mean absolute error between predicted and observed chlorophyll-a concentration and variance captured by machine learning and multiple linear regression models (2009-2018 training set).

Model (TMDL station #1)	**MAE (µg/L)**	**Variance Captured**
K-Nearest Neighbor (KNR)	3.4	0.52
Random Forest Regressor (RFR)	1.4	0.92
Gradient-Boosted Regressor (GBR)	1.0	0.96
Multi-Layer Perceptron (MLP)	14.8	-3.2
Multiple Linear Regression	3.3	0.43

The RFR and GBR models captured >90% of the variance in observed chlorophyll-a concentrations without incorporation of nutrient data (using only Day-Level-TDS-Uw), and mean absolute error (MAE) values were only about 30-40% that of the multiple linear regression model (Table 6).

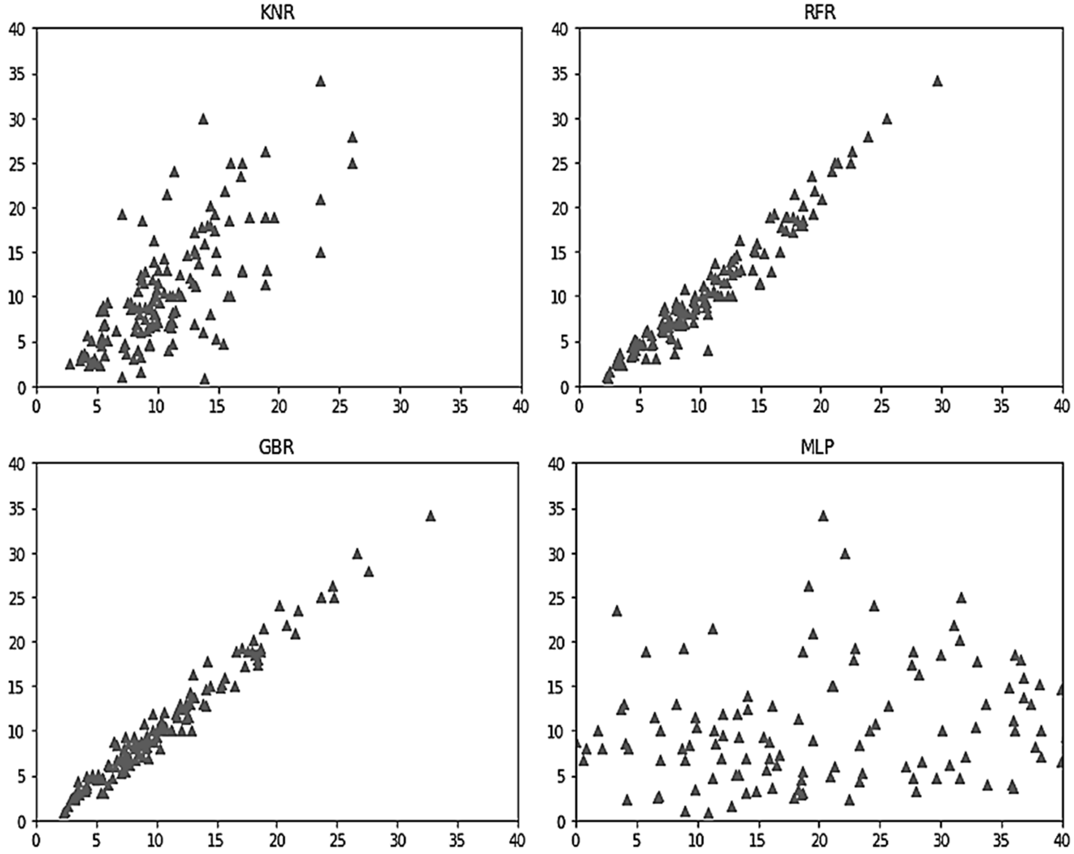

Figure 6. Scatter plots comparing predicted (x-axis) and observed (y-axis) chlorophyll-a concentrations using a) k-nearest neighbor regressor (KNR), b) random forest regressor (RFR), c) gradient-boosted regressor (GBR), and d) multi-layer perceptron (MLP) algorithms.

The RFR and GBR models had significant predictive power for 2019, capturing 58% and 73% of the variance in observed chlorophyll-a (compared with only 36% for the multiple linear regression model), although MAE values were much higher than the 2009-2018 training set. (For reference, a temperature-nutrient model captured <10% of variance in observed chlorophyll-a, underscoring the complex relationships governing algal productivity in the Lake.)

Table 6. Mean absolute error between predicted and observed chlorophyll-a concentrations and variance captured by machine learning and multiple linear regression models (2019 validation set).

Model (TMDL #1)	MAE (µg/L)	Variance Captured
Random Forest Regressor (RFR)	4.5	0.58
Gradient-Boosted Regressor (GBR)	5.9	0.73
Multiple Linear Regression	6.3	0.36

B. Internal Recycling and Hypolimnetic Mass Balance

Internal nutrient recycling is recognized as an important part of the nutrient budget of the Lake (Santa Ana Water Board, 2005). Ortho-phosphate-P (PO_4-P), sometimes also referred to as soluble reactive P (SRP), is released from bottom sediments via reductive dissolution of ferric iron-bound phosphate phases under anoxic conditions and through microbially-mediated dephosphorylation of organic matter. Similarly, NH_4-N is released from bottom sediments by deamination of organic matter. Under stratified conditions, PO_4-P and NH_4-N accumulate in the hypolimnion and their increase in concentrations allows calculation of *in situ* recycling rates.

Station #1 nearest the dam is the deepest of the four main sampling stations and is often observed to exhibit some thermal stratification during the spring through early-mid summer. One consequence of the development of thermal stratification is that nutrients released from sediments accumulate in the bottom waters and their concentrations increase over time, with NH_4-N and PO_4-P reaching, *e.g.,* up to 0.8 mg/L and 0.2 mg/L in the summer of 2010 (Figure 7).

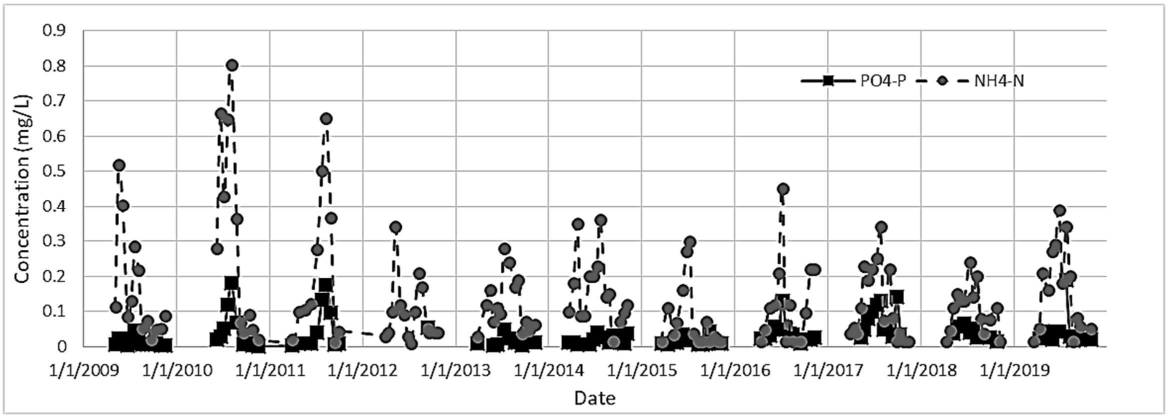

Figure 7. Concentrations of PO4-P and NH4-N in bottom water samples at TMDL station #1 (dam).

The concentrations in bottom waters tracked quite closely the magnitude of stratification, represented by △T (the difference in temperature between the 1 m and bottom depths) (e.g., Figure 8). That is, concentrations tended to increase with increasing △T, while mixing of the water column (△T near 0°C) was associated with sharp reductions in dissolved nutrients due to their mixing throughout the water column.

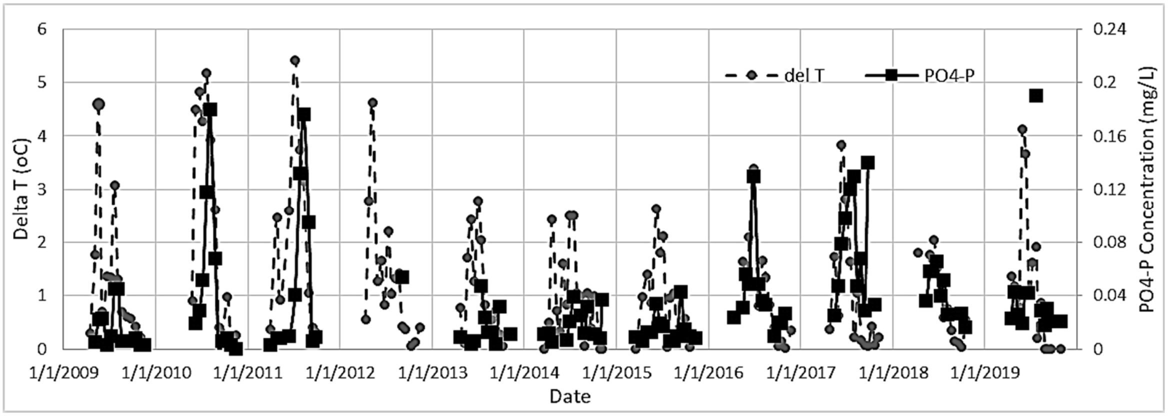

Figure 8. Relationship between bottom water PO₄-P concentrations and temperature difference between 1 m and bottom depths (△T or del T).

Stratification also results in widely-recognized loss of dissolved oxygen (DO), as aerobic bacteria consume DO; with DO unable to be replenished through exchange with the upper well-aerated mixed portion of the water column (epilimnion), oxygen demand quickly depletes DO in the hypolimnion, and is restored when the water column mixes later in the summer (Figure 9).

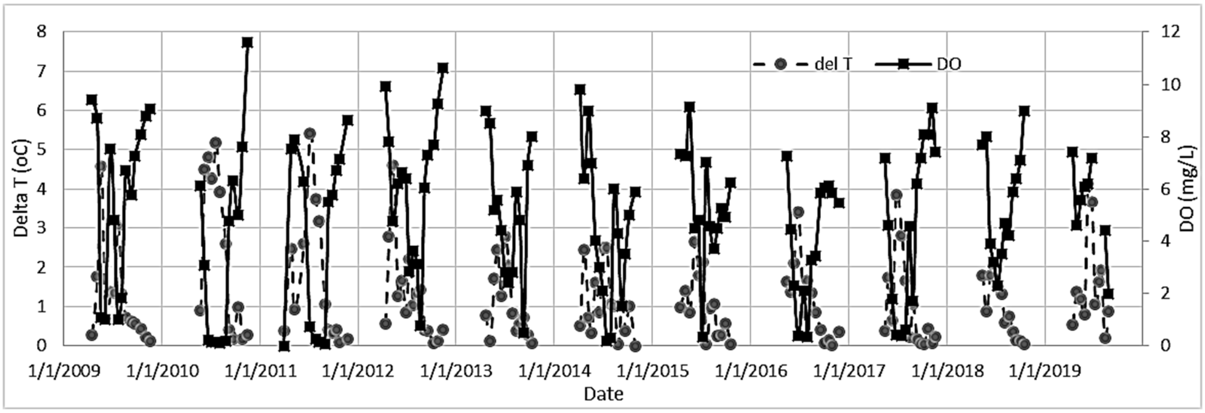

Figure 9. Relationship between bottom water DO concentrations and temperature difference between 1 m and bottom depths (△T or del T).

The increases over time in NH_4-N and PO_4-P and loss of DO (Figures 7-9) during periods of stratification (△T > 0.5 - 1°C) were used to calculate *in situ* internal recycling and areal hypolimnetic oxygen deficit (AHOD) at TMDL station #1 (Table 7). Included in this table are results from laboratory core-flux measurements in 2002-03 and following alum applications in 2004-06 and 2015 in which intact sediment cores were collected from the lake and incubated in the lab at temperature and DO conditions present at the time of sampling. Good agreement was found between 2002-03 laboratory and 2010-11 *in situ* PO_4-P flux values, while lower *in situ* values were found for NH_4-N flux. *In situ* estimates of PO_4-P flux preceding and following the 2015 alum application were in good agreement with pre- and post-laboratory core-flux incubations. AHOD rates have not previously been measured in the Lake, so *in situ* calculations provide valuable new information about this important process. Moreover, i*n situ* AHOD values are consistent with the trophic state of the lake, and were reduced following the 2015 alum treatment. It should also be noted that similar PO_4-P and NH_4-N flux rates were measured in lab core-flux incubations following 2004 and 2015 alum treatments, indicating general reliability of alum treatments to inhibit PO_4-P release.

Table 7. Internal nutrient loading and areal hypolimnetic oxygen demand (AHOD) rates measured in laboratory and estimated from in situ hypolimnetic mass balance approach.

	Lab			*In Situ*	
Parameter	2002-03	2004-06 (post-alum)	2015 (post-alum)	2010-11	2015-17 (post-alum)
PO_4-P Flux (mg/m^2/d)	13.0 ± 2.8	3.3 ± 2.2	0.7 ± 0.2	15.9 ± 0.1	3.2 ± 1.0
NH_4-N Flux (mg/m^2/d)	92.6 ± 19.7	38.7 ± 2.7	40.3 ± 6.3	50.9 ± 10.4	26.0 ± 13.3
AHOD (g/m^2/d)	NA	NA	NA	0.46 ± 0.04	0.31 ± 0.05

Summary

To augment the water quality summaries provided in the TMDL annual reports, additional statistical and advanced machine learning analyses were conducted. Analyses focused on chlorophyll-a as the key response variable. The ratio of total N to total P), often used to identify nutrient limitation, confirm P-limitation principally in place regulating algal production. Correlations developed between total P, total N, TIN and chlorophyll-a for each of the 4 TMDL sampling stations (n=150 for each station) indicate relatively weak correlations with nutrient concentrations, so it is clear that phytoplankton levels are a more complex function of conditions in the lake. Multiple linear regression (MLR) using TN, TP, TIN, TDS and lake level yielded R^2-values of 0.31-0.55 depending upon TMDL sampling station.

Since significant portions of variance in observed chlorophyll-a concentrations remained uncaptured using MLR, machine learning was also evaluated. Random forest and gradient-boosted regressor algorithms applied to TMDL station #1 data using day of year, lake level, TDS concentration and windspeed were able to capture most (0.92-0.96) of the observed variance in chlorophyll-a for the 2009-2018 training set, notably without considering concentrations of total N or total P. For comparison, MLR using this same set of independent variables captured 0.43 of variance. The gradient-boosted regressor model also demonstrated strong forecasting power, capturing 0.73 of variance in predicted chlorophyll-a concentrations of the 2019 data set (compared with 0.36 for the equivalent MLR model). Machine learning was thus able to identify relationships and develop regressor models that reproduce and forecast concentrations with considerable accuracy.

Water column profile data were also used to quantify rates of internal nutrient recycling and AHOD. Internal nutrient recycling rates have been measured on a limited number of dates since 2002 using the laboratory core-flux method, while AHOD rates have not previously been measured at the lake. The *in situ* hypolimnetic mass balance approach using measured water column concentrations of ammonium as N (NH_4-N) and orthophosphate as P (PO_4-P) yielded recycling rates for 2010-2011 and 2015-2017 that were similar to previously measured values confirming the importance of nutrient recycling in lake biogeochemistry and nutrient budgets, and establishing the reliability of alum treatments in suppressing PO_4-P release. The analysis also yielded *in situ* estimates of late spring-early summer AHOD rates at TMDL station #1 of approximately 0.5 g/m^2/d.

III. DEVELOPMENT OF 2-D HYDRODYNAMIC- WATER QUALITY MODEL FOR BIG BEAR LAKE

Numerical modeling with process-based models is routinely used to simulate historical/baseline and future conditions in lakes and reservoirs. Water quality models represent lake properties and processes through mathematical equations that can vary widely in their complexity, from simple 0-D models such as BATHTUB that involves basic mass balance calculations combined with empirical chlorophyll-a-nutrient responses (Walker, 1987), to highly complex 2-D models such as CE-QUAL-W2 (Wells, 2020) and 3-D hydrodynamic water quality models such as AEM3D (Hodges and Dallimore, 2014; Hipsey, 2014) that solve the Navier-Stokes equation and have highly complex sets of mathematical equations describing ecological interactions and water quality. Nonetheless, even with the most complex models, such models are inherently simplifications of lake ecosystems. The complexity of the model developed and its parameterization is also dependent upon the information available about the lake ecosystem. Big Bear Lake exhibits significant horizontal and vertical gradients in water quality and hydrodynamics, indicating that a 2-D laterally-averaged or 3-D representation of the lake is appropriate. Solution to the Navier-Stokes equation in 3-D is computationally extremely demanding, so 3-D hydrodynamic-water quality models are generally limited to relatively short-term simulation periods, often just months to a few years in duration, making calibration to and simulation of longer time periods often impractical. A 2-D laterally-averaged hydrodynamic-water quality model often provides sufficient resolution to capture longitudinal and vertical gradients in conditions, including local effects of inflows and outflows, while allowing for multi-year calibration of complex biogeochemical processes and simulations of decade-plus time scales.

A 2-D (longitudinal-vertical) hydrodynamic water quality model for Big Bear Lake was developed using CE-QUAL-W2 (Wells, 2018). The model was originally developed at the U.S. Army Corps of Engineers Waterways Experiment Station, extensively refined over time, and has been used for over 450 lakes and reservoirs, nearly 300 rivers, and numerous estuaries and other waterbodies (Wells, 2018). The model quantifies heat and water budgets, 2-D hydrodynamics, and predicts concentrations of nutrients, DO, chlorophyll-a, turbidity, and other parameters. The 2-D (longitudinal-vertical) representation assumes the primary gradients in water column properties and water quality are in the vertical and longitudinal directions, and well-mixed in the lateral direction; model branches can be added for embayments that allow a quasi-3-D representation of the lake. Advantages of CE-QUAL-W2 over the WASP model, which was used in early TMDL work (RWQCB, 2005), include the better spatial representation of the lake, hydrodynamic and water quality models are incorporated into a single model within CE-QUAL-W2, and it allows for multiple algal, macrophyte, and epiphyte species simulating their growth, respiration and mortality, and corresponding influence on nutrient cycling and other processes. CE-QUAL-W2 was recommended to replace the use of WASP in the 2010 TMDL Action Plan (Big Bear Lake TMDL Task Force, 2010).

A. Approach

Development and application of the model requires extensive bathymetric, hydrologic, meteorological, water quality, and other data. The model was developed focusing on the 2009-2019 time period. This period was selected based upon a number of factors, including the wide range of hydrologic and water quality conditions in the lake, and availability of extensive lake monitoring and meteorological data, as well as some watershed monitoring data. The 2-D laterally-averaged model grid was developed from the bathymetric survey data collected by Fugro Pelagos Inc. (2006), including the original dam, which was represented as an internal weir within the model. The model grid included 85 segments with 1 m vertical layers and 5 branches: branch 1, with 58 segments representing the main Lake spanning Stanfield Marsh to the Dam; and branches 2-5 representing Kidd Bay, Boulder Bay, Metcalf Bay and Grout Bay, respectively (Figure 10). Good agreement was in place between model-derived and survey-derived elevation-volume curves, with 0.36% difference in volumes at full pool (Figure 10). The model grid includes Stanfield Marsh, which was not included in original WASP simulation, and allows simulation of supplemental water through the marsh to the main lake.

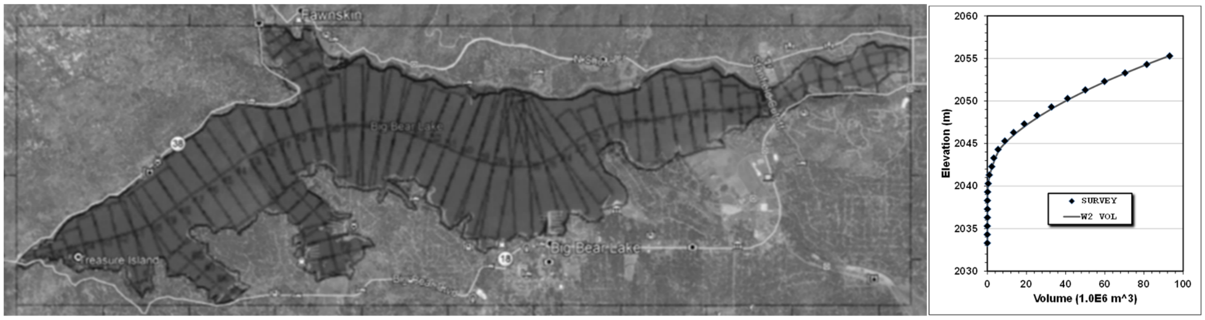

Figure 10. CE-QUAL-W2 model grid developed for Big Bear Lake. Inset depicts agreement between model and measured volume-elevation relationships.

