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Newell Creek Reservoir Data Organization and Phytoplankton Bloom Analysis

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Cover photo of Newell Creek Reservoir algae bloom courtesy of Erin Stanfield.

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Executive Summary

The Newell Creek Reservoir (also known as Loch Lomond) in the Santa Cruz Mountains is a critical water source for the City of Santa Cruz, while the majority of surrounding land provides the public with recreation opportunities such as fishing, boating, and hiking. During the summer months when the reservoir is utilized most intensively, freshwater phytoplankton blooms have been observed. These blooms can deplete oxygen within the water column and produce toxins, which can alter ecosystem dynamics and the integrity of the water. In the Newell Creek Reservoir, these blooms have affected fish populations, water quality, water treatment efficiency and supply, in addition to recreational use of the reservoir.

Due to these issues and difficulties mitigating the blooms in an effective manner, the Santa Cruz Water Department (SCWD) seeks to better understand bloom dynamics, to identify environmental predictors and to optimize treatment efforts. To facilitate this goal, the California State University Monterey Bay (CSUMB) ENVS660 Fall 2012 class compiled historic data related to the Newell Creek Reservoir from the past 54 years in an online public database and developed this report to summarize the data and perform basic analyses of phytoplankton bloom dynamics within the reservoir.

We performed several types of analyses with ten years of hydrologic, water quality and phytoplankton data to examine potential predictors of phytoplankton blooms within the reservoir. First, we characterized the system from a hydrologic standpoint in addition to visualizing various water quality parameters. Then we analyzed peak phytoplankton abundance over time at different depths, at various locations within the reservoir, among different phytoplankton groups, and with chlorophyll concentrations and algaecide treatments. Last, we assessed relationships of peak phytoplankton abundance with a variety of the hydrologic and water quality parameters using graphical depictions, time-series analyses and correlation tests.

From these results, we made several inferences regarding dynamics within the Newell Creek Reservoir and drivers of phytoplankton blooms. The best

predictor of blooms was the positive relationship between peak winter flows and phytoplankton blooms in the following summer. This relationship indicated that high discharge from the watershed into the reservoir may have stimulated blooms through the addition of limiting nutrients. However, analyses were limited by time constraints, and lack of nutrient data within the reservoir and from contributing sources of water to reservoir. Although a few inferences were made, we were not able to clearly identify specific causes of phytoplankton blooms. To better anticipate, prevent, and mitigate nuisance blooms in the future, we recommend enhanced monitoring of nutrient concentrations into the reservoir from various sources and to explore the time lag between environmental parameters (precipitation and temperature) and bloom events.

Table of Contents

1 Introduction

1.1 Background

Newell Creek Reservoir is a man-made reservoir in the Santa Cruz Mountains that is widely known as Loch Lomond. The reservoir was created with construction of the Newell Creek Dam in 1960 as a source of water for the Santa Cruz area. The earth-fill, parabolic dam is 190 feet tall and 750 feet long, has an elevation of 577.5 feet above mean sea level, and a catchment of 8,650-acre feet (AF) (Bean & Berry 2011). Loch Lomond Recreation Area, located on the eastern shores of the reservoir, was opened as a recreation area in 1963 and is currently open to visitors from March to October with approximately 50,000 visitors each year. The recreation area was a required feature for the development of the reservoir and has 174 acres of water available for fishing and boating, and 181 acres of land designated for day-use (Bean & Berry 2011).

The Newell Creek Reservoir receives the majority of its water from the Newell Creek watershed, which is a sub-watershed of the San Lorenzo River watershed. The Newell Creek watershed covers approximately 5,312 acres, ranges from 600 to 2,300 feet above sea level, and contains four main streams that flow into the reservoir (SLVWD 2009). The Newell Creek Reservoir also receives an average of 350 AF per year of its water input from the San Lorenzo River via a diversion and pumping facility located in Felton, CA (SLVWD 2009). An inflatable dam, constructed in 1974 (SCWD 2005), impounds water from the river, which is pumped from the dam location to a booster pump and then up to the reservoir (Fig. 1).

The Santa Cruz Water Department (SCWD) currently operates and maintains the Newell Creek Reservoir and is permitted to operate the dam and pumping system between September and June, and pump up to 20 cubic feet per second (CFS), with a yearly maximum of 3,000 AF of water. However, the total volume of water pumped per year is limited physically and temporally by discharge of the San Lorenzo River and the fact that the current pumping system is only capable of delivering nine CFS of water to the reservoir (SLVWD 2009). Additionally, physical constraints of the current pumping system limit the amount of water pumped to the reservoir.

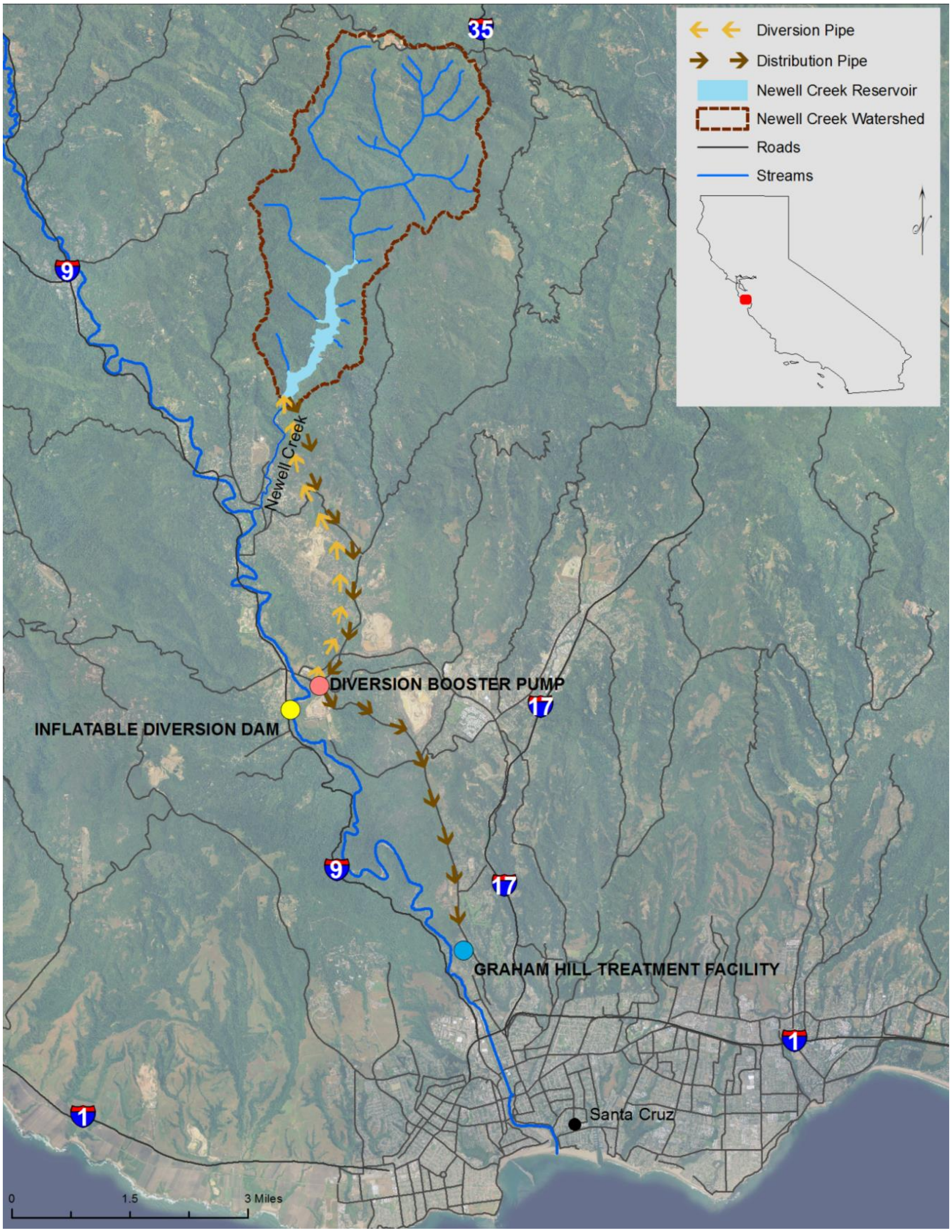

Figure 1. The Newell Creek Reservoir receives water from four tributaries within the Newell Creek watershed and diverted water from the San Lorenzo River. Water is captured at inflatable diversion dam and pumped from the San Lorenzo River to the Newell Creek Reservoir. Disclaimer: Pipe locations may not be accurate.