Hydrologic data defining inflows, outflows, and withdrawals were developed from annual Water Master reports. The annual Water Master reports use measured outflows at the dam and water withdrawals by Bear Mountain Ski Resort, evaporative losses estimated using the Blaney Criddle equation, and measured lake surface elevations to derive monthly inflows to the lake. Hourly meteorological conditions were taken from Big Bear Airport and CIMIS Station #199 located at the golf course. Data included solar shortwave radiation (W/m^2), air temperature (°C), dewpoint temperature (°C), windspeed (m/s), wind direction (°) and cloud cover (%). Cloud cover was determined from sky cover conditions reported in METAR data for the airport. The model was calibrated against measured lake level, *in situ* profiles of temperature and dissolved oxygen (DO), and laboratory analyses of water samples collected at the lake.

1. Initial calibration and simulations of lake level, temperature and TDS

The initial model calibration efforts focused on reproducing observed lake levels (water balance) and water column temperatures (heat budget). Surface heat exchange was calculated term-by-term (shortwave, longwave, evaporative, and convective heat flux) with ice cover algorithm and fetch correction active. Vertical eddy viscosity was determined using the turbulent kinetic energy (TKE) formulation, with the Chezy bottom friction solution. Default heat exchange and hydraulic coefficients were generally used in simulations and are summarized in Appendix A.

Evaporation plays a dominant role in both water budget and heat budget calculations. As noted above, the Watermaster uses the Blaney Criddle equation, which is a very simple relationship that uses monthly average temperature and mean daily fraction of annual daylight hours (based on site latitude), to estimate monthly average reference evapotranspiration rate (ET_0) and evaporation rate. In contrast, CE-QUAL-W2 uses local windspeed and the vapor pressure gradient between water surface (based on water surface temperature) and overlying atmosphere (based on air temperature-relative humidity-dewpoint temperature) to determine evaporative heat and water flux on a sub-hourly basis, similar to approaches described in Chapra (2008) and Martin and McCutcheon (1999). The Blaney Criddle equation has been replaced in most applications by more sophisticated models, such as that described above for evaporation from free water surface, or the Penman-Montieth equation for reference ET_0 for estimated water demand for crops. One consequence of the use of a more accurate approach to calculating evaporation from the Lake is that inflows, which were calculated as residuals of water balance equation based upon monthly evaporation from Blaney Criddle equation, were not consistent with the improved evaporative flux rates in CE-QUAL-W2, resulting in over-estimates of water level (not shown). Thus, consistent with the Water Master approach, inflows were calculated from water balance with known lake levels, volumes and losses (with improved evaporative losses) using the CE-QUAL-W2 water balance utility. Also, as noted, the Blaney Criddle equation calculates monthly average evaporative loss, so the Water Master reports present monthly average inflows. Since weekly water surface elevation data was available, the water balance utility was able to provide finer resolution to the computed inflow data (Figure 11a). Outflow and seasonal withdrawals by the ski resort were used as reported in the Water Master Reports (Figure 11b). The severe storms and runoff generated in early 2011 represented the only substantial outflows from the lake beyond the in-stream flow requirements for Bear Creek downstream of the dam (Figure 11b). For initial water balance and TDS simulations, the distributed tributary approach was used. Allocations for specific creek discharges were used in water quality simulations and are described in more detail below.

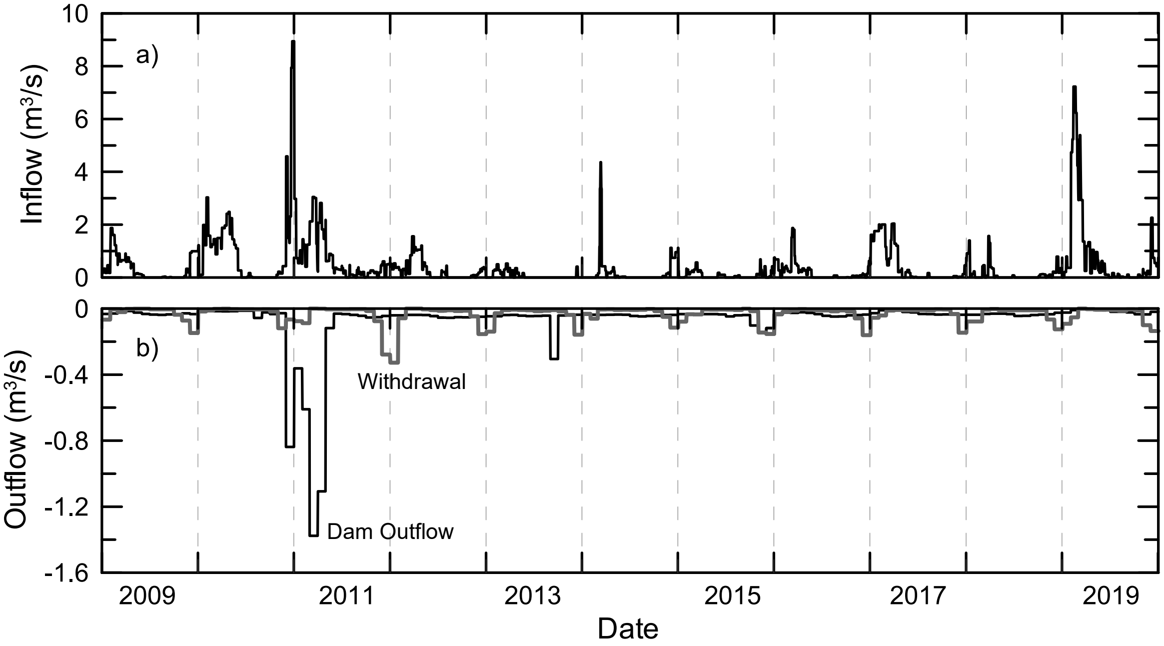

Figure 11. Hydrologic temporal boundary conditions for model calibration (2009-2019): a) total inflow and b) outflows due to withdrawals and dam outflow (from Water Master reports).

The outcome of the water balance calculations was an accurate prediction of lake level over the 2009-2019 calibration period (Figure 12). With the fitting of inflows, mean absolute error (MAE) between predicted and observed lake surface elevation was 3.6 cm.

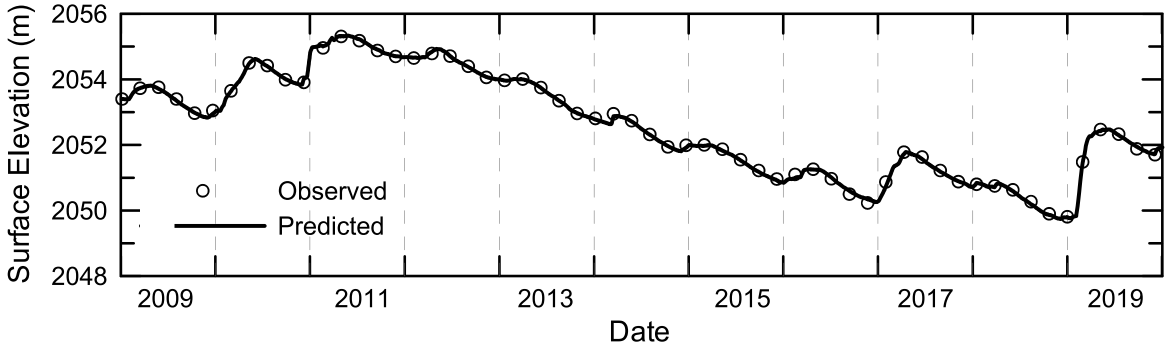

Figure 12. Predicted and observed water surface elevations.

Agreement between predicted and observed water levels is only partial confirmation of the suitability of the model for predicting water balance, since heat flux associated with evaporation is also a key component of the heat budget of lakes (Martin and McCutcheon, 1999). That is, water budgets and heat budgets are explicitly linked through the specific heat of vaporization of water. This is especially important for Big Bear Lake, where evaporation represents the principal mechanism for water loss from the lake (Santa Ana Water Board, 2005). The model quite accurately reproduced temperature profiles in the lake (Figure 13). (Additional profile calibration figures are provided in Appendix B.)

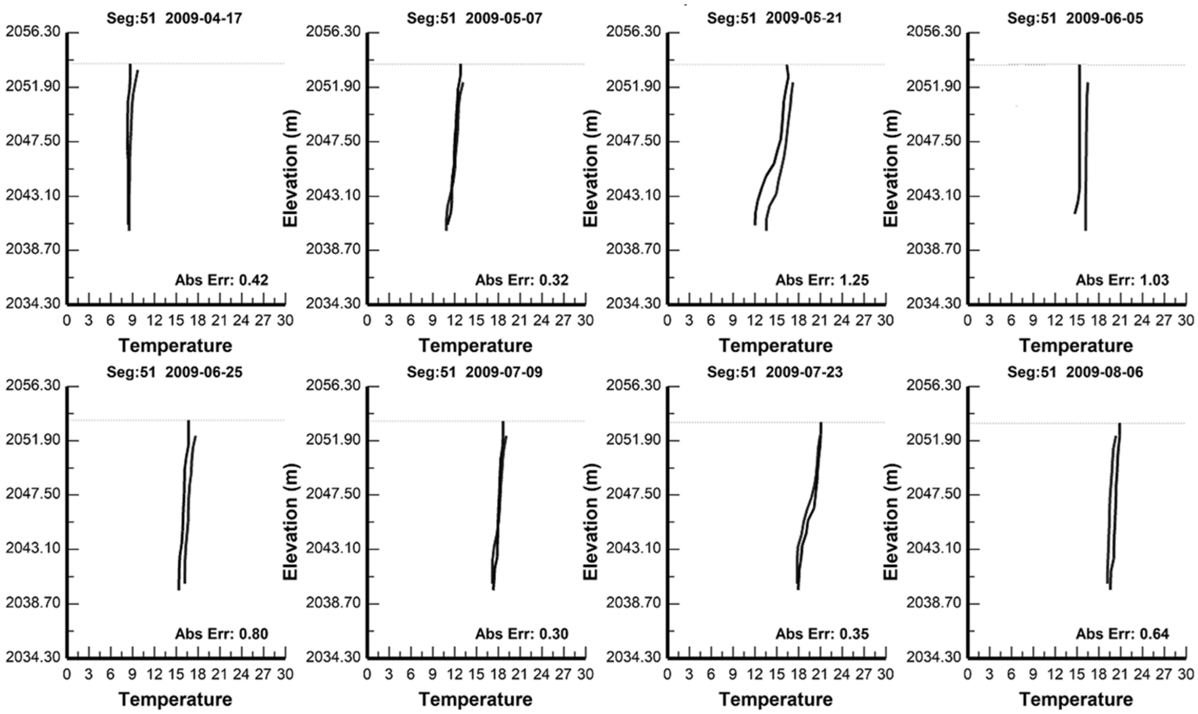

Figure 13. Model predicted and observed water column temperature profiles at station #1 (April 17 – August 6, 2009).

Mean absolute error (MAE) for temperature for profiles collected at the four TMDL sampling stations ranged from 0.95 – 1.14 °C (145 profiles, with 858-1974 discrete temperature measurements depending upon station) (Table 8).

Table 8. Mean absolute error for model predictions of water column temperatures at the four TMDL sampling stations (145 profiles; 858-1974 discrete measurements in each profile).

	#1 (Dam)	#2 (Gilner Pt)	#6 (Mid-lake)	#9 (Stanfield)
MAE (°C)	1.14	0.99	0.95	1.02

TDS concentrations were also simulated in the preliminary phase of model development and calibration. TDS concentration (g/L) was calculated from *in situ* specific conductance (mS/cm) in profile measurements with a proportionality constant of 0.65. Information about TDS (conductivity) of inflowing water was available only for very limited points in time, generally under low-moderate flow conditions. It was thus not feasible to develop comprehensive discharge-TDS relationships from available data. As an alternative, a general form of the discharge-TDS relation (inverse power law) developed from USGS gage #10260500 at Deep Creek was fitted to the Big Bear watershed of the form:

$$TDS\ (mg/L) = 36 * Q\ (m^3/s)^{-0.26} \tag{1}$$

where Q represents the total flow to the lake derived from water budget calculations described previously. The relationship yielded a MAE of 13.3 mg/L (relative error of 15.4%) when applied to Metcalf and Summit Creek data.

Application of the TDS-flow equation to lake inflows, and simulation with CE-QUAL-W2 captured main features and trends in measured lake TDS (from conductivity) for 2009-19 (Figure 14). The MAE between predicted and observed lake TDS concentrations was 11.9 mg/L (4.8% relative error).

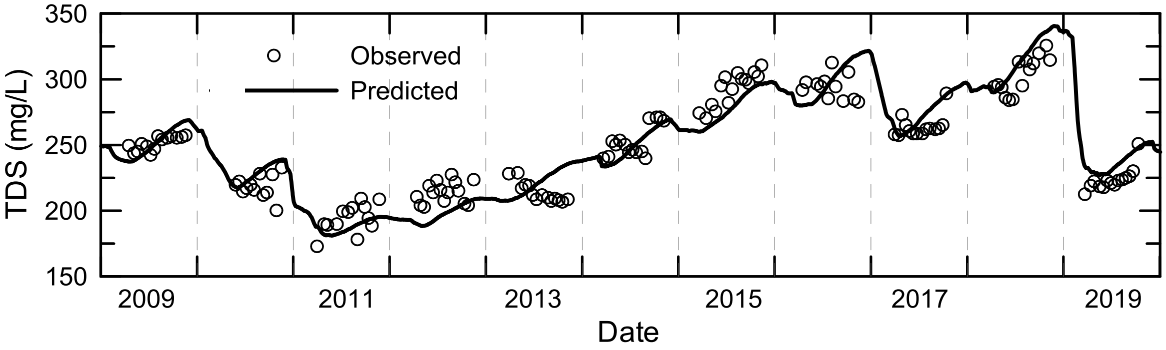

Figure 14. Predicted and observed TDS concentrations.

With the model reasonably representing lake level, water column temperature and TDS concentrations over the wide range of conditions present during 2009-2019, attention was then turned to water quality, focusing on nutrient and chlorophyll-a concentrations.

2. Calibration to Water Quality Data for Big Bear Lake

Lakes are recognized as complex ecosystems influenced by complicated physical, chemical, and biological properties, processes, and inter-relationships. Through the well-designed and high quality lake monitoring program conducted in support of the TMDL at Big Bear Lake, an excellent record of water column conditions and water quality is available with which to calibrate the CE-QUAL-W2 model. Watershed sampling has also been incorporated into the monitoring program, thus providing more extensive empirical information about nutrient and sediment contributions to the lake that were not available in earlier work, which chiefly relied on HSPF simulations of watershed runoff and loading to the lake.

As thoroughly described in the TMDL staff report, loading of nutrients to Big Bear Lake is from (i) external loading from point and nonpoint sources within the watershed, (ii) atmospheric deposition, (ii) internal recycling from bottom sediments, and (iv) macrophyte growth, senescence and death (Santa Ana Water Board, 2005). These processes were integral to the development and application of the CE-QUAL-W2 model for the lake, and are discussed in some detail below.

(i) External loading from the watershed

External loading (EL) (kg/d) from the watershed is the product of inflow rate Q_i (m^3/d) and influent concentrations C_i (kg/m^3) for each source i:

$$EL = \sum_{i=1}^{n} Q_i \, C_i \qquad (2)$$

Runoff rates from specific source areas were derived in previous modeling from HSPF simulations (Figure 15) and linked to WASP model segmentation, which excluded Stanfield Marsh (Figure 16) (Tetra Tech, 2004).

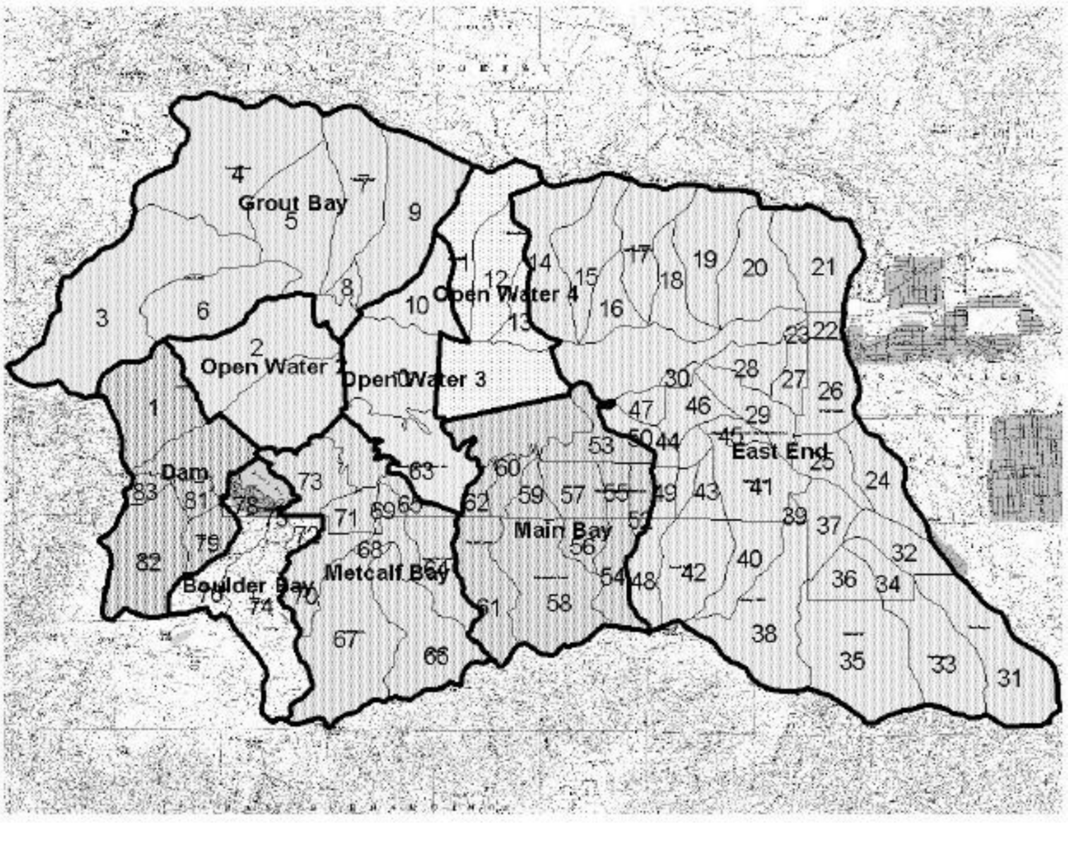

Figure 15. Contributing watershed areas to WASP segments developed from HSPF watershed model (Tetra Tech, 2004).

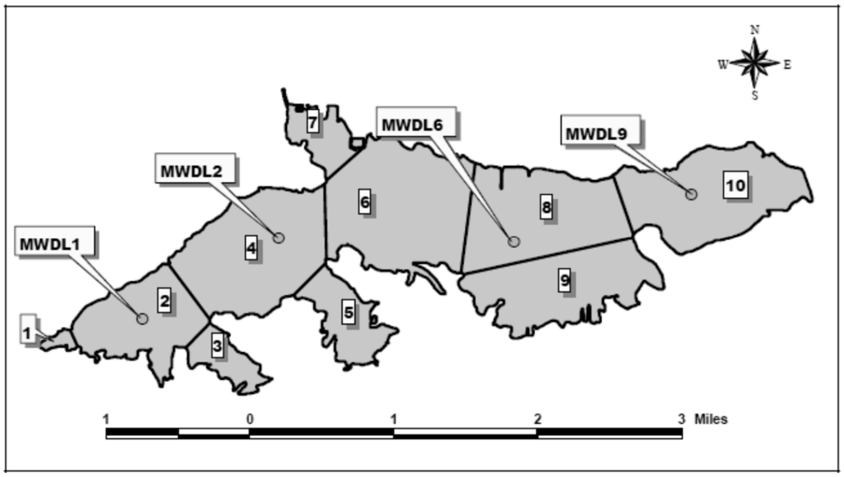

Figure 16. Model segmentation in previous WASP model simulations (Tetra Tech, 2004).

Total inflows, derived from water balance calculations described above, were allocated to regions of the lake following the approach used in the original WASP model. Total inflows (Figure 11a) were allocated to Boulder Bay, Metcalf Bay, Grout Bay and Rathbun Creek (Figure 17), based upon median % flows from prior HSPF simulation results. One difference with the earlier HSPF-WASP model approach is that the WASP model included flows to WASP segment 9 (Figure 16) as a distinct input; the coarse level segmentation in WASP does not map onto the 2-D laterally averaged grid of the CE-QUAL-W2 model, so distributed flow was used to represent both flows to segment 9 and from additional non-point sources (e.g., WASP segments 8 and 4 on the north side of the lake) (Figure 17). Distributed and Rathbun Creek flows in the CE-QUAL-W2 model collectively comprised over 65% of the total inflows to the lake.