The City of Santa Cruz owns 46% of the Newell Creek watershed, with 2,385 acres closed to public access for the purpose of source water protection. While these areas are closed to the public, required fire and access roads can contribute to erosion and suspended sediment within the reservoir. Additionally, private development of homes and wineries within the watershed may contribute to nutrient loadings. There are currently 1,664 acres of timberlands, 30 miles of mapped road, and eight stream crossings within the city-owned portion of the watershed (SCWD 2011a). We depicted historic and current land use of the Newell Creek watershed as these elements have potential to alter water quality and phytoplankton dynamics within the reservoir.

The reservoir currently supplies approximately 17% of the water for the City of Santa Cruz, surrounding unincorporated areas, and parts of the City of Capitola (SCWD 2003). Water is pumped nine miles from the reservoir to the SCWD Water Treatment Facility on Graham Hill Road for treatment before municipal distribution. The reservoir is considered a supplement to SCWD surface and groundwater supplies, and is used most intensively from May to October and during drought years. SCWD is currently permitted to withdraw 3,200 AF per year from the reservoir, with 12.5% of this volume reserved for use by the San Lorenzo Valley Water District (SLVWD 2010).

Between 2000 and 2010, the annual water requirements of the Santa Cruz area ranged between 9,513.5 and 12,275.5 AF. Historically, the SCWD has been able to meet the Santa Cruz area's water requirements seven out of ten years, and 90% of the requirements nine out of ten years. However, projected population increases indicate that there will be a 0.4% to 0.8% increase in water requirements for the area by the year 2020, which is equal to 4,365 MGY (SCWD 2011b). Additionally, in-stream flow releases for salmon habitat conservation, required by the Endangered Species Act, will increase water use beginning in 2013 (C. Berry, SCWD, pers. comm. 2012). If no alternative sources of water are found or existing resources augmented, these increased water requirements will likely need to be satisfied by the Newell Creek Reservoir, particularly during summer months.

During the summer months, when water supply needs are high and the reservoir is open as a recreation area, the reservoir periodically experiences phytoplankton blooms. Due to the extreme growth rate of these photosynthetic organisms, the water in the reservoir can go from clear to murky over the course of a warm weekend (C. Berry, SCWD, pers. comm. 2012) While most of these blooms are not harmful and can be filtered from the water before municipal distribution, there are consequences and costs associated with the blooms. Detrimental effects of phytoplankton blooms can include (SCWD 2002):

- Harmful toxins that can affect wildlife and humans
- Oxygen depletion which can alter reservoir biogeochemistry and ecosystem dynamics resulting in phenomena such as fish kills
- Undesirable color and odor of the recreation area water and potential loss of beneficial recreational use
- Undesirable color and odor in potable water
- High concentration of Total Organic Carbon (TOC) resulting in formation of disinfection byproducts during the treatment process that may exceed primary drinking water standards
- Clogging of filters at the water treatment plant

Because the Newell Creek Reservoir is both a critical source of water and a valuable recreation area during the summer months when conditions promote phytoplankton blooms, the SCWD has expressed that bloom growth must be limited (SCWD 2002). Although blooms can be mitigated by chemical means if detected in a timely manner, the use of algaecides is expensive and the effective timing and degree of application is highly variable. Identification of environmental drivers may allow the timing of blooms to be predicted, which would greatly improve SCWD's ability to treat the water. Better understanding of the specific conditions that promote blooms and the dynamics of their growth and succession at Newell Creek Reservoir is needed to potentially prevent blooms and optimize mitigation efforts.

1.2 Goal

The goal of this study was to digitize and organize data from SCWD relevant to phytoplankton blooms in Newell Creek Reservoir and to utilize the data for preliminary analysis of phytoplankton dynamics. We sought to accomplish this goal by establishing a public database designed to facilitate quantitative characterizations, system models and management decisions. We aimed to summarize, graphically represent, and interpret available phytoplankton data to assist SCWD in the identification of phytoplankton bloom predictors.