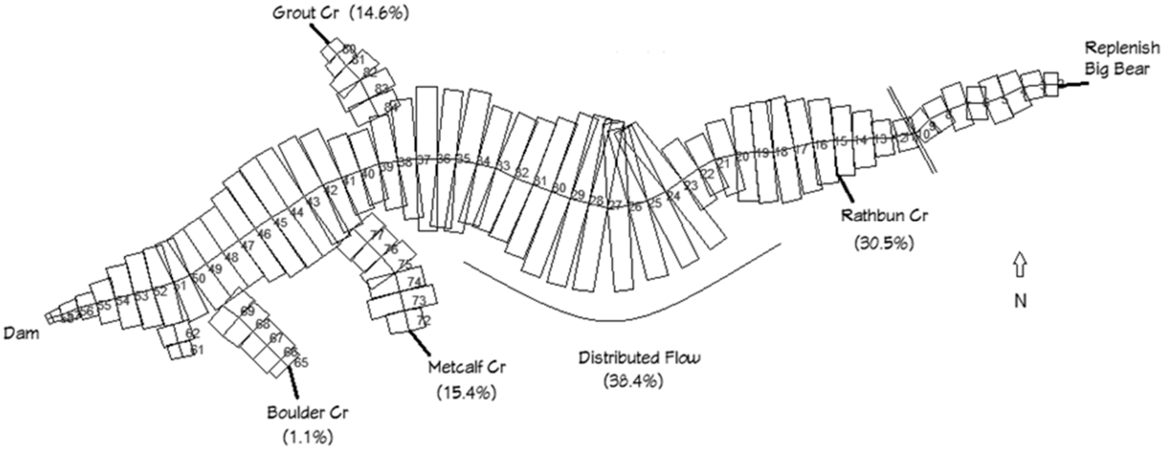

Figure 17. CE-QUAL-W2 model segmentation showing branch, tributary and distributed inflows.

Concentrations of nutrients within these different inflows over time were determined from available watershed monitoring data, rather than HSPF simulations as done in the initial WASP model (More recent HSPF simulations have apparently been conducted, but results were unavailable.) Median concentrations based upon available data are provided in Table 9, while concentration ranges are presented in Table 10. A very limited set of measurements were identified for Boulder Creek and Grout Creek based on sampling in 2010-2011 (n=7 and 12, respectively). More extensive sampling was conducted for Knickerbocker, Rathbun, and Summit Creeks over 2010-2011 and 2016-2019 (n=53, 28 and 27, respectively). Although complete laboratory analyses on all samples were not always available. For example, laboratory measurements of total Kjeldahl N (TKN), dissolved Kjeldahl N (DKN), total organic carbon (TOC) and dissolved organic carbon (DOC) were only available for samples collected since 2016.

Table 9. Median concentrations (mg/L) of nutrients and organic C in creek water samples.

Creek	**TP**	**o-P**	**TN**	**TKN**	**DKN**	**NH$_4$-N**	**NO$_3$-N**	**TOC**	**DOC**
Boulder (n=7)	0.009	0.007	0.184	-	-	0.011	0.022	-	-
Grout (n=12)	0.024	0.015	0.282	-	-	0.008	0.121	-	-
Knickerbocker(n=53)	0.055	0.038	0.374	0.34	0.22	0.130	0.130	2.9	2.7
Rathbun (n=28)	0.055	0.038	0.786	0.46	0.36	0.419	0.419	5.1	4.9
Summit (n=27	0.069	0.021	0.530	0.52	0.25	0.180	0.180	6.0	3.6

Concentrations of total and dissolved forms of N and P varied widely, often by an order of magnitude or more, within the sampling conducted at the creeks (Table 8).

Table 10. Range in concentrations (mg/L) of nutrients and organic C in creek water samples.

Creek	**TP**	**o-PO$_4$-P**	**TN**	**NH$_4$-N**	**NO$_3$-N**
Boulder	0.005 - 0.017	0.005 - 0.009	0.130 - 1.103	0.007 - 0.040	0.002 - 0.042
Grout	0.010 - 0.037	0.010 - 0.026	0.083 - 1.263	0.005 - 0.057	0.011 - 1.054
Knickerbocker	0.020 - 0.320	0.010 - 0.160	0.142 - 1.770	0.005 - 0.290	0.021 - 1.200
Rathbun	0.020 - 0.180	0.010 - 0.100	0.270 - 1.890	0.008 - 0.300	0.005 - 1.190
Summit	0.020 - 0.378	0.003 - 0.155	0.023 - 1.300	0.007 - 0.220	0.003 - 0.602

Table 10 (contd). TOC and DOC values not reported for Boulder or Grout Creek.

Creek	**TKN**	**DKN**	**TOC**	**DOC**
Knickerbocker	0.12 - 1.20	0.012 - 0.67	1.3 - 12.0	1.4 - 8.8
Rathbun	0.077 - 1.40	0.21 - 0.77	2.9 - 7.7	2.6 - 7.1
Summit	0.10 - 0.95	0.00 - 0.78	2.8 - 7.5	2.2 - 7.0

Water quality in runoff can vary strongly depending upon characteristics of the basin, including land use, land cover, amount of impervious surfaces and other factors, and are reflected in the higher concentrations of nutrients in Knickerbocker, Rathbun, and Summit Creeks compared with Boulder and Grout Creeks (Tables 9, 10). The nature and intensity of storms (rain, snow, rain-on-snow), meteorological, and antecedent watershed conditions influence discharge and also influence water quality, contributing to the wide range in concentrations observed at the creeks (Table 10). Since a very limited number of point estimates of flow were available, it was not feasible to develop reach-specific discharge-water quality relationships, but total flows to the lake were known from water balance considerations. Measured nutrient concentration were statistically evaluated for possible correlations with total flow rates (Table 11). Sample sizes varied by creek, with only 7 and 12 samples collected from Boulder Creek and Grout Creek, respectively, while Knickerbocker, Rathbun, and Summit Creeks were sampled 53, 28 and 27 times, respectively. Weak correlations with total flow were observed for most variables, although total flow accounted for a meaningful fraction of the total variance in NO_3-N concentrations (up to R-value of 0.62, or R^2 of 0.38, representing 38% of observed variance in NO_3-N concentration for Rathbun Creek). Nonetheless, regressions even for NO_3-N had modest predictive power (Table 11, Figure 18). Assumptions about inflows and influent concentrations were necessitated by the limited amount of data and thus represent a significant source of uncertainty in model predictions.

Table 11. Correlation coefficients between flow and constituent concentrations.

Creek	**TP**	**o-P**	**TN**	**TKN**	**DKN**	**NH_4-N**	**NO_3-N**	**TOC**	**DOC**
Boulder	0.41	0.31	-0.13	-	-	0.29	-	-	-
Grout	0.52	0.61	0.52	-	-	0.42	0.48	-	-
Knickerbocker	0.00	0.06	-0.03	0.01	0.00	-0.14	0.19	0.13	0.34
Rathbun	-0.21	-0.20	0.28	0.04	0.38	-0.12	0.62	0.43	0.53
Summit	-0.05	0.04	0.08	0.21	0.66	-0.02	0.52	0.18	0.38

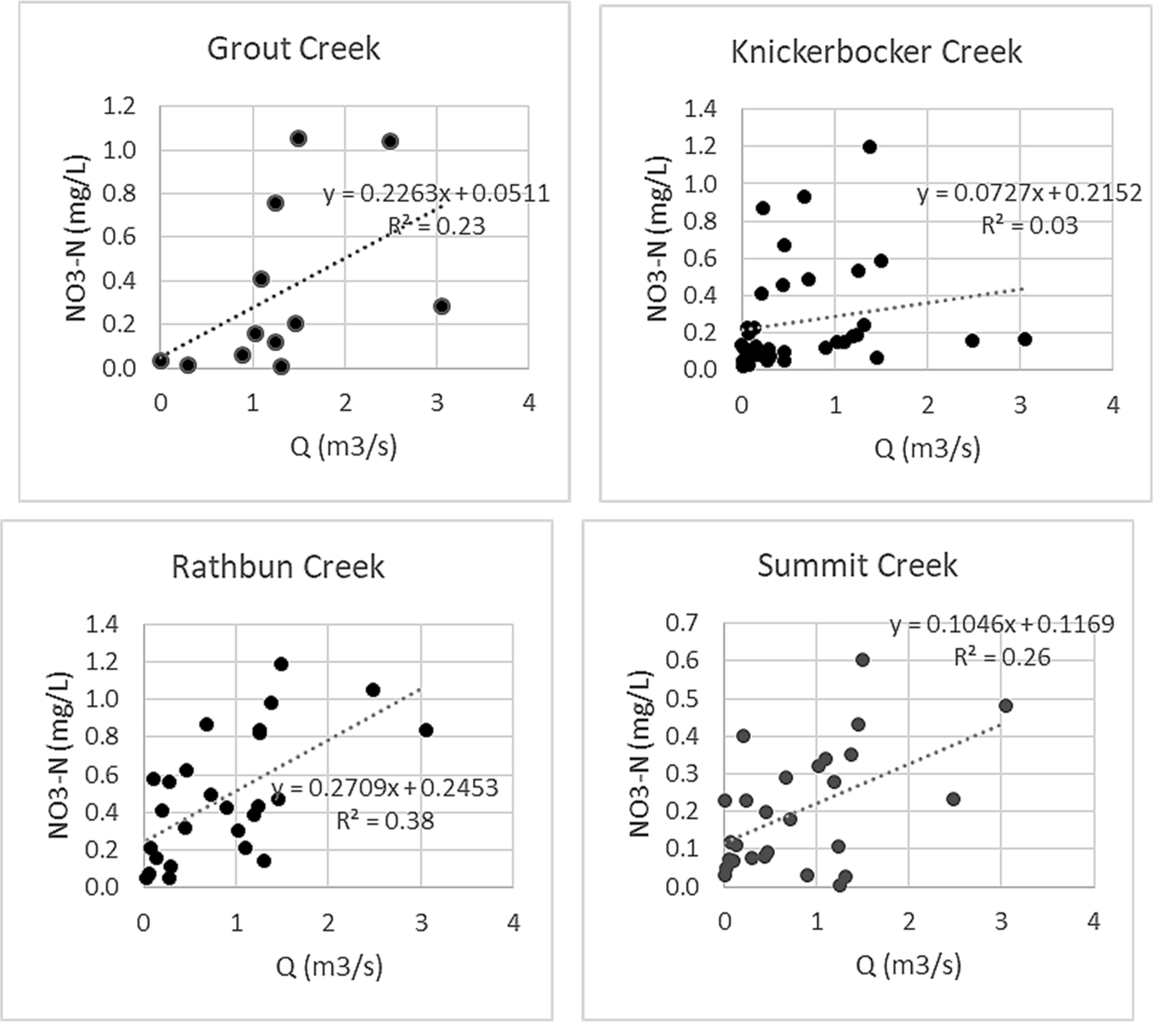

Figure 18. Plots and regression lines between NO3-N concentrations and total (lakewide) flow for a) Grout Creek, b) Knickerbocker Creek, c) Rathbun Creek, and d) Summit Creek.

Measured nitrogen and phosphorus concentrations were used when available and assumed to represent influent concentrations for the entire month in which the measurements were made; for time periods when measured values were not available, median values were used, except as follows: NO_3-N (all creeks except Boulder) and PO_4-P (Grout and Knickerbocker only), when concentrations were estimated from regressions with total flow for that date. The incorporation of measured, median, and regression-based influent concentrations into model input time-series is illustrated for Rathbun Creek (Figure 19).

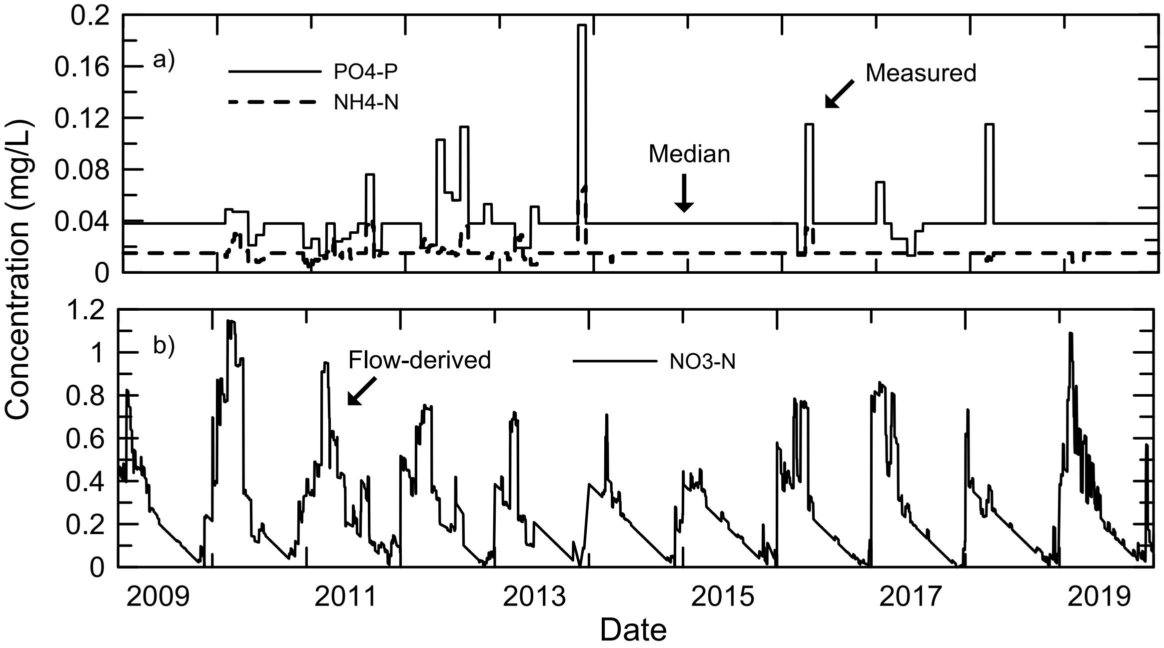

Figure 19. Modeled input nutrient concentrations in Rathbun Creek: a) PO4-P and NH4-N illustrating use of measured values when available and median values when not, and b) NO3-N concentrations derived from regression with total flow rate.

Particulate forms of N, P, and C were calculated by difference between total and dissolved forms. Following White et al. (2010) and Wetzel (1984), organic matter was further partitioned into labile and refractory forms (approximately 25 and 75%, respectively).

(ii) Atmospheric deposition

In addition to external loading from the watershed, atmospheric deposition is also an important source of N and P to Big Bear Lake. Based upon available studies by Mark Fenn and others in the San Bernardino Mountains, direct deposition of N onto the lake (assumed for modeling purposes to be equimolar NH_4 and NO_3) was estimated to be approximately 10 kg/ha/yr, while direct deposition of total P was assumed to be 1/20th that of N, or 0.5 kg/ha/yr (Santa Ana Water Board, 2005). The CE-QUAL-W2 model does not simulate transformations and release of P bound to inorganic particles, so it was assumed that 40% of the total P (chiefly as fine inorganic dust particles) was in a bioavailable form and deposited as PO_4-P.

(iii) Internal recycling from bottom sediments

Release from bottom sediments through mineralization of organic matter and reductive dissolution of ferric oxyhydroxides was simulated in CE-QUAL-W2 using the dynamic 1st-order sediment decay model combined with the 0-order SOD model. The 1st-order sediment model uses a sediment compartment to accumulate organic sediments as a result of settling of algae and particulate organic matter, and allow their decay, releasing NH_4-N and PO_4-P back to the water column (Figure 20).

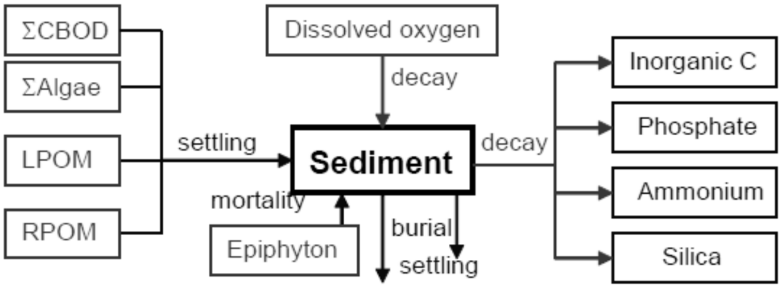

Figure 20. Schematic of 1st-order sediment subroutine in CE-QUAL-W2.

As a 1st-order process, the greater the amount of organic matter settling to the sediment compartment results in greater amounts of organic matter decayed, and N and P mineralized and released back to water column (i.e., recycled). Simulation values are provided in Table 12.

Table 12. 1st-order sediment model parameter values used in simulations. Default W2 values from Wells (2019).

Parameter	Default	Value	Description
SEDCI	0	4.4	Initial reactive sediment concentration (g/m^3)
SEDS	0.1	0.08	Sediment settling rate (m/d)
SEDK	0.1	0.1	Sediment decay rate (d^{-1})
FSOD	1	0.23	Fraction of 0-order SOD rate used
FSED	1	1	Fraction of 1st-order sediment concentration used
SEDBR	0.01	0.01	Sediment burial rate (d^{-1})

The 1st-order model simulates aerobic decomposition reactions, so sediment oxygen demand is also dynamically calculated based upon amount and type of organic matter and temperature, and depletion of DO in turn reduces rates of organic matter mineralization and deamination-dephosphorylation reactions. The 1st-order sediment model thus doesn't simulate nutrient release under anaerobic conditions, although, anaerobic decomposition and reductive dissolution reactions can be important processes within nutrient cycling. As a result, the 0-order SOD model (Figure 21) was used to simulate N and P nutrient release during anaerobic conditions. Maximum values for SOD were varied from 0.1 for shallow low organic matter sediments to 1.0 g/m^2/d at TMDL station #1 and 1.2 g/m^2/d for deepest high organic sediments adjacent to the dam; rates were assumed to vary linearly with temperature between 4 and 30°C, corresponding to a maximum summer 0-order SOD rate of about 0.6 g/m^2/d at TMDL station #1.

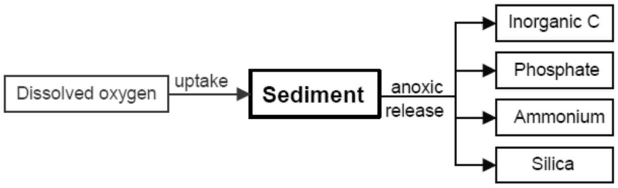

Figure 21. Schematic of 0th-order sediment oxygen demand subroutine in CE-QUAL-W2.

(iv) Macrophyte growth, senescence, and death

Macrophytes are an important component of Big Bear Lake's ecosystem, providing habitat for fish, zooplankton, larval aquatic insects, a variety of benthic animals, and epiphytic periphyton. Aquatic vegetation surveys have periodically been conducted, with coontail, common waterweed, and Eurasian watermilfoil often comprising much of the total macrophyte biomass. Macrophyte growth, senescence, and death are also important features of the nutrient cycle of the lake. Harvesting and herbicide applications have helped control macrophyte growth, with harvesting also serving as strategy to export nutrients from the lake. CE-QUAL-W2 includes macrophyte subroutines that simulate plant life cycles and their effect on hydrodynamics, nutrients, light, and other factors.

Since detailed information about the species composition, density, and distribution of macrophytes over the 2009-2019 timeframe was not available, a composite macrophyte group was incorporated into the model. CE-QUAL-W2 modeling conducted by the USGS (2013) for the Klamath River upstream of Keno Dam, Oregon served as the basis for macrophyte submodel parameterization (Table 13). The composite macrophyte extracted nutrients from the water column, as coontail and to a slightly lesser extent milfoil do, and from bottom sediments, as typical rooted aquatic vascular plants do.

Table 13. Macrophyte model parameter values used in simulations.

Parameter	USGS[a]	Value	Description
MG	0.34	0.3	Maximum macrophyte growth rate (d^{-1})
MR	0.09	0.09	Maximum macrophyte respiration rate (d^{-1})
MM	0.06	0.06	Maximum macrophyte mortality rate (d^{-1})
MSAT	5	10	Light saturation intensity at max photosynthesis rate (W/m^2)
MPOM	0.7	0.7	Fraction of macrophyte biomass converted to POM upon death
LRPMAC	0.2	0.2	Fraction of POM that becomes labile POM
PSED	0.4	0.27	Fraction of P uptake from sediments
NSED	0.4	0.27	Fraction of N uptake from sediments
MBMP	40	40	Threshold concentration when growth to next layer (g/m^3)
MMAX	108	1000	Maximum macrophyte concentration (g/m^3) (W2 default = 500 g/m^3)
CDDRAG	0	1	Macrophyte drag coefficient
MT1	14	14	Lower temperature for rising growth rate function (°C)
MT2	24	24	Upper temperature for rising growth rate function (°C)
MP	0.004	0.005	Stoichiometric ratio between P and biomass (g/g)
MN	0.054	0.05	Stoichiometric ratio between N and biomass (g/g)
MC	0.51	0.5	Stoichiometric ratio between C and biomass (g/g)

[a] *composite macrophyte based on average of values for Coontail and Common Waterweed. USGS (2013).*

v. Epiphyton dynamics

A vast majority of algal species can colonize surfaces, including macrophytes, and can approach or exceed primary production of macrophytes (*e.g.,* Jones, 1984). Given the relatively shallow depths in the embayments and eastern end of the lake and relatively high water clarity much of the year, epiphyton were also included in the model. Epiphyton are subject to the same environmental factors and processes as phytoplankton with the exception of settling loss from the water column (Table 14).

Table 14. Epiphyton model parameter values used in simulations. Default W2 values from Wells (2019).

Parameter	Default	Value	Description
EG	2	2	Maximum epiphyton growth rate (d^{-1})
ER	0.04	0.045	Maximum epiphyton respiration rate (d^{-1})
EE	0.04	0.045	Maximum epiphyton excretion rate (d^{-1})
EM	0.1	0.1	Maximum epiphyton mortality rate (d^{-1})
EB	0.001	0.001	Epiphyton burial rate (d^{-1})
EHSP	0.003	0.003	Epiphyton half-saturation for P-limited growth (g/m^3)
EHSN	0.014	0.014	Epiphyton half-saturation for N-limited growth (g/m^3)
EHSSI	0	0	Epiphyton half-saturation for Si-limited growth (g/m^3)
ESAT	75	75	Light saturation intensity at max photosynthesis rate (W/m^2)
EHS	35	82	Biomass limitation factor (g/m^2)
ENEQN	2	2	Ammonia preference factor equation (1 or 2)
ENPR	0.001	0.001	N-half saturation preference constant (g/m^3)
EP	0.005	0.003	Stoichiometric ratio between P and biomass (g/g)
EN	0.08	0.082	Stoichiometric ratio between N and biomass (g/g)
EC	0.45	0.45	Stoichiometric ratio between C and biomass (g/g)

vi. Phytoplankton dynamics

With information about external nutrient loading from the watershed, atmospheric deposition, internal nutrient recycling, and role of macrophytes and epiphyton, attention was then turned to parameterization of the model to reproduce seasonal and interannual phytoplankton dynamics as expressed through trends in chlorophyll-a. Algal levels are governed by the availability of nutrients and light, and regulated by a complex set of processes, including respiration, settling, grazing, and mortality (Figure 22):

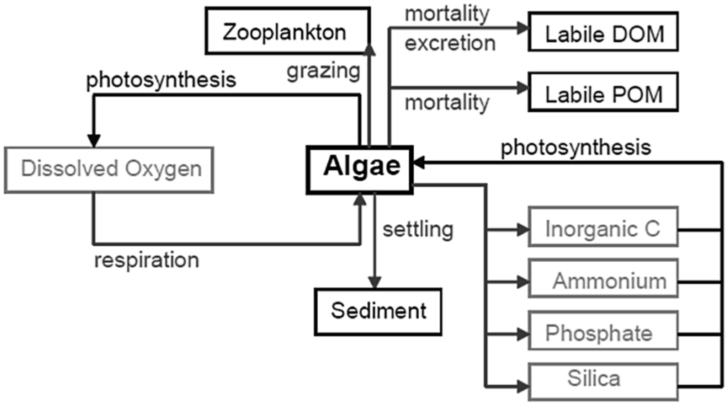

Figure 22. Schematic of phytoplankton subroutine in CE-QUAL-W2.

No specific genus or species was simulated and parameter values at or near CE-QUAL-W2 default values were used (Table 15). Two phytoplankton groups were simulated, with algal group #2 capable of N_2-fixation.

Table 15. Phytoplankton model parameter values used in simulations. Default W2 values from Wells (2019).

Parameter	Default	Algae 1	Algae 2	Description
AG	2	2	1.7	Maximum algal growth rate (d^{-1})
AR	0.04	0.04	0.05	Maximum algal respiration rate (d^{-1})
AE	0.04	0.04	0.05	Maximum algal excretion rate (d^{-1})
AM	0.1	0.1	0.1	Maximum algal mortality rate (d^{-1})
AS	0.1	0.1	0.1	Algal settling rate (d^{-1})
AHSP	0.003	0.003	0.005	Algal half-saturation for P-limited growth (g/m^3)
AHSN	0.014	0.03	0	Algal half-saturation for N-limited growth (g/m^3)
AHSSI	0	0	0	Algal half-saturation for Si-limited growth (g/m^3)
ASAT	100	90	100	Light saturation intensity at max photosynthesis (W/m^2)
ALPOM	0.8	0.8	0.8	Fraction of algae lost by mortality to POM
ANEQN	2	1	1	Ammonia preference factor equation (1 or 2)
ANPR	0.001	0.001	0.001	N-half saturation preference constant (g/m^3)
AP	0.005	0.003	0.0031	Stoichiometric ratio between P and biomass (g/g)
AN	0.08	0.09	0.09	Stoichiometric ratio between N and biomass (g/g)
AEC	0.45	0.45	0.45	Stoichiometric ratio between C and biomass (g/g)

3. Model Calibration Results

As previously noted, water quality in Big Bear Lake varied widely over 2009-2019 (Table 1). The model reproduced seasonal and inter-annual variations in chlorophyll-a concentrations reasonably well, including increased concentrations in the latter half of the 2009-2019 study period associated with lower lake levels (Figure 23).

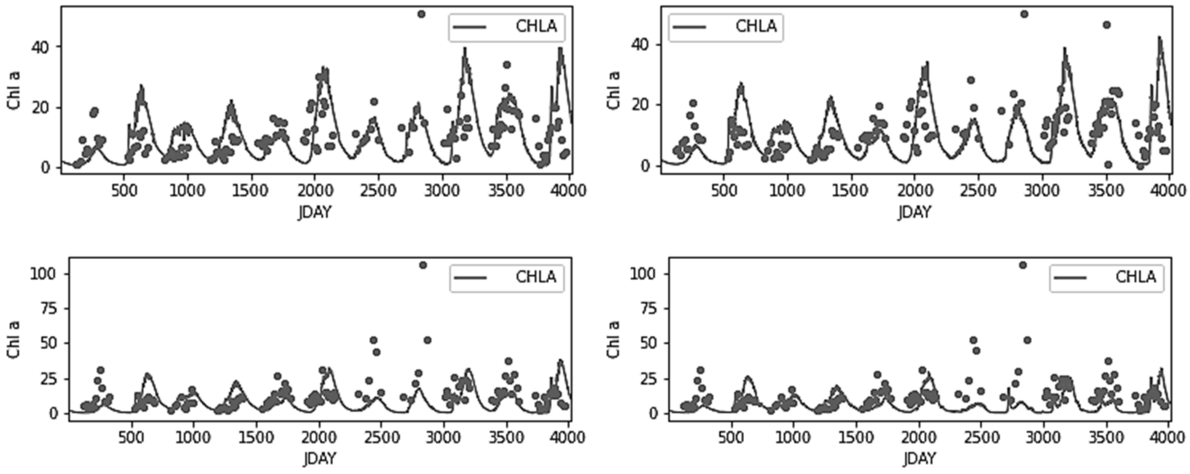

Figure 23. Predicted (line) and observed (circles) chlorophyll-a concentrations (µg/L) over 2009-2019 calibration period for TMDL sampling stations: a) #1 (dam), b) #2 (Gilner Point), c) #6 (Mid-lake), and d) #9 (Stanfield). JDAY represents simulation day (elapsed Julian day) since 1/1/2009.

The model also reproduced central tendencies present in measured TP concentrations, including seasonal variations and trends of increased concentrations in the latter half of the 2009-2019 study period, but predicted seasonal variations that were dampened relative to reported data (Figure 24). In particular, the model over-predicted total P around day 2300-2600 which corresponds to the alum application in 2015. CE-QUAL-W2 doesn't have subroutines specifically simulating an alum application, and after some effort, it was deemed not readily feasible to accurately simulate the flocculation, sorption, and settling of alum and sorbed P and N within CE-QUAL-W2. Some limitations to the macrophyte submodel were also identified (Appendix C).

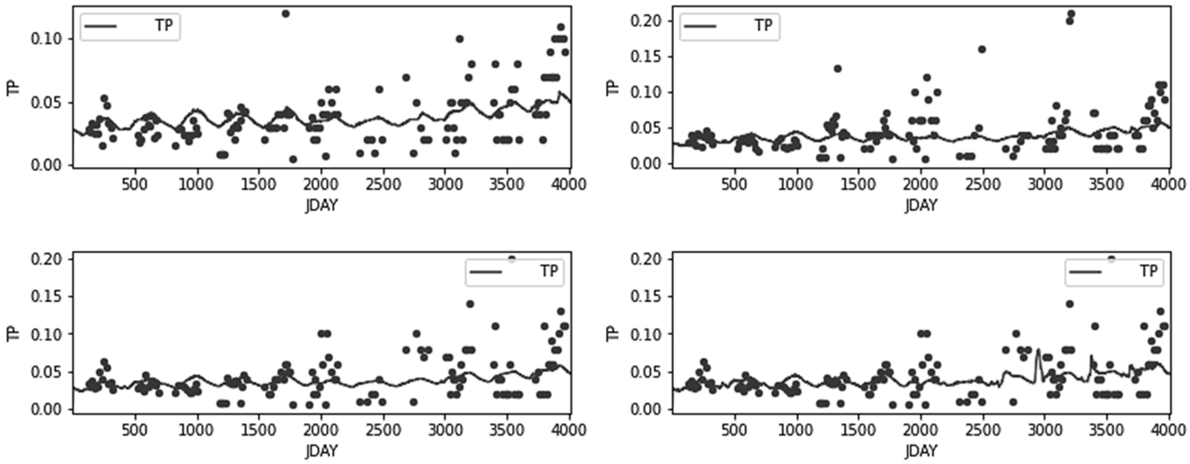

Figure 24. Predicted (line) and observed (circles) total P (TP) concentrations (mg/L) over 2009-2019 calibration period for TMDL sampling stations: a) #1 (dam), b) #2 (Gilner Point), c) #6 (Mid-lake) and d) #9 (Stanfield). JDAY represents simulation day (elapsed Julian day) since 1/1/2009.

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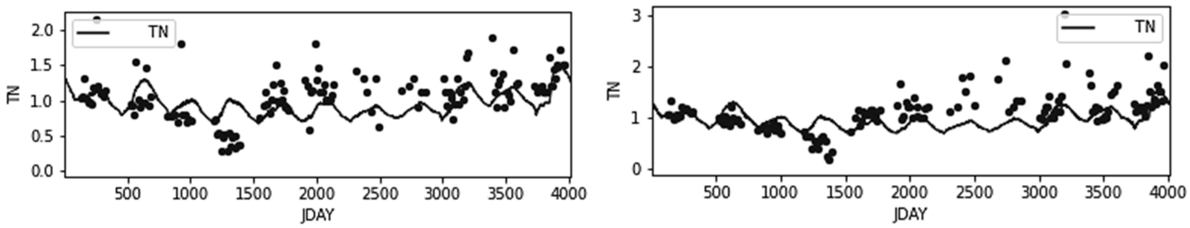
might be expected to increase N concentrations somewhat, as further P-limitation would restrict amount of N also incorporated into algal biomass.



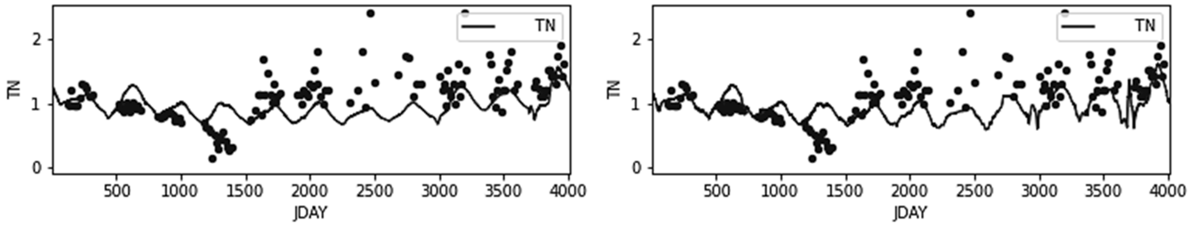


Figure 25. Predicted (line) and observed (circles) total N (TN) concentrations (mg/L) over 2009-2019 calibration period for TMDL sampling stations: a) #1 (dam), b) #2 (Gilner Point), c) #6 (Mid-lake) and d) #9 (Stanfield). JDAY represents simulation day (elapsed Julian day) since 1/1/2009.

As evident in Figures 23-25, very wide swings in reported total nutrient and chlorophyll-a concentrations were sometimes present, with sample concentrations occasionally up to 3-5 times higher than samples collected immediately prior to or immediately thereafter (e.g., Figure 24, TP concentration of 0.12 mg/L around day 1700 for TMDL station #1). While analytical error is present in all measured values, a Grubbs outlier test was used to identify outliers at $p<0.01$ prior to calculation of model error statistics. A total of 7/424 outliers were statistically identified for chlorophyll-a, 5/600 for total P, 2/600 for total N and 6/600 for total inorganic N. Outliers removed due to analytical, sample handling, or other errors thus constituted only 0.33-1.6% of total reported values. Even with removal of outliers at $p<0.01$, it nonetheless bears noting that model calibration errors have field and laboratory errors imbedded within them, as well as from other factors (Harmel et al., 2006). Model error statistics, including mean error, mean absolute error, and root mean square error, are summarized in Table 16.

Table 16. Model error results for nutrients and chlorophyll-a.

Property	N	Range	ME	MAE	RMSE	RRMSE (%)[a]
Chlorophyll-a (µg/L)	417	0.5 – 43.2	-1.3	7.9	10.3	24.0
Total P (mg/l)	595	0.005 - 0.180	-0.010	0.022	0.031	17.7
Total N (mg/L)	598	0.126 - 2.415	-0.148	0.310	0.413	18.0
Total Inorganic N (mg/L)	594	0.007 - 0.319	-0.049	0.050	0.092	29.5

[a]=(RMSE/Range)*100

Dissolved oxygen concentrations are influenced by, and also often regulate, the biogeochemical processes operating in the lake. It was previously shown that the model adequately reproduced water column temperatures (Figure 13, Table 8); the model was also generally successful in reproducing measured DO concentrations (*e.g.*, Figure 26, Table 17). (Additional profiles provided in Appendix D). While the lake was often relatively well-mixed vertically, low DO concentrations above the sediments were frequently present as a result of aerobic decomposition and respiration reactions.

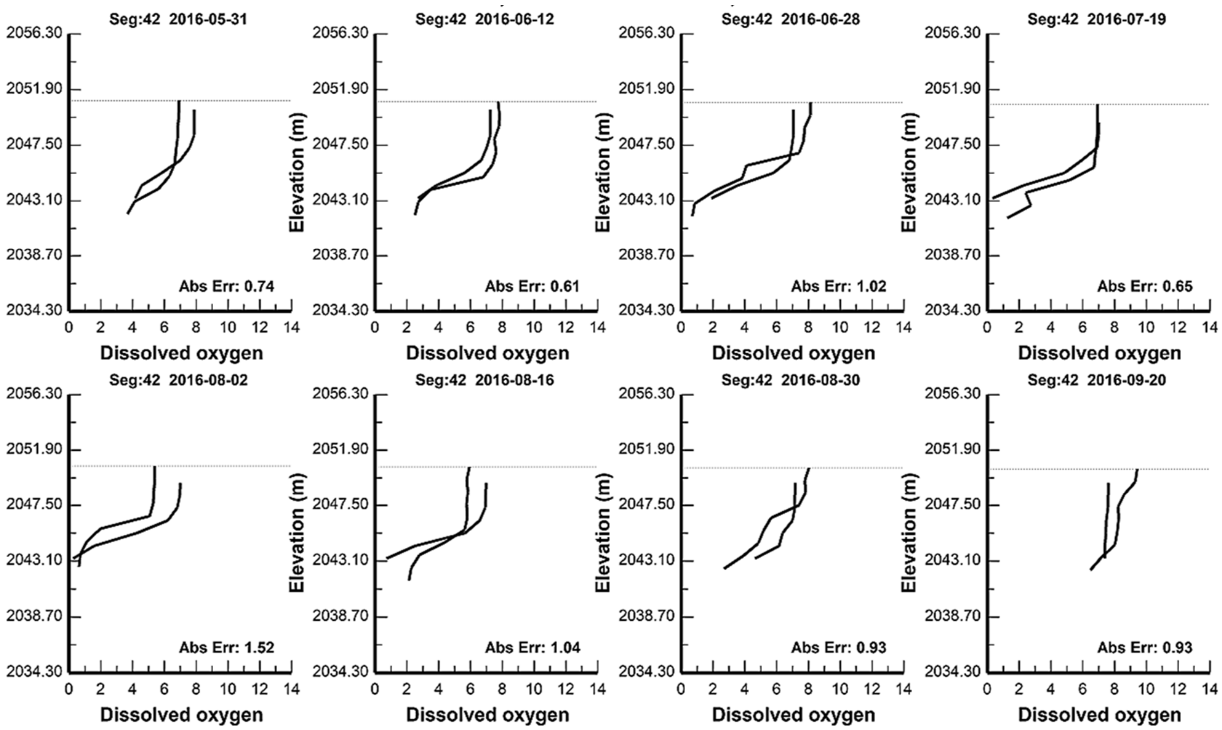


Figure 26. Example dissolved oxygen profiles at TMDL station #2 highlighting agreement between predicted and measured concentrations and periodic loss of DO in lower water column.

Table 17. Mean absolute error for model predictions of water column DO concentrations at the four TMDL sampling stations (145 profiles; 858-1974 discrete measurements in each profile).

	#1 (Dam)	#2 (Gilner Pt)	#6 (Mid-lake)	#9 (Stanfield)
MAE (mg/L)	1.40	1.25	1.16	1.02

Summary

A 2-D (longitudinal-vertical) hydrodynamic -water quality model for Big Bear Lake was developed using CE-QUAL-W2. The 2-D laterally-averaged model grid was developed from the bathymetric survey data collected by Fugro Pelagos Inc. (2006). Hydrologic data defining inflows, outflows, and withdrawals were developed from annual Big Bear Water Master reports. Hourly meteorological conditions were taken from Big Bear Airport and California Irrigation Management Information System (CIMIS) Station #199 located at the golf course. Data included solar shortwave radiation, air temperature, dewpoint temperature, windspeed, wind direction and cloud cover. Cloud cover was determined from sky cover conditions reported in METAR data for the airport. The model was calibrated against measured lake level, *in situ* profiles of temperature and DO, and laboratory analyses of water samples collected at the lake for 2009-2019. The model was first developed and calibrated for lake level, water column temperature profiles and TDS, where generally very good agreement was achieved (mean absolute errors of 3.6 cm, 0.79-0.89 °C, and 11.9 mg/L, respectively). Following this, model calibration to water quality data was conducted. The model included external nutrient loading from the watershed, atmospheric deposition, internal nutrient recycling, and nutrient uptake and release associated with macrophyte and epiphyton growth, senescence and death. Two algal groups were simulated, included one representing cyanobacteria capable of N_2-fixation. The 1st-order dynamic sediment model was combined with the 0th-order SOD model to simulate nutrient recycling and DO uptake in the surficial bottom sediments. Relative root mean square error was 17.7% for total P, 18.0% for total N, 29.5% for TIN, and 24.0 % for chlorophyll-a. Mean absolute errors for DO ranged from 1.02 – 1.40 mg/L for the 4 TMDL sampling stations.

IV. APPLICATION OF MODEL TO EVALUATE CONDITIONS WITH REPLENISH BIG BEAR PROJECT

With some confidence that the model is able to reproduce trends in water quality over a wide range of conditions, the model was used to evaluate changes in lake level and water quality under selected Replenish Big Bear project treatment scenarios. For these simulations, 1,920 af of BBARWA WWTP effluent was delivered annually through Stanfield Marsh and subsequently to the Lake. Three progressive levels of treatment assuming advanced nutrient removal and reverse osmosis (RO) technologies were evaluated (Treatment Alternatives):

(i) Alternative 1: TIN & TP Removal
(ii) Alternative 2: 70% RO (70% RO + 30% TIN & TP Removal)
(iii) Alternative 3: 100% RO

The composition of the supplemental water used in simulations varied quite substantially depending upon level of treatment (Table 18).

Table 18. Water quality of supplemental water used in model simulations (WSC, 2020b).