2 Data Acquisition and Archival

2.1 Acquisition

We acquired hardcopy and digital data maintained by SCWD related to Newell Creek Reservoir which spans between 1958 and 2012. Data from 1958 to 1986 exist as hard copies while the majority of data from 1987 to 2012 exist as electronic documents. We digitized all hardcopy data by means of manual entry into spreadsheet format and archived the data into an online public database. It should be noted that digitized data was not quality-checked for manual data entry errors. SCWD may also possess additional archived historic data related to the Newell Creek Reservoir and phytoplankton dynamics that have yet to be discovered.

2.2 Data Locations

Data provided by SCWD included a variety of physical and biological parameters from the following locations: Newell Creek watershed, Newell Creek Dam, Newell Creek mainstem and tributaries, the Loch Lomond Recreation Area, and the Newell Creek Reservoir (Fig. 3). Data for the watershed, dam and tributaries includes mostly hydrologic data and some water quality data, which were collected from precipitation and stream gages. Data for the Newell Creek Reservoir includes physical limnological and biologic data, which were derived from five sampling sites. The location with the highest amount of available data is Sample Site 2 in the Newell Creek Reservoir.

2.3 Data Summary

SCWD data span from 1958 to 2012 and include data in the following categories: water quality, nutrients, metals, hydrology, and biota. Water quality data are summarized in Figure 4, while nutrients, metals, hydrology, and biota data are summarized in Figure 5. Water quality, nutrient, and metal data were obtained from samples collected intermittently in the mornings of 1960 to 2012 and include the following parameters: pH, turbidity, color, hardness, alkalinity, temperature, taste, odor, chlorophyll, Secchi depth, conductivity, dissolved oxygen, manganese, hydrogen sulfide, phosphate, chloride, iron, nitrate and copper. Pesticide use was also recorded between 1970 and 1990 and is also available for recent years. Biota data consist mainly of plankton (phytoplankton and zooplankton) data between 1967 and 2012, although plankton data between 1987 and 2003 remain in hardcopy format and still require electronic entry. California red-legged frog and western pond turtle count data also exist. Daily precipitation data span from 1961 to 2001, while monthly precipitation data are available from 2002 to 2012. Weekly lake elevations also exist from 1967 to 2012.