Constituent (mg/L)	Alternative 1	Alternative 2	Alternative 3
TDS	450	150	50
NO_3-N	0.6	0.2	0.05
NH_4-N	0.2	0.1	0.05
PO_4-P	0.25	0.06	0.02
Dissolved Organic N	1.33	0.76	0.5
Dissolved Organic P	0.24	0.04	0.01
Particulate Organic N	0.07	0.04	0.00
Particulate Organic P	0.01	0.002	0.00

These three Treatment Alternatives, with varying concentrations of TDS, phosphorus, and nitrogen (Table 18), and a flow rate of 1,920 af/yr were simulated to evaluate effects of supplementation on lake levels and concentrations of TDS, nutrients and chlorophyll-a concentrations for comparisons with baseline (2009-2019) conditions. This analysis thus allows one to compare how different Replenish Big Bear Treatment Alternatives would have altered lake conditions over the past decade, which included extreme variations in lake level and water quality.

A. Lake Level

A simple water balance calculation indicates that 1,920 af/yr of water added to Big Bear Lake would add approximately 0.2 m/yr to lake level. This level of supplementation represents about a 20% increase in average total annual inflow on a calendar year basis, with substantially larger relative contributions during periods of drought (e.g., nearly doubling the very low inflow shown in Fig. 11a during 2013). Simulations confirm that supplemental water would have increased lake level substantially over the natural 2009-2019 period (Baseline scenario), up to 1.7 m by late 2018 relative to no project (Figure 27).

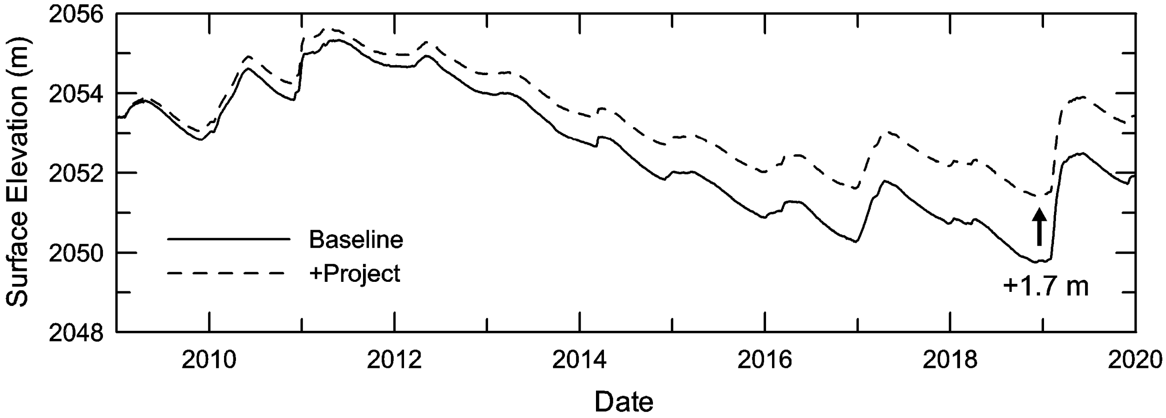


Figure 27. Predicted lake surface elevations over 2009-2019: baseline and with project.

B. Lake Area

The supplemental water also translates to increased lake surface area (Figure 28) that is a function of elevation-volume-area relationships for the Lake basin (Figure 9). Benefits of increased Lake area are especially evident during periods of drought, when Lake shoreline has substantially receded, limiting recreational and homeowner access, and resulting in extensive loss of the littoral community. For example, supplementation with project water would have increased lake area by about 300 acres, from less than 1,900 acres in 2018 to nearly 2,200 acres (Fig. 28). Moreover, the benefits of supplementation to Lake level and Lake surface area in terms of recreational access, aesthetics, ecological habitat, etc. accrue over time, especially evident during drought, until large inflows restore lake level and reset hydrologic conditions in the Lake.

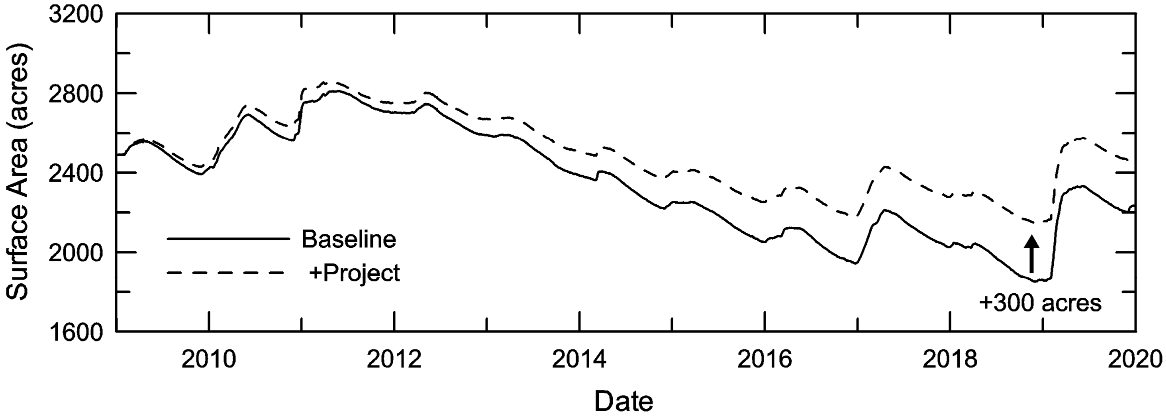


Figure 28. Predicted lake surface area over 2009-2019: baseline and with project.

C. TDS

Addition of 1,920 AFY of Alternative 1 effluent with a TDS of 450 mg/L, predictably increased TDS relative to the Baseline scenario, while Alternative 2 effluent yielded predicted TDS concentrations similar to those present in 2009-2019, and Alternative 3 effluent lowered TDS levels below the Baseline scenario (Figure 29; Table 19).

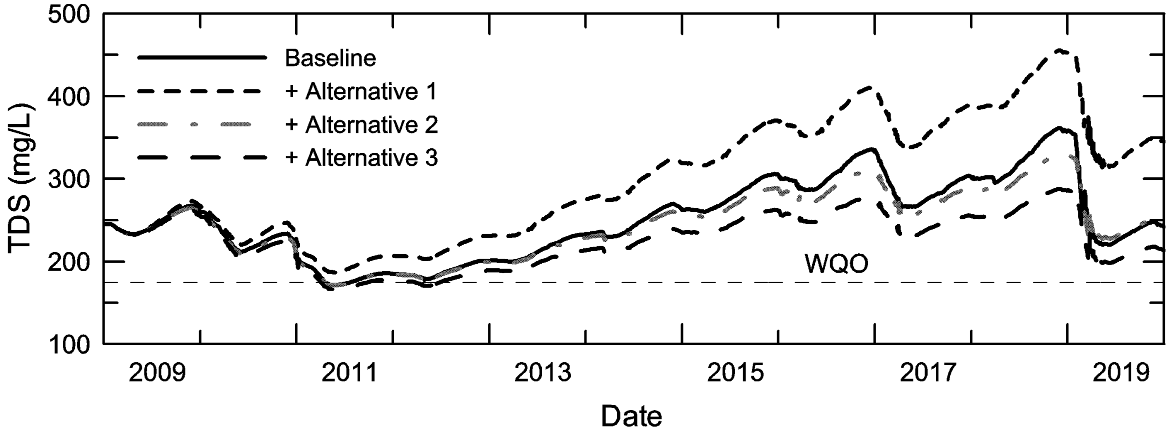


Figure 29. Predicted TDS concentrations over 2009-2019: baseline and with project.

Predicted TDS for the Baseline scenario exceeded the WQO of 175 mg/l (dashed line) 97.6% of the time over 2009-2019, a frequency equivalent to that of the Alternative 2 treatment scenario, and greater than that with Alternative 3 treatment scenario (Table 19).

Table 19. Summary of TDS concentrations for 2009-2019 under natural conditions and with project.

Scenario	Average TDS (mg/L)	Range TDS (mg/L)	WQO Exceedance Frequency (%)
Baseline	251	172-362	97.6
Alternative 1	300	187-455	100.0
Alternative 2	244	171-329	97.6
Alternative 3	226	166-287	93.3

D. Nutrients and Chlorophyll-a

Nutrients entering the lake add to the inventory of nutrients already present, which are subject to a wide array of biogeochemical processes. To help put nutrients derived from supplemental water of differing levels of treatment into context, it is useful to consider their composition and loading relative to watershed sources. Median watershed concentrations and concentrations in Alternative 1-3 effluents are provided in Table 20. Alternative 1 effluent substantially exceeds median watershed concentrations for virtually all nutrients, while addition of RO in Alternatives 2 and 3 lowers concentrations, often to levels comparable to or in some cases below median watershed levels.

Table 20. Comparison of nutrient concentrations in watershed runoff and supplemental water with the three Treatment Alternatives.

	Median Watershed Concentrations (mg/L)					Nutrient Concentrations (mg/L)		
Variable	Boulder Cr	Grout Cr	Knickerb Cr	Rathbun Cr	Summit Cr	Alt 1	Alt 2	Alt 3
NO_3-N	0.05	0.183	0.13	0.419	0.19	0.6	0.2	0.05
NH_4-N	0.011	0.01	0.015	0.015	0.015	0.2	0.1	0.05
PO_4-P	0.007	0.015	0.038	0.038	0.021	0.25	0.06	0.02
Total N	0.184	0.378	0.312	0.716	0.481	2.2	1.1	0.6
Total P	0.009	0.023	0.055	0.055	0.075	0.5	0.1	0.03
TN/TP	20.4	16.4	5.7	13.0	6.4	4.4	11	20

Normalizing project concentrations as ratios to median watershed concentrations allows comparison of relative enrichment factors for supplemental water (concentration basis) (Table 21):

Table 21. Concentration enrichment factors (supplemental/watershed).

	Concentration Enrichment Factor		
Variable	Alternative 1	Alternative 2	Alternative 3
NO_3-N	3.3	1.1	0.3
NH_4-N	13.3	6.7	3.3
PO_4-P	11.9	1.6	0.5
Total N	5.8	2.3	0.8
Total P	9.1	1.8	0.4

One thus recognizes that Alternative 1 (TIN & TP Removal) effluent represents about 6-times and 9-times greater concentrations of TN and TP, respectively, compared with the watershed, while Alternative 2 (70% RO) is on the order of about 1-2 times higher concentrations, and Alternative 3 (100% RO) is significantly lower than typical concentrations of most forms of nutrients delivered from the watershed (Table 21). Importantly, Alternative 1 effluent is not only much higher in nutrient concentrations, it also has a very low TN:TP ratio (Table 20), that could potentially favor N_2-fixing blue-green algae.

Simulations demonstrated that water quality in the Lake is broadly similar between the Baseline scenario and the Alternative 2 and 3 treatment scenarios, but is significantly degraded with Alternative 1 effluent, with marked predicted increases in TP, TN, and chlorophyll-a concentrations (Figure 30).

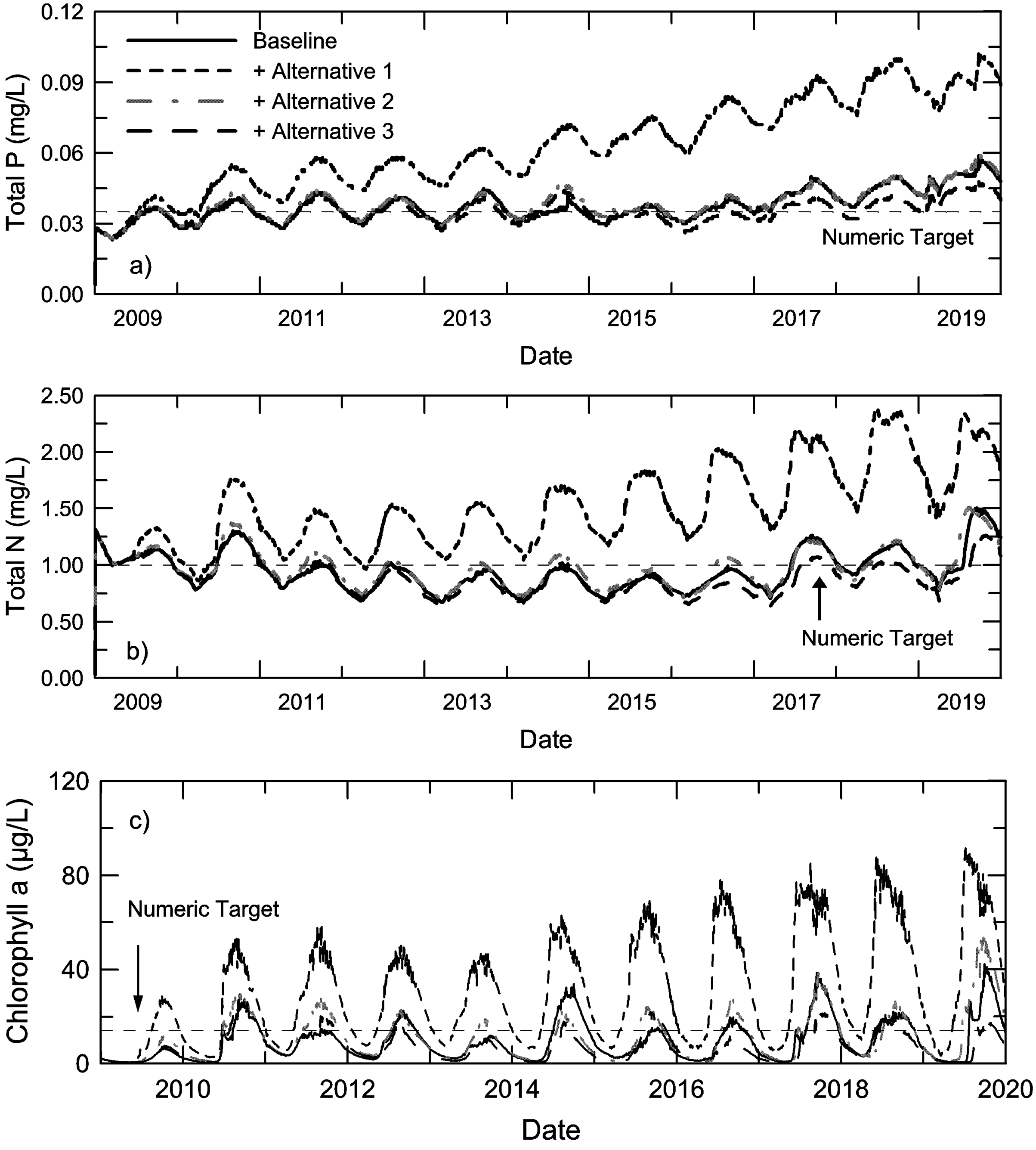


Figure 30. Predicted concentrations of a) total P, b) total N, and c) chlorophyll-a at TMDL station #2 (photic zone).

Supplementation with Alternative 1 effluent also significantly increased littoral plant production, often doubling peak values relative to that predicted under the Baseline scenario and with treatment alternatives 2 and 3 (Figure 31).

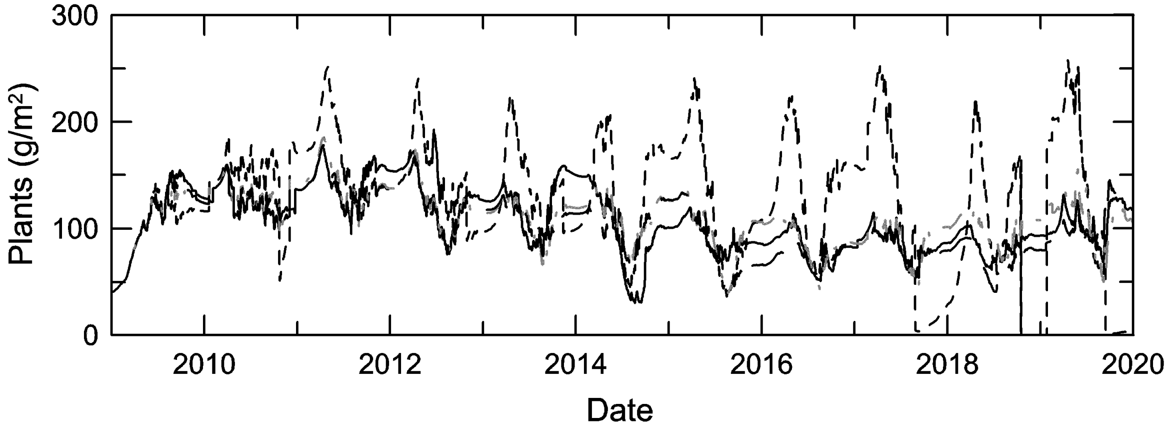


Figure 31. Predicted plant biomass at TMDL station #2 (photic zone). Legend shown in Fig. 30a.

Average concentrations at TMDL station #2 (Gilner Point) for the 11-yr simulation period highlight substantial predicted increases in total P, PO_4-P, and total N resulting from supplementation with Alternative 1 effluent (Table 20). The large increase in P concentrations also yielded a substantial increase in predicted average chlorophyll-a concentration (30.5 vs 9.3 µg/L). Supplementation with Alternative 1 effluent also increased TIN concentrations compared with the Baseline scenario and increased (non-phytoplankton) plant production. Supplementation with Alternative 2 effluent yielded predicted average water quality quite similar to the Baseline scenario, while supplementation with Alternative 3 effluent was predicted to improve average water quality somewhat (Table 22).

Table 22. Average concentrations of nutrients and chlorophyll-a for 2009-2019 period under the Baseline scenario and with supplementation with water from the three Treatment Alternatives.

Scenario	Total N (mg/L)	Total P (mg/L)	Chl a (µg/L)	PO_4-P (µg/L)	TIN (mg/L)	Plants (g/m^2)
Baseline	0.948	0.037	9.3	3.5	0.049	106.9
Alternative 1	1.511	0.063	30.5	7.8	0.120	126.3
Alternative 2	0.979	0.038	10.9	3.6	0.047	110.2
Alternative 3	0.894	0.035	7.1	3.3	0.046	103.1

Supplementation of treated effluent from the BBARWA WWTP is thus predicted to yield different water quality in Big Bear Lake depending upon effluent water quality. Supplementation with Alternative 1 effluent is predicted to substantially increase lake total P and PO_4-P concentrations, which may also increase N_2-fixing blue-green algae, as well as increase epiphyte and macrophyte production. Supplementation with Alternative 2 effluent is predicted to yield water quality conditions similar to natural conditions, while providing increased lake volume, lake surface area, and additional (non-planktonic) plant biomass. Further treatment of effluent in Alternative 3 was predicted to slightly improve water quality compared with that predicted for the 2009-2019 Baseline scenario.

Cumulative distribution functions for basin-wide volume-averaged concentrations of TP and TN highlight the substantial increase in nutrients that would result from the addition of Alternative

1 effluent, while also demonstrating that Alternative 2 effluent is predicted to yield nutrient levels similar to predicted 2009-2019 levels, while supplementation with Alternative 3 effluent is predicted to yield slightly improved (lower) concentrations (Figure 32).

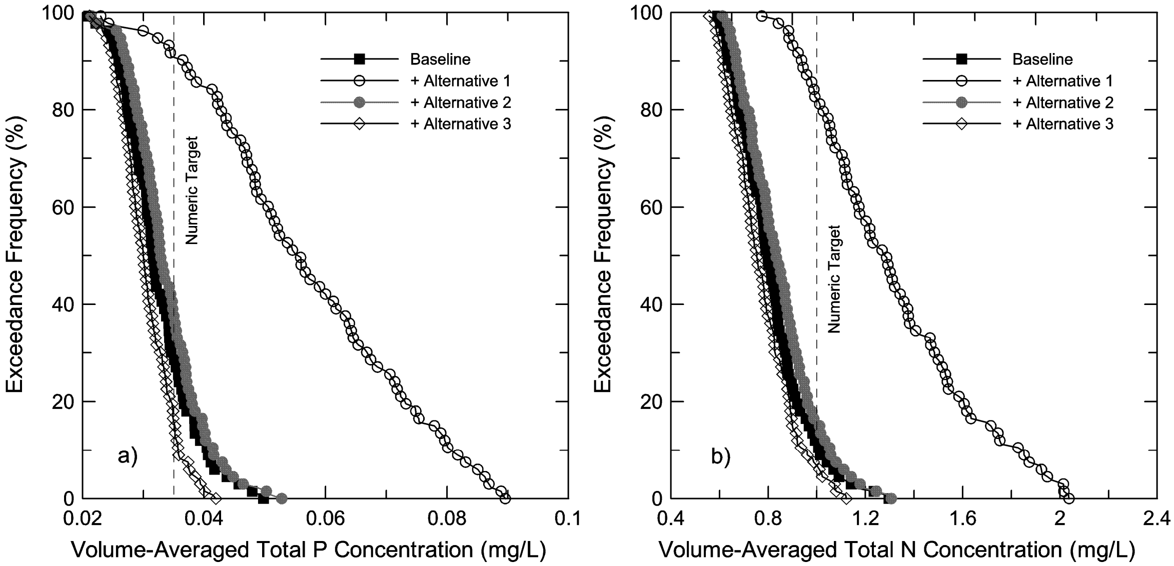


Figure 32. Cumulative distribution functions for predicted baseline and supplementation scenarios of volume-weighted concentrations of a) total P and b) total N.

<u>Summary</u>

Supplementation of natural flows with 1,920 af/yr of Replenish Big Bear water was predicted to add about 0.2 m annually to the lake relative to levels observed in 2009-2019 (baseline), and which accrued over time such that the lake was predicted to be 1.7 m higher in late 2018 compared to the level present at that time. Supplementation also increased lake volume and surface area, with lake area about 300 acres (16%) larger in late 2018 compared with actual area (approximately 2200 acres vs 1900 acres, respectively). Addition of 1,920 af/yr of Alternative 1 water significantly increased TDS levels in the lake, increasing average predicted TDS from 251 mg/L for the baseline (natural) condition for 2009-2019 to 300 mg/L, while Alternatives 2 and 3 were predicted to yield slightly lower average TDS concentrations of 244 and 226 mg/L, respectively. Exceedance of the TDS water quality objective of 175 mg/L was predicted to occur 97.6% of the time for both the baseline condition and for Alternative 2, while exceedance frequency increased to 100% for Alternative 1 and was reduced to 93.3% for Alternative 3.

Nutrient concentrations in the Replenish Big Bear water varied markedly with treatment, with total N and total P concentrations in Alternative 1 being about 6-9x higher than median watershed concentrations, while concentrations in Alternative 2 were projected to be 1.8-2.3x larger and Alternative 3 being about 0.4-0.8x that of median watershed values. The increased nutrient loading from Alternative 1 had a strongly detrimental effect on water quality, increasing average concentrations over 2009-2019 baseline of total N by about 50%, total P by 70%, and chlorophyll-a by 300%. In comparison, further treatment of effluent yielded average concentrations comparable to (Alternative 2) or slightly improved (Alternative 3) relative to the baseline (natural no-project) condition.

V. PREDICTED LONG-TERM FUTURE CONDITIONS WITH REPLENISH BIG BEAR PROJECT

Simulations were extended from the reference period (2009-2019) to include 30 additional years, for a total of 41 simulation years that yielded potential trajectories for water level, area, TDS, and nutrients out to the beginning of 2050. As previously noted, the model requires extensive data for meteorological conditions (air temperature, dewpoint temperature, wind speed, wind direction, cloud cover, and solar radiation), as well as water inflows, outflows, and withdrawals. While hourly weather forecasts are available 7-10 days in advance from the National Weather Service (NWS) and 5-10 day flow forecasts are available for limited gaged stations from the NWS River Forecast Centers, we obviously do not know *a priori* these detailed meteorological and hydrological conditions for the next 30 years. Similarly, while downscaled global climate models provide some projections about trends in air temperature and precipitation, they do not provide information with sufficient resolution to allow direct use in our simulations.

Given these constraints, existing meteorological and flow data for 2009-2019 were used as the basis for forecasts. (An effort was made to expand the meteorological record to include additional years, but available weather data for the Big Bear Airport only go back to April 2007, thus providing only one additional full year of record, so existing data were used.) The 2009-2019 period included record or near record air temperatures and intervals of both extreme drought and very high precipitation/runoff that captured much of the anticipated inter-annual variability in meteorology and hydrology (e.g., Table 23). For example, average precipitation over 2009-2019 period was not statistically significantly different than that of the past 43 years (e.g., 31.7±15.6 vs 34.8±14.7 in/yr at Bear Valley Dam). Precipitation was better described as log-normally distributed; however, with geometric mean values very similar to median values, and both being slightly lower (reflecting increased prevalence of drought) but well-captured in the 2009-2019 dataset. Perhaps more importantly, minimum and maximum values for the 2009-2019 period were also similar to the larger 1977-2019 dataset (e.g., the highest annual precipitation at the Big Bear Community Services District (BBCCSD) was recorded in 2010, within the 2009-2019 record).

Table 23. Annual precipitation (calendar year) recorded at Bear Valley Dam and BBCCSD. (Water Master, 2019).

Precipitation (in/yr)	Bear Valley Dam		BBCCSD	
	1977-2019	2009-2019	1977-2019	2009-2019
Average	34.8	31.7	14.9	17.5
Geometric Mean	31.6	29.1	13.3	16.3
Median	31.8	27.8	14.1	14.8
Minimum	13.2	14.4	3.8	8.2
Maximum	73.8	64.1	33.2	33.2

Assuming that 2009-2019 is broadly representative of likely future meteorological and hydrologic conditions, Monte Carlo techniques were used to randomly select 100 different 30-year annual records from this set of data. Thus, any given future year was assumed to essentially have a 1-in-11 chance of looking like any one of the years from the 2009-2019 period in terms of meteorological conditions, inflows, withdrawals, and releases for downstream flow requirements. Impacts of climate change were considered; air temperature increases would increase evaporation losses from lake, but also likely yield more rain and rain-on-snow events that would increase runoff and inflows to lake. Without detailed watershed modeling, it is not possible to resolve these conflicting impacts on the water budget for the lake, so for the purposes of this analysis, they were assumed to cancel out. The Monte Carlo analysis yielded 30-year average flow rates that ranged from 6,891 to 15,115 af/yr (Figure 33). Individual year flow rates varied more widely, ranging from 1,961 – 27,579 af/yr (not shown).

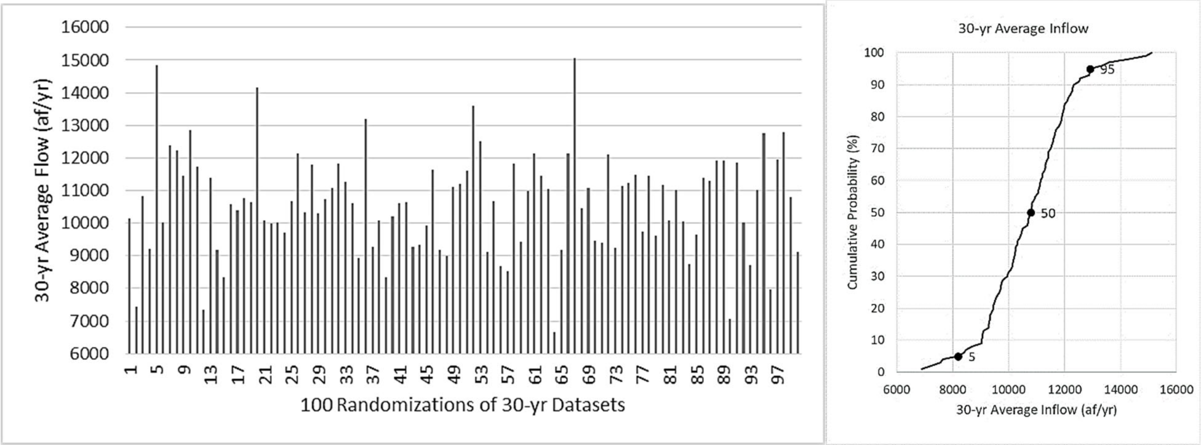


Figure 33. Thirty year average flow rates for 100 random datasets.

From this dataset (Figure 33), three hydrologic scenarios were selected for further analysis corresponding to the 5th-percentile, 50th-percentile (median), and 95th-percentile 30-yr average flow rates. The 5th-percentile corresponds to an average inflow rate of 8,646 af/yr and represents extended drought, not unlike that present in the 1950's-60's, while the 50th-percentile hydrologic scenario corresponds to intervals of both high runoff and drought, comparable to 2009-2019 (average annual inflow of 10,595 af/yr), and the 95th-percentile represents a period of protracted above average rainfall and runoff (average annual inflow of 12,225 af/yr). Cumulative inflows for these 3 hydrologic scenarios are presented in Figure 34. The corresponding meteorological, outflow and withdrawal conditions were used as input for CE-QUAL-W2 simulations. The 3 simulations represent forecasts of conditions subject to the temporal boundary conditions (inflows, meteorological conditions, etc.), and thus are not predictive of conditions at specific points of time in the future. On that basis, results are presented as cumulative distribution functions rather than time-series to convey information in a statistical-probabilistic framework rather than as strict forecasts in time. Lake properties are contrasted between baseline conditions under the 3 hydrologic scenarios and with implementation of the Replenish Big Bear project.

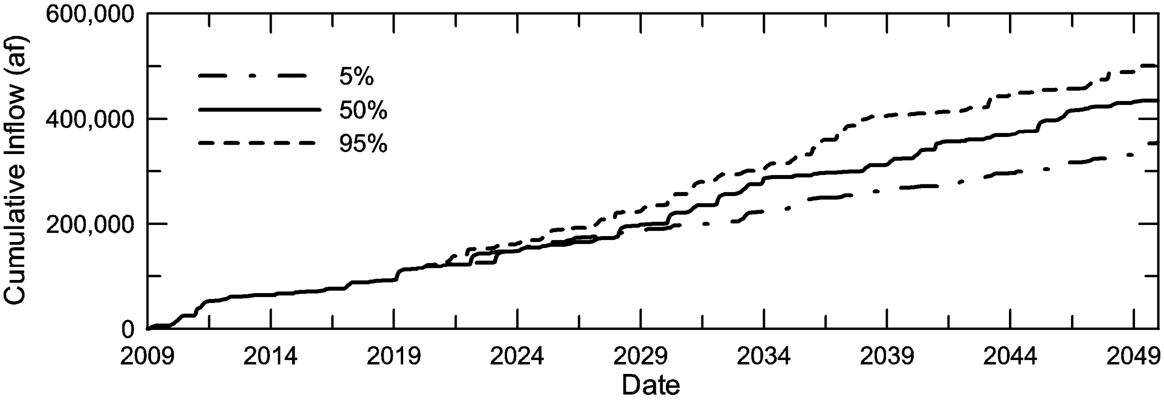


Figure 34. Cumulative inflows under 5th-, 50th- and 95th-percentile 30-yr average hydrologic scenarios.

A. Lake Surface Elevation

The 3 hydrologic scenarios had pronounced effects on predicted lake levels, with the 5th-percentile (chronic drought) scenario yielding elevations as low as 2044.9 m above MSL and a median elevation of 2048.8 m (Figure 35a). The 50th- and 95th-percentile hydrologic scenarios yielded predictably higher lake levels (e.g., median levels of 2052.2 and 2053.1 m, respectively) (Figure 35a). Supplementation with 1,920 af/yr of Replenish Big Bear water markedly increased lake levels, *e.g.*, raising the minimum level for 5th-percentile scenario by up to 4.6 m and increasing median level from 2048.8 m for baseline to 2052.0 m (Figure 35b).

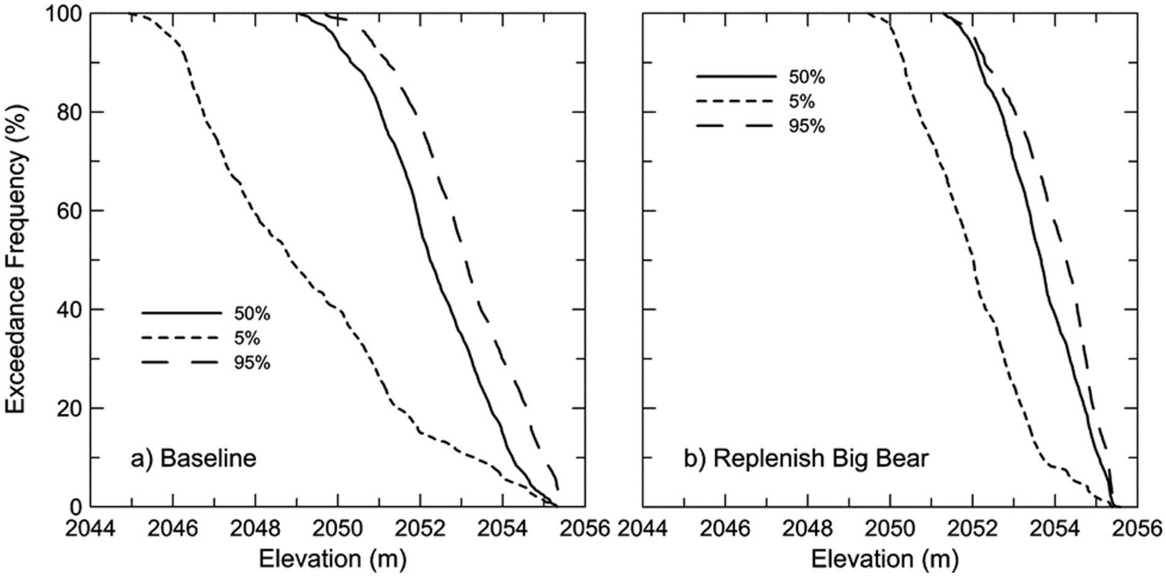


Figure 35. CDFs of predicted lake elevations at 5th-, 50th- and 95th-percentile hydrologic scenarios for a) baseline conditions and b) supplementation with Replenish Big Bear water.

B. Lake Volume

Supplementation also substantially increased lake volumes, with volumes potentially as low as 6,000 af and a median volume of about 23,000 af for the 5th-percentile (drought) scenario (Figure 36). Supplementation with Replenish Big Bear water resulted in significant increases in lake volume for the other hydrologic scenarios as well (Figure 36).

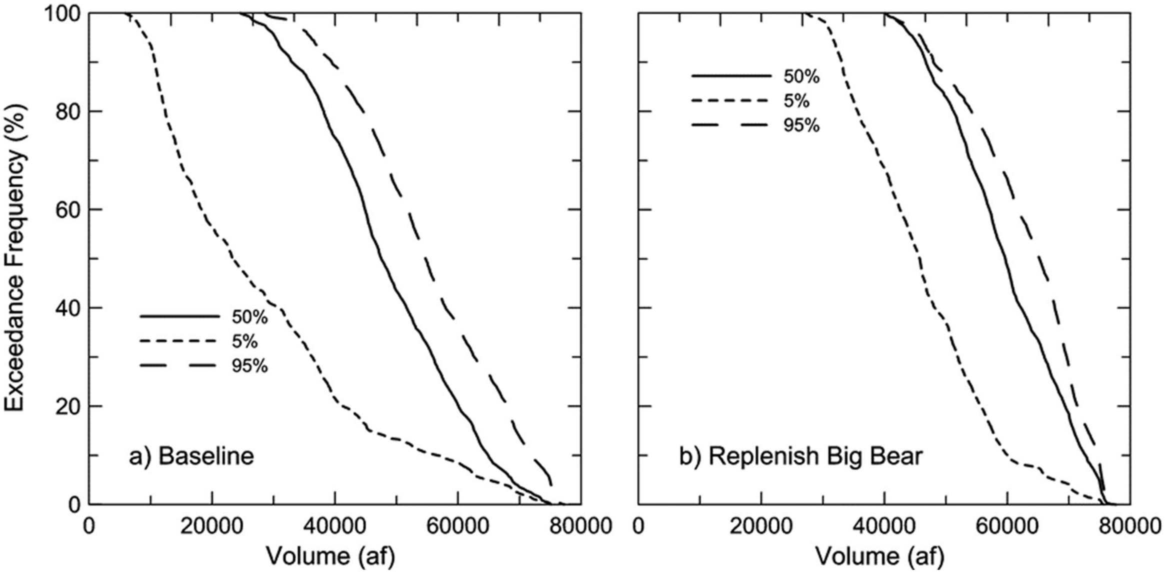


Figure 36. CDFs of predicted lake volumes at 5th-, 50th- and 95th-percentile hydrologic scenarios for a) baseline conditions and b) supplementation with Replenish Big Bear water.

C. Lake Surface Area

The 5th-percentile hydrologic scenario also yielded very low lake surface areas, potentially <1000 acres and a median area of about 1700 acres (Figure 37a). The minimum predicted lake surface areas were about 2x larger and median surface areas were approximately 2300 and 2500 af for the 50th- and 95th-percentile hydrologic scenarios, respectively. Supplementation substantially increased lake area, shifting all CDFs to higher area values (Figure 37b). This can be seen more graphically in Figure 38, where the areas corresponding to the minimum and 75% exceedance frequencies (predicted to occur 25% of the time under the simulated protracted drought condition) are projected onto the natural lake boundary for the baseline and with project. At the minimum area, the lake divides into the impounded area behind the dam and a 2nd very shallow mid-basin, while the Project is able to maintain an extensive and contiguous lake area through the main body of the lake (Figure 38a). A considerable additional area is also maintained at the 75% exceedance frequency with supplementation (Figure 38b).

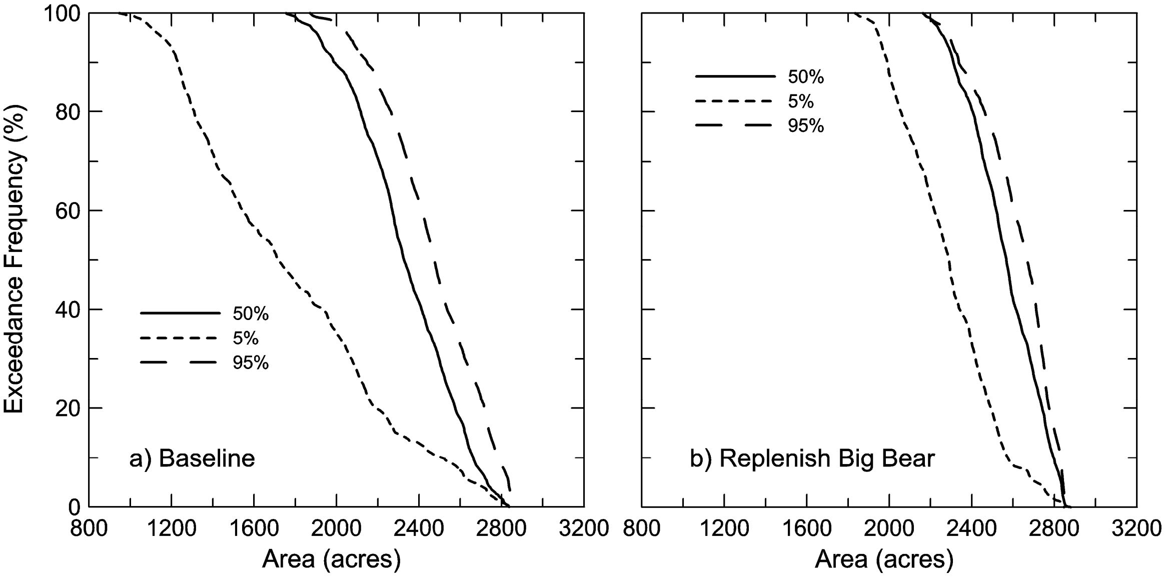


Figure 37. CDFs of predicted lake areas at 5th-,50th- and 95th-percentile hydrologic scenarios for a) baseline conditions and b) supplementation with Replenish Big Bear water.

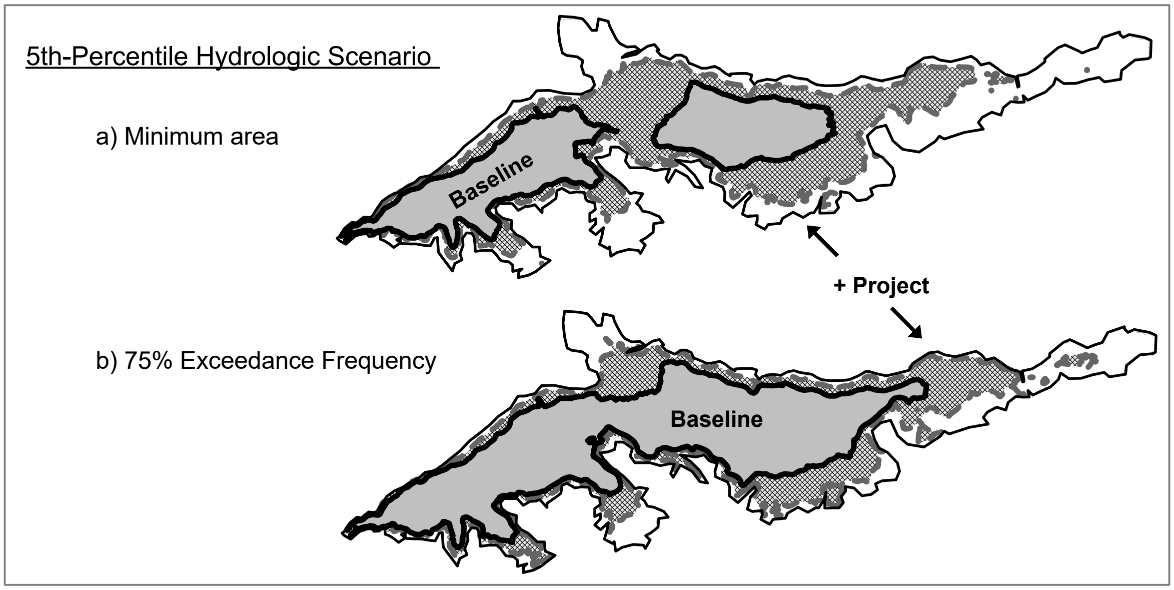


Figure 38. Lake surface under 5th-percentile flows (protracted drought) depicting areas under baseline conditions (solid gray) and with project (cross-hatched) at a) minimum area and b) 75% exceedance frequency (predicted to occur 25% of the time under the simulated protracted drought condition).