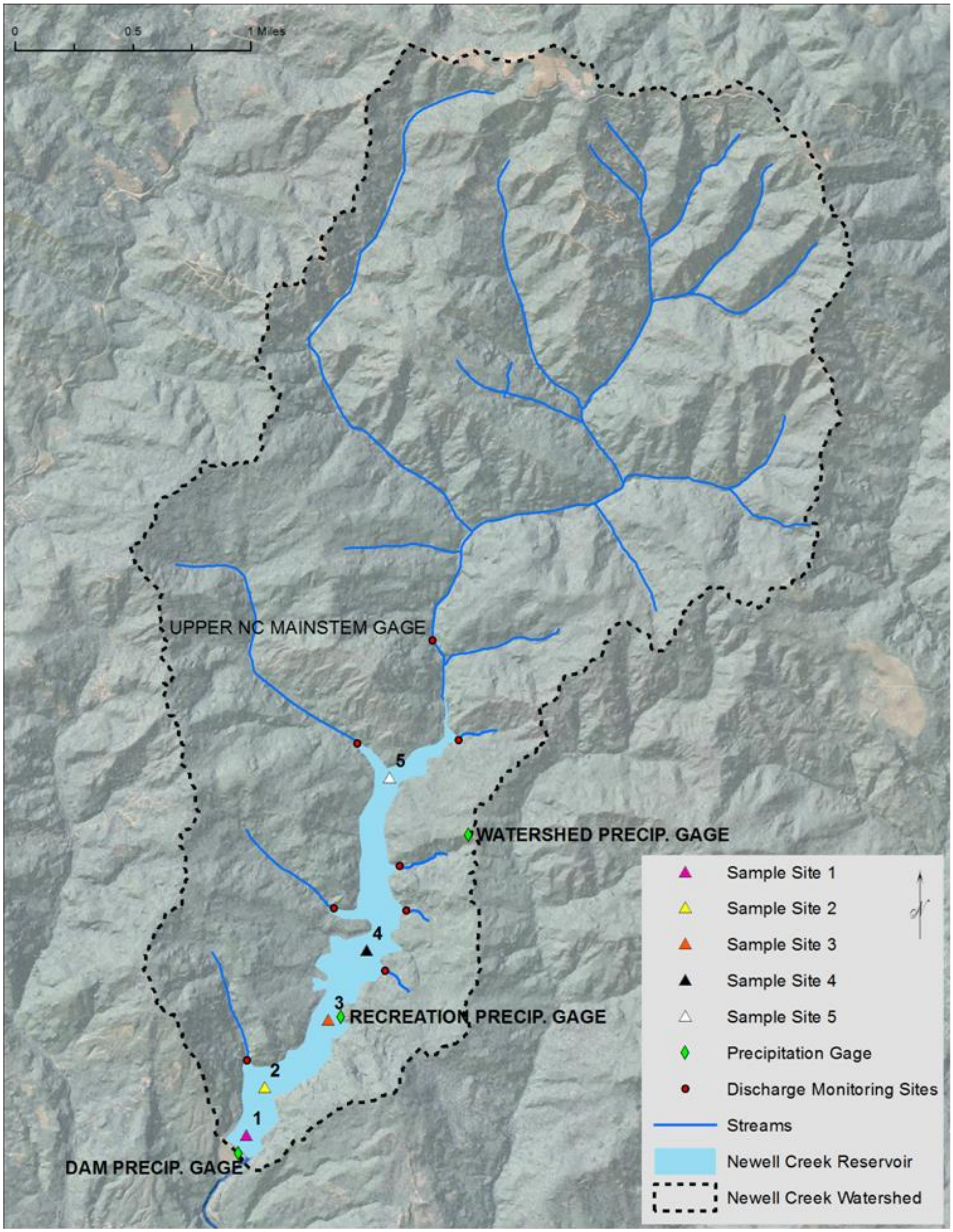

Figure 3. Monitoring sites and gages within the Newell Creek watershed utilized by SCWD to collect various types of data. Note: Mapped sampling sites and gages may be slightly inaccurate.

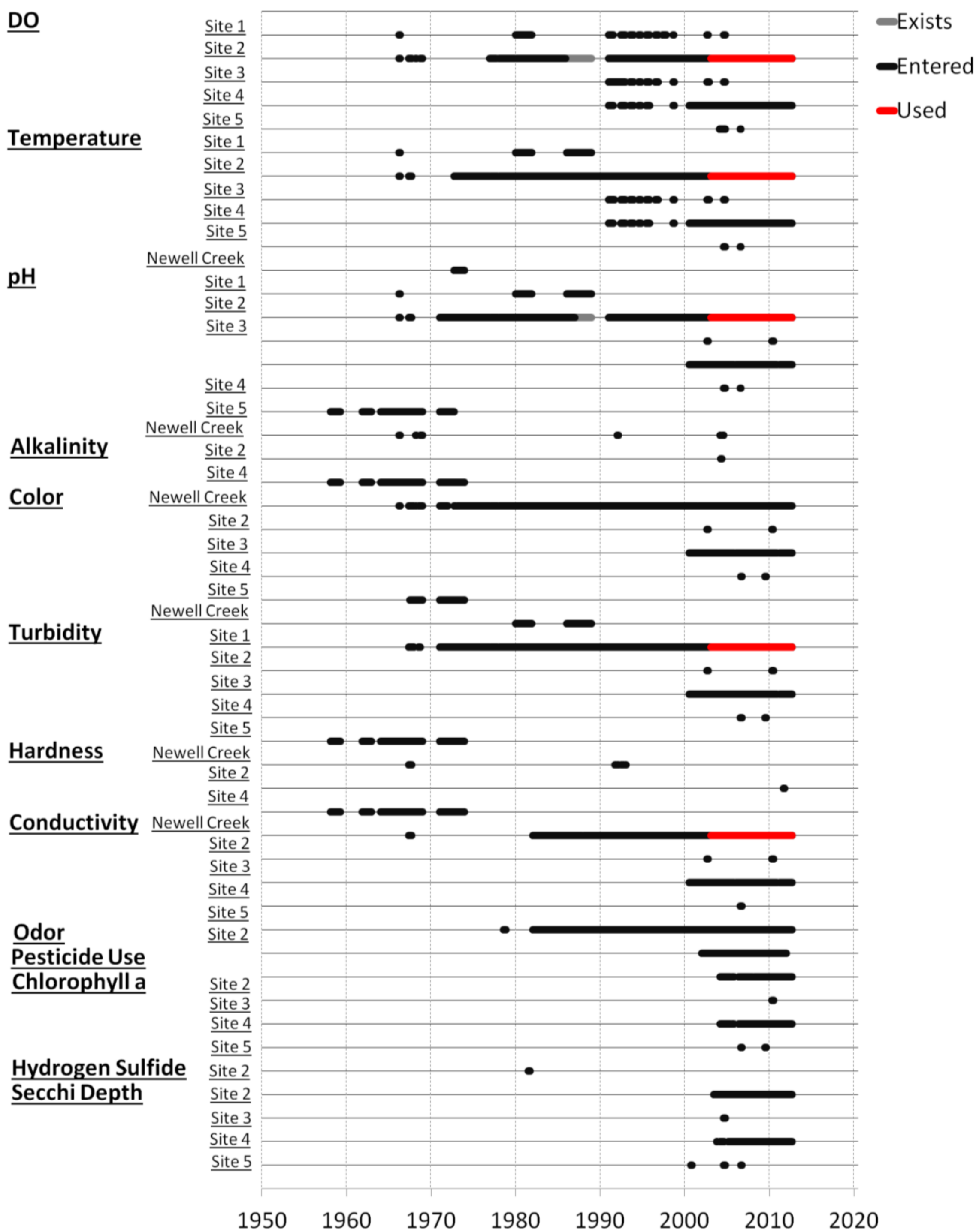

Figure 4. Data availability plot for Newell Creek Reservoir water quality parameters. Note that there was not a physical location given for the Pesticide Use data. “Exists” refers to data that is available in hardcopy and still requires digitization, “Entered” refers to data that were digitized, and “Used” refers to the data used in the analysis portion of this report.

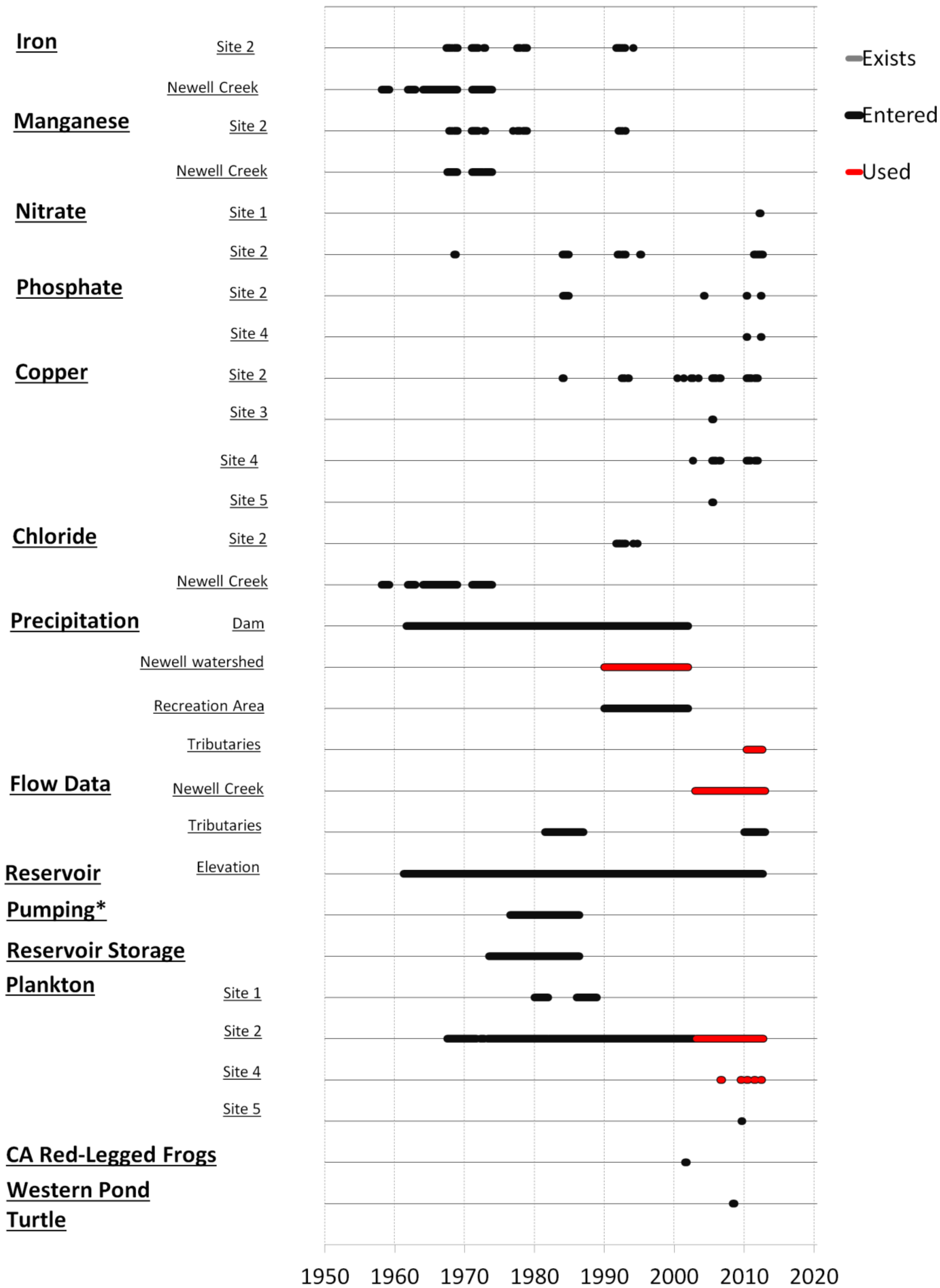

Figure 5. Data availability plot for nutrients, metals, hydrology parameters, plankton (phytoplankton and zooplankton) and other biota for the Newell Creek Reservoir.

2.4 Archival

All data acquired from SCWD from 1958 to 2012 are provided in a permanent digital database at the CSUMB Central Coast Watershed Studies website:
(http://ccows.csumb.edu/pubs/proj_pubs/2012/ENVS660_NewellCreekReservoir/).
The database contains two Microsoft Excel workbooks that summarize and organize the data. The database also includes this report and a Microsoft PowerPoint presentation given to SCWD regarding data organization and phytoplankton bloom analysis.

3 Hydrology

Based on historic data provided by SCWD, we characterized the Newell Creek watershed from a hydrologic standpoint by analyzing precipitation, water flow, and reservoir elevation. Available data exist at a daily and monthly timescale from 1961 to 2012. However, due to the limited availability of electronic data at the outset of the project, we only analyzed hydrologic parameters that spanned from 2003 to 2011 on a daily timescale. It should be noted that zeros were inserted into the dataset wherever measurements were not recorded.

Flows into the Newell Creek Reservoir are highly dependent on precipitation as 76% of the water is supplied by natural runoff from the Newell Creek watershed (SCWD 2011). The remainder of water to the Newell Creek Reservoir is supplied via pumping from the San Lorenzo River by means of the Felton Diversion Facility during high winter flow events (SLVWD 2009). The Newell Creek watershed has an average annual rainfall of 43 inches and contains four main streams that supply water to reservoir: McFarlane Creek, Newell Creek mainstem, and the North and South tributaries of Newell Creek (SLVWD 2009). The type of water year (wet, normal, dry, and critically dry) has a large impact on the amount of water supplied to the reservoir and therefore the overall reservoir elevation and water supply. For example, in a dry year much more water is pumped from the San Lorenzo River to supplement the reservoir water supply than in an average year (C. Berry, SCWD, pers. comm. 2012).

Historic precipitation and elevation data at the Newell Creek Reservoir have been collected by SCWD over the past 50 years, but the majority of precipitation data was recorded at the Newell Creek Dam. Starting in January 1990, precipitation measurements were measured in two additional locations: at the eastern Newell Creek watershed boundary and in the Loch Lomond Recreation Area (Fig.3). Available data from SCWD for flow into the Newell Creek Reservoir includes