D. Total Dissolved Solids

The concentrations of TDS in Big Bear Lake vary naturally as a function of lake level as a result of runoff inputs and evapoconcentration. Thus, predicted TDS concentrations were greatest for the 5th-percentile hydrologic scenario (protracted drought) and lower for the 50th- and 95th-percentile hydrologic scenarios (Figure 39a). Unlike lake elevation, volume and area which are independent of the type of effluent treatment, predicted TDS concentrations in the lake are quite sensitive to it (Figure 39b-d).

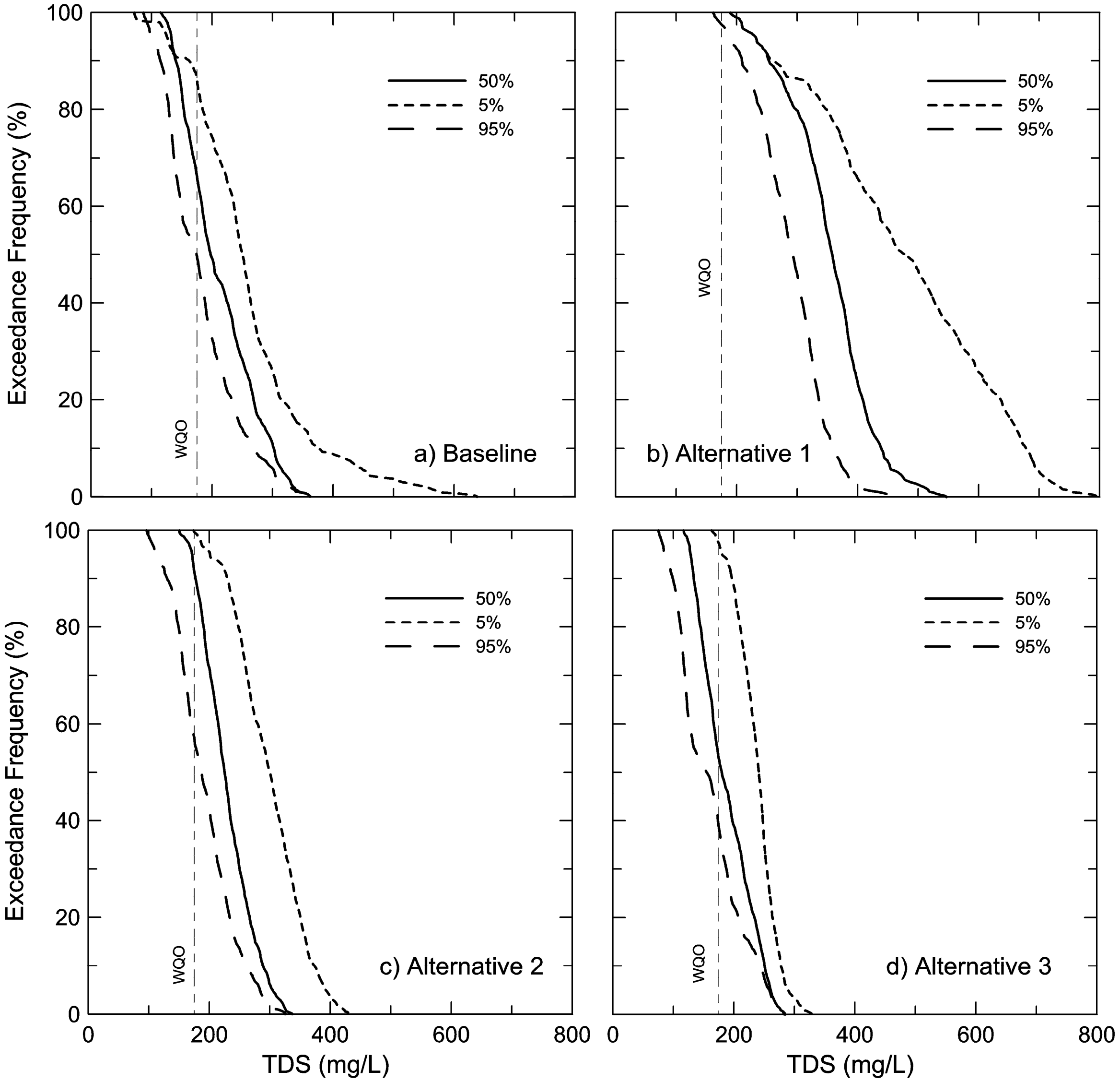


Figure 39. CDFs of predicted lake TDS at 5th-,50th- and 95th-percentile flows for a) baseline conditions, and supplementation with b) Alternative 1, c) Alternative 2 and d) Alternative 3 water.

Alternative 1 treatment, involving only nutrient removal, yielded high concentrations of TDS that was predicted to exceed the water quality objective by wide margins (Figure 38b), while Alternative 2 shifted CDFs from baseline to slightly higher TDS levels, and the highest level of treatment (Alternative 3) yielded slightly lowered concentrations relative to Baseline scenario (Figure 39c,d).

E. Total P

Total P concentrations for the baseline condition were predicted to vary under the 3 hydrologic scenarios, exceeding 0.05 mg/L with some frequency under the drought scenario (Figure 40a).

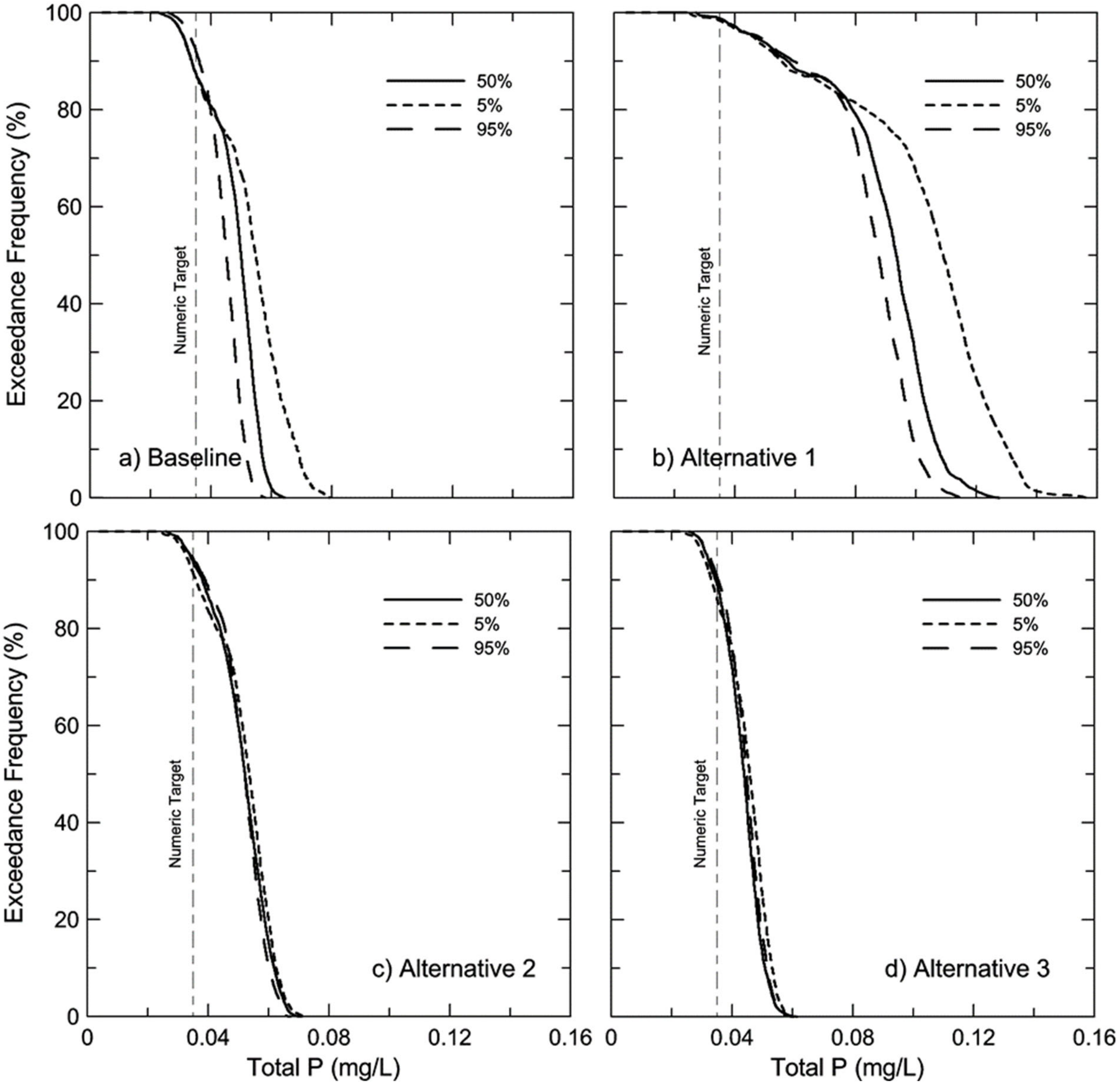


Figure 40. CDFs of predicted total P levels at 5th-, 50th- and 95th-percentile hydrologic scenarios for a) Baseline, and supplementation with b) Alternative 1, c) Alternative 2 and d) Alternative 3 water.

As noted in simulations for 2009-2019, supplementation with Replenish Big Bear effluent substantially degraded predicted water quality, and increased total P (Figure 40b), as well as total N (Figure 41b) and chlorophyll-a (Fig. 42b). Supplementation with higher quality Alternative 2 and 3 water reduced natural variability and provided comparable or lower levels (Figure 40c,d).

F. Total N

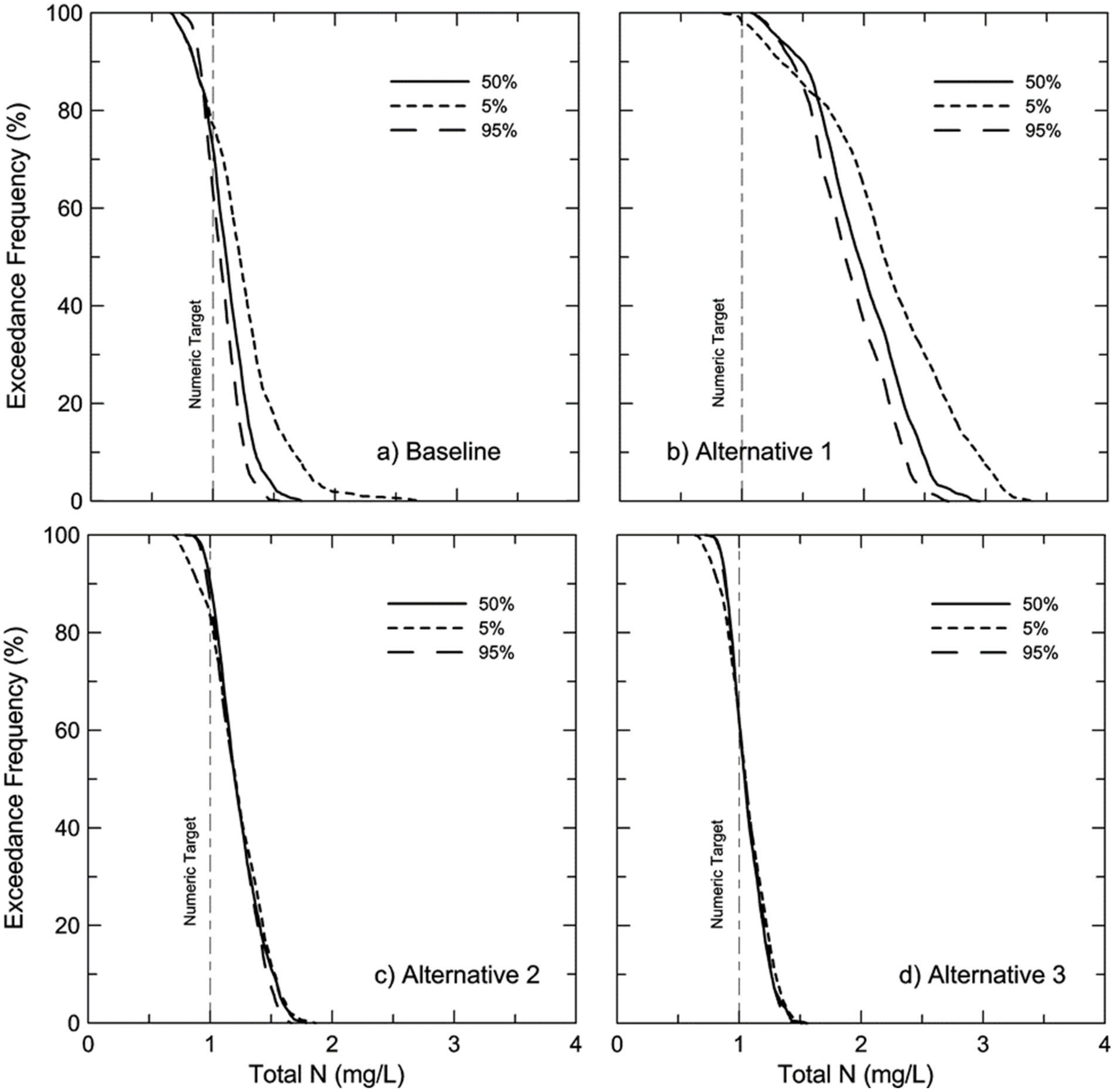


Figure 41. CDFs of predicted total N levels at 5th-, 50th- and 95th-percentile hydrologic scenarios for a) baseline conditions, and supplementation with b) Alternative 1, c) Alternative 2 and d) Alternative 3 water.

Predicted total N concentrations (Figure 41) followed the same trends as total P (Figure 40), with Alternative 1 significantly increasing concentrations, while Alternatives 2 and 3 reduced variability in baseline case due to stabilization of lake level with high quality water (Figure 41).

G. Chlorophyll-a

Chlorophyll-a concentrations followed similar trends as noted for total P and total N, with a >5x increase in median predicted concentrations with Alternative 1 compared with baseline, while Alternatives 2 and 3 yielded comparable or slightly higher predicted concentrations (Figure 42).

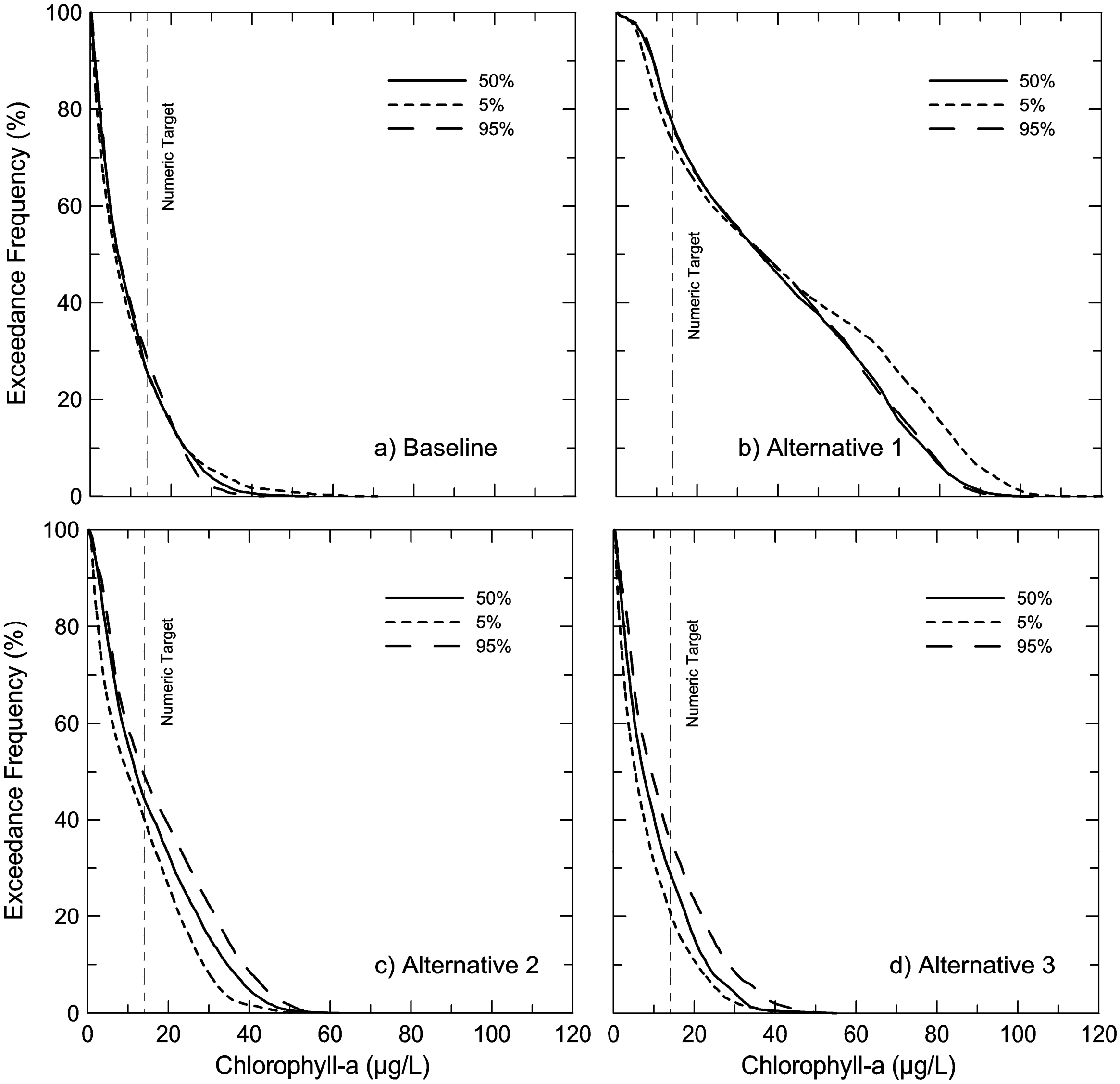


Figure 42. CDFs of predicted chlorophyll-a levels at 5th-, 50th- and 95th-percentile hydrologic scenarios for a) Baseline, and supplementation with b) Alternative 1, c) Alternative 2 and d) Alternative 3 water.

CDF Summary

CDFs convey a great deal of information, although it is often not easy to readily resolve differences across multiple graphs. Median lake dimensions for the 3 different hydrologic scenarios with and without supplementation with water from the Replenish Big Bear project from Figures 34-36 are summarized in Table 24.

Table 24. Influence of hydrologic scenarios and supplementation on median lake dimensions.

Parameter	Scenario	5th-Percentile	50th-Percentile	95th-Percentile
Elevation (m)	Baseline	2048.9	2052.2	2053.1
	+Project	2052.0 (+3.2)	2053.7 (+2.2)	2054.3 (+1.6)
Volume (af)	Baseline	23,404	47,536	54,724
	+Project	45,746 (+22,342)	59,664 (+12,128)	65,204 (+10,480)
Area (acres)	Baseline	1717	2328	2474
	+Project	2290 (+572)	2568 (+240)	2669 (+195)

Median concentrations of TDS, total N, total P and chlorophyll-a under the different hydrologic scenarios and levels of treatment are summarized in Table 25. As evident in the CDFs, the level of treatment of the supplemental water substantially affects the resulting water quality in the lake. Treated effluent with nutrient removal (Alternative 1), without additional treatment, offsets or other strategies, is predicted to have significant negative impacts to water quality in the lake, nearly doubling median concentrations of total P and total N, and increasing median chlorophyll-a concentrations by >5x relative to levels predicted for the natural (baseline) scenario (Table 25). Further advanced treatment of effluent (Alternatives 2 and 3), however, yielded predicted water quality broadly similar to or slightly better than the baseline case (Table 25).

Table 25. Influence of hydrologic scenarios and supplementation with alternative levels of treatment on predicted median concentrations of TDS, total N, total P and chlorophyll-a.

Parameter	Scenario	5th-Percentile	50th-Percentile	95th-Percentile
TDS (mg/L)	Baseline	250	198	175
	Alternative 1	478	358	293
	Alternative 2	300	225	187
	Alternative 3	241	180	155
Total P (mg/L)	Baseline	0.055	0.050	0.045
	Alternative 1	0.109	0.094	0.088
	Alternative 2	0.054	0.052	0.052
	Alternative 3	0.046	0.044	0.045
Total N (mg/L)	Baseline	1.22	1.11	1.06
	Alternative 1	2.17	1.96	1.85
	Alternative 2	1.21	1.20	1.20
	Alternative 3	1.05	1.05	1.05
Chlorophyll-a (µg/L)	Baseline	6.2	6.9	7.0
	Alternative 1	36.1	35.6	36.5
	Alternative 2	9.7	11.9	13.7
	Alternative 3	5.4	7.3	9.4

Summary

Simulations for 2009-2019 were extended to 2050 to evaluate possible long-term conditions in the lake under natural hydrologic variability with and without supplemental water from

Replenish Big Bear. Three hydrologic scenarios representing the 5th-, 50th- and 95th-percentile 30 year average annual flow records were used for predictions of future conditions in the lake. The 5th-percentile corresponded to an average inflow rate of 8,646 af/yr and represents extended drought, while the 50th-percentile (median) corresponded to intervals of both high runoff and drought comparable to 2009-2019 (average annual inflow of 10,595 af/yr), and the 95th-percentile represented a period of protracted above average rainfall and runoff (average annual inflow of 12,225 af/yr).

Supplementation with Replenish Big Bear was predicted to influence long-term (2009-2050) conditions in the lake which varied under the 3 hydrologic scenarios. Under the 50th-percentile hydrologic scenario, Replenish Big Bear was predicted to increase average lake level by 1.5 m, lake volume by nearly 13,000 af, and lake area by 260 acres relative to the predicted long-term baseline (no-project) condition. Water quality varied with level of effluent treatment, with Alternative 1 nearly doubling predicted long-term average concentrations of TDS, total P and total N and quadrupling average predicted chlorophyll-a levels. Long-term simulations indicate slight increases in average TDS, total P and total N and modest increase in chlorophyll-a for Alternative 2, and generally slight reductions or no significant change in concentrations with Alternative 3. Supplementation was predicted to have more substantial effects under the 5th-percentile hydrologic (drought) scenario, providing an average increase in lake level of 3.4 m, increase in volume of 16,104 af, and an additional average 638 surface acres (about 40% increase) relative to baseline. As with the 50th-percentile hydrologic scenario, supplementation with Alternative 1 effluent substantially degraded lake water quality, while further treatment as provided in Alternatives 2 and 3 yielded comparable or slightly improved water quality in the lake. Effects of Replenish Big Bear were more modest at the 95th-percentile runoff scenario, when supplementation is less important, owing to the lower overall contributions of water and TDS and nutrients relative to the watershed.

VI. ROUTING OF SUPPLEMENTAL WATER THROUGH STANFIELD MARSH

Simulations involved the delivery of Replenish Big Bear project water through Stanfield Marsh and into the main body of the lake. Wetlands are often very good at improving water quality by filtering and settling out of particulate matter, biological uptake of dissolved forms of nutrients, and under favorable conditions also denitrification and loss of NO_3-N to the atmosphere. Stanfield Marsh was predicted to be an effective sink for total P in supplemental water with Treatment Alternatives 1 and 2 but was a modest source of total P for Alternative 3 water (Figure 43, Table 26).

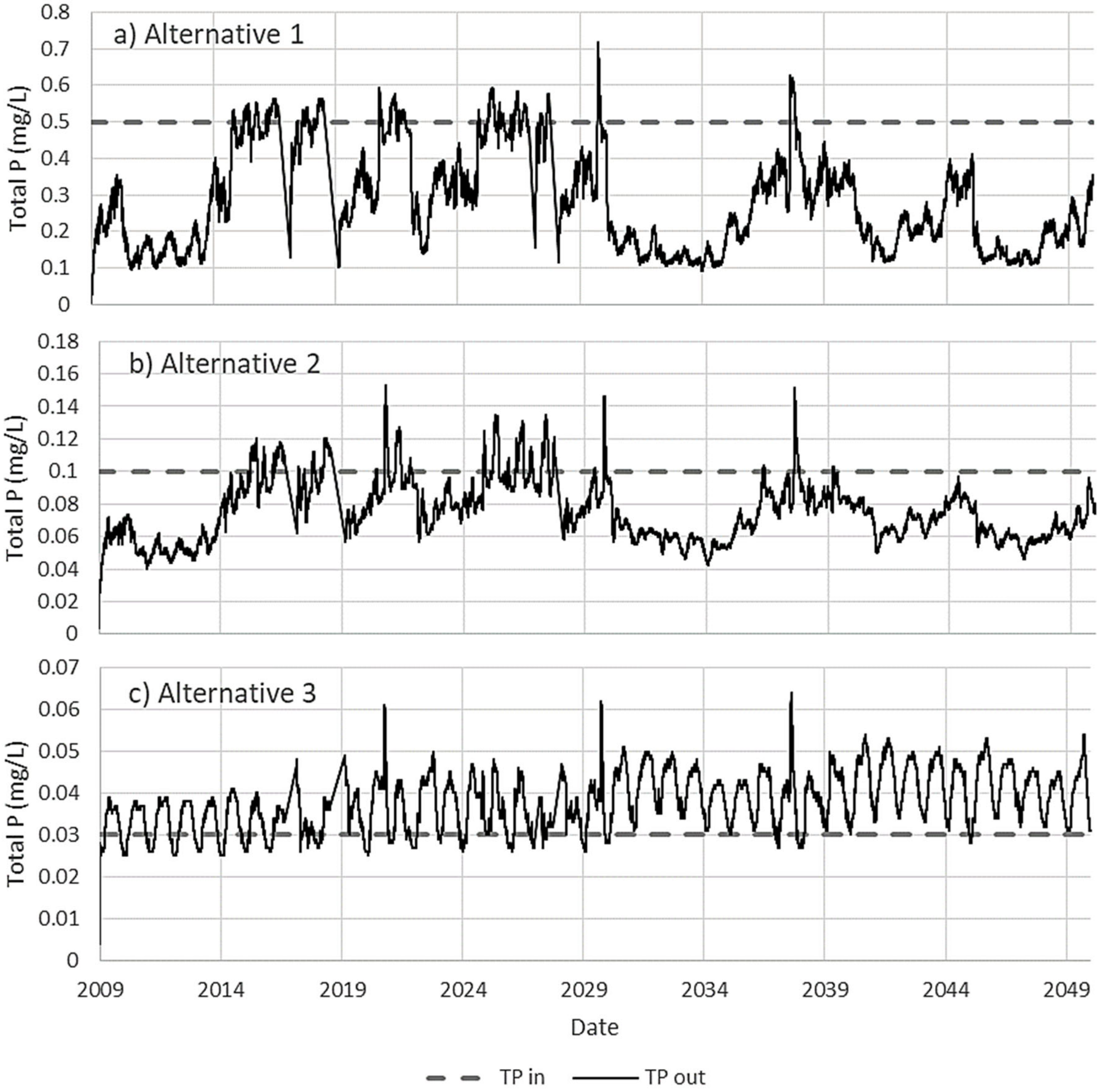


Figure 43. Total P concentrations into and out of Stanfield Marsh: a) Alternative 1, b) Alternative 2, and c) Alternative 3.

Interestingly, the marsh was predicted to be a net source of N for all 3 treatment scenarios; the basis for this is not entirely clear at this time, but sediment mineralization and potentially some N_2-fixation may be occurring during periods of intense primary production that could increase the total N concentration. Stabilization of the water level within the marsh through some hydraulic control would presumably increase nutrient retention and could promote denitrification, although additional work is needed to understand the dynamics within the Marsh, especially given natural variations in lake levels and intervals of wetting and desiccation.

Table 26. Predicted average total P and total N removal in Stanfield Marsh.

	Alternative 1		Alternative 2		Alternative 3	
	% Removal	kg/yr	% Removal	kg/yr	% Removal	kg/yr
Total P	14.8	175	8.4	20	-10.3	-7
Total N	-22.5	-1174	-17.0	-442	-19.0	-270

Summary

Simulations indicate net removal of total P from Alternative 1 and Alternative 2 effluents during flow through Stanfield Marsh, while the Marsh was predicted to be a modest source of total P to Alternative 3 water with very low influent concentrations. Interestingly, the Marsh was predicted to be a source of total N across all levels of treatment, due presumably to sediment decay, some N_2-fixation and subsequent decay in response high PO_4-P concentrations and high TN:TP ratios in the effluent. Further work is needed, however, to better understand the role of the Marsh as a net sink and/or source for nutrients.

VII. SUMMARY

Lake conditions and water quality in Big Bear Lake varied significantly over 2009-2019, with wide natural variations in lake level, volume and surface area, as well as concentrations of TDS, nutrients and chlorophyll-a. Statistical, machine learning and hypolimnetic mass balance analyses provided valuable new information about water quality in Big Bear Lake, while CE-QUAL-W2 was able to reproduce observed trends in lake conditions. Supplementation of natural runoff with Replenish Big Bear water significantly increased lake levels, volumes and surface areas, especially during periods of drought, with resulting recreational, aesthetic, community and related benefits. The level of treatment had dramatic effects on water quality, however. Nutrient removal (Alternative 1) was not sufficient to protect water quality in Big Bear Lake, although nutrient removal with further treatment (Alternatives 2 and 3) was predicted to yield water quality comparable to or slightly improved relative to baseline conditions.

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APPENDIX C: REPLENISH BIG BEAR: MODELING OF HIGHER FLOWS AND WITH ZERO TP LOAD

REPLENISH BIG BEAR: MODELING OF HIGHER FLOWS AND WITH ZERO TP LOAD

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Introduction

It was previously noted that water quality was predicted to vary markedly with the level of treatment of added Replenish Big Bear (RBB) recycled water, with Alternative 1 (TIN and TP removal) significantly degrading water quality in Big Bear Lake relative to predicted baseline conditions, while Alternative 2 (70% RO) modestly increased average predicted concentrations of TN, TP and chlorophyll-a, and Alternative 3 (100% RO) was predicted to slightly improve average water quality for the 2009-2019 period (Anderson, 2021, Table 22). Long-term simulations for different hydrologic scenarios yielded similar results, with 100% RO yielding predicted water quality typically comparable to baseline conditions. Notwithstanding, some subtle differences were observed between predicted median baseline concentrations and those for Alternative 3 which assumed steady annual flows of 1920 af/yr of 100% RO water (Anderson, 2021, Table 25).

Recent engineering work indicates that slightly higher inflows, up to 2210 af/yr, can be attained by the Replenish Big Bear project by employing additional brine minimization technology (Table 1). Note that a portion of the water produced by RBB may be discharged to Shay Pond and the earlier "Alternative 3" scenario had excluded those flows (up to 80 af/yr) from the analysis. However, to be conservative for permitting purposes, this analysis is based on discharging all of the recycled water produced to the Lake.

Table 1. Initial and recently updated Replenish Big Bear (RBB) flow projections.

Scenario	**Annual RBB Inflow (af)**	**Daily RBB Inflow (MGD)**
Baseline	0	0
Alternative 3 [(a)]	1920	1.71
High Flow (99% recovery) [(b)]	2210	1.57 – 2.18
Mid Flow (90% recovery) [(b)]	2009	1.42 – 1.98

Notes:

[(a)] Alternative 3 was assessed in the 2021 Lake Analysis and assumed that of the total Replenish Big Bear effluent contribution considered in the Lake Analysis (i.e., 2,000 AFY), 80 AFY would be delivered to Shay Pond. Therefore, only 1,920 AFY would be discharged to the Lake.

[(b)] The updated model analysis assumed that no discharge to Shay Pond would occur and all recycled water would be discharged to the Lake under two different total recovery rates scenarios.

Moreover, deliveries are expected to vary seasonally (Fig 1), thus varying from the earlier "Alternative 3" scenario that assumed uniform flows of 1.71 MGD throughout the year. Inflows to the WWTP are lower in the summer months due to reduced inflow.

Since the Replenish Big Bear project does not have a waste load allocation for total P (TP) in the current TMDL, it is proposing to offset the TP load in the project inflows delivered to Big Bear Lake. While RO is extremely effective at removing dissolved and particulate substances, there nonetheless is a small quantity of TP that is expected to evade treatment (the projected RO effluent concentration is 0.03 mg/L, principally as o-PO_4-P). Elimination of all TP through the treatment process is not practicable, so removal of an equivalent load of TP (up to 200 lbs/yr) from elsewhere in the lake or watershed will be necessary.

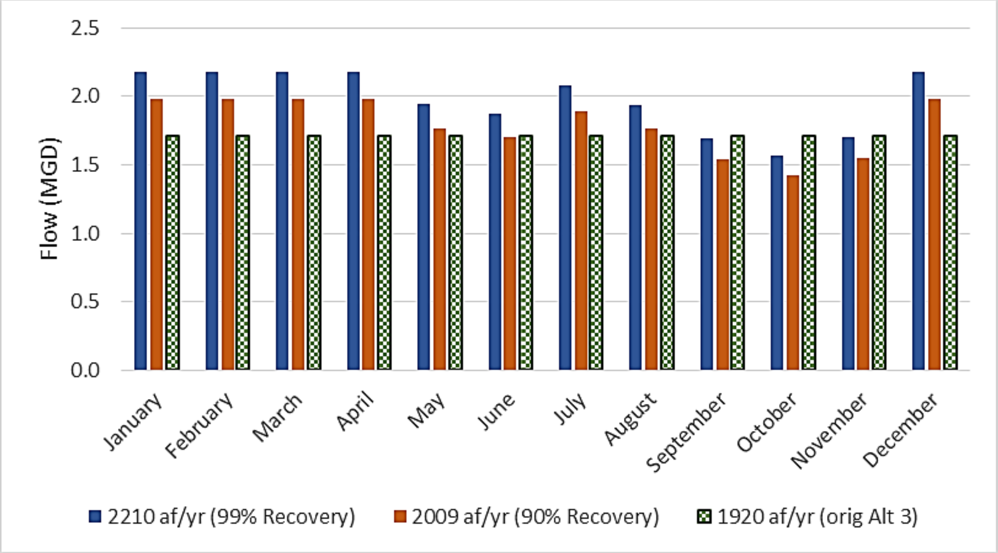

Fig. 1. Monthly flow rates (projected 2040) for Replenish Big Bear under three project inflow scenarios.

In light of these factors, further modeling was conducted to evaluate predicted water quality under these operational scenarios (increased and time-varying flows, with and without TP offset) for comparison with the previously predicted baseline condition and Alternative 3 scenario. Given the complexity of nutrient budgets of lakes, array of possible offset strategies, and equivalence of a given form of nutrient irrespective of its particular origin, TP offset will be modeled as equivalent to 0 influent concentration. This is an approximation that holds when considering whole-lake nutrient budget, but is nonetheless a simplification; depending upon details of offset, hydrodynamic considerations and other factors, some modest lateral gradients in water quality may result. The 50th percentile hydrologic scenario for 2009-2050 was used in this analysis, noting that it includes a wide array of runoff conditions, included extended drought and as well as periods of high runoff. All other hydrologic, meteorological, biological, chemical and sedimentological factors, variables and conditions were identical to those used in prior simulations of long-term future conditions (Anderson, 2021).

Results

Long-term averaged predicted concentrations of TDS, TIN, total P, total N and chlorophyll-a were lower with addition of RBB water compared with predicted baseline conditions (no supplementation) (Table 2). For reference, TMDL target values are included in the table. Focusing on chlorophyll-a as the key response target, baseline conditions were predicted to yield growing-season average chlorophyll-a concentration that slightly exceeded (by 0.1 µg/L) the TMDL target value of 14 µg/L, while Alternative 3 matched the target value, and larger inputs of RBB inflow that varied seasonally (Fig. 1) yielded values below baseline and TMDL target values (Table 2). Zeroing out the load of TP in RBB inflow yielded further reductions in chlorophyll-a; larger inflow volumes with reduced summer flows and no net TP loading were predicted to yield growing season average chlorophyll-a concentrations as low as 9.5 - 10.2 µg/L, significantly below predicted baseline and TMDL concentrations (Table 2).

Table 2. Long-term average predicted concentrations of total P, total N and chlorophyll-a in Big Bear Lake under different operational scenarios (total P and total N expressed as annual average concentrations; chlorophyll-a shown as growing season average concentrations).

Operational Scenario (all at 50th % hydrology)	**TDS (mg/L)**	**TIN (mg/L**	**Total P (µg/L)**	**Total N (mg/L)**	**Chlorophyll-a (µg/L)**
Baseline	**195**	**0.069**	**47.7**	**1.15**	**14.1**
Alternative 3 (1920 af)	182	0.052	43.3	1.07	14.0
2210 af (99% recovery)	**179**	**0.045**	**42.3**	**1.04**	**13.1**
2009 af (90% recovery)	**180**	**0.041**	**43.4**	**1.06**	**12.9**
2210 af + 0 total P	179	0.072	39.9	1.00	10.2
2009 af + 0 total P	180	0.040	40.9	1.00	9.5
TMDL target			***35.0***		***14.0***

Supplementation with RBB inflow also lowered concentrations of total P and total N relative to predicted baseline levels (Table 2). This is consistent with the reduced concentrations of total N and total P (and most dissolved forms of N and P) in RO water relative to watershed runoff concentrations (Anderson, 2021, Table 20), with concentrations projected to be only 40% - 80% of average watershed runoff concentrations (Anderson, 2021, Table 21). Interestingly, zeroing out the influent TP concentration not only lowered the predicted average total P concentration but also reduced the predicted total N concentrations, highlighting the complex biogeochemical coupling of these two key nutrients. While it is important to recognize the uncertainty in model predictions, it is nonetheless noteworthy that revised project flows, with varying seasonal flow and TP offset, yielded average chlorophyll-a concentrations significantly below baseline and TMDL values and also yielded long-term average TN concentrations approaching or reaching 1 mg/L, which is being considered by the Regional Water Board. Predicted long-term average TP concentrations remained above the TMDL target, but were nonetheless meaningfully lower than the predicted baseline level (Table 2). Average TDS and TIN concentrations were also lower than predicted baseline conditions (with exception of 2210 af + 0 TP, where a period of higher NO_3-N was predicted).

Inter-annual differences in water quality are nonetheless expected to persist. Cumulative distributions functions (CDFs) highlight the predicted wide range in annual and growing season average concentrations (Fig. 2). While addition of RBB inflow shifted CDFs to lower annual average total P and total N concentrations and growing season average chlorophyll-a concentrations, wide ranges in predicted concentrations remained in place (Fig. 2). Thus, the growing season average chlorophyll-a target of 14 µg/L was predicted to be exceeded about 53% of the time under baseline conditions, and exceeded about 41% and 31% of the time with RBB inflows of 2210 af/yr without and with TP offset, respectively (Fig. 2c; Table 3). Results for all scenarios are summarized in Table 3.

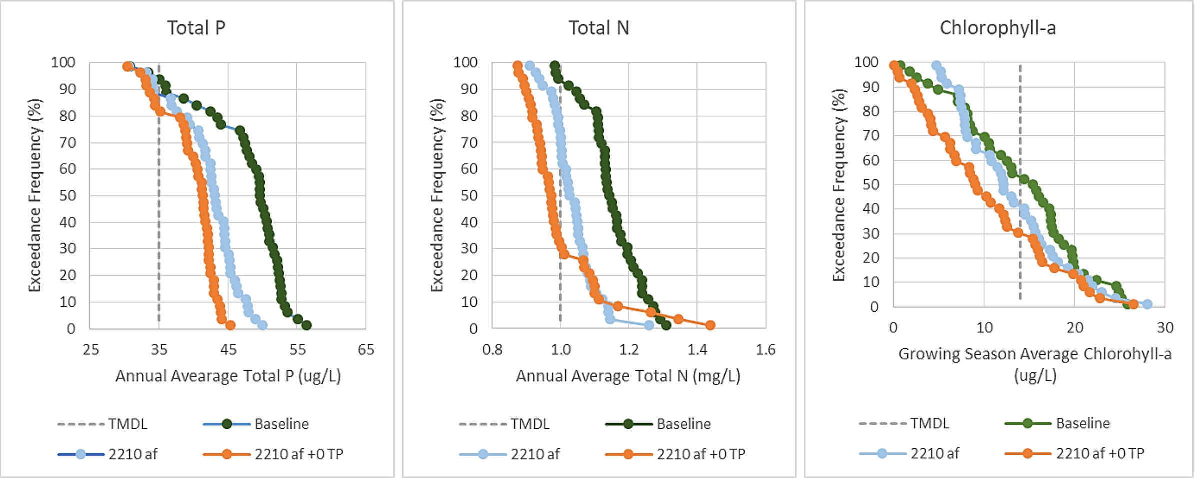

Fig. 2. Cumulative distribution functions for predicted annual total P and total N concentrations and growing season average chlorophyll-a concentrations for baseline condition and with 2210 af of RBB inflow with and without TP offset.

Table 3. Predicted frequency of exceeding TMDL target under baseline conditions and different RBB inflow and TP offset scenarios (annual average or growing season average basis). Observed annual exceedance frequencies for 2009-19 period shown in parentheses under Baseline.

Variable	**Baseline**	**1920 af**	**2210 af**	**2210 af+0 TP**	**2009 af**	**2009 af+0 TP**
Total P	94 % (100%)	87 %	87 %	82 %	91 %	90 %
Total N[a]	91 % (na)	72 %	72 %	30 %	80 %	55 %
Chlorophyll-a	53 % (55%)	51 %	41 %	31 %	40 %	22 %

[a]*possible TMDL target*

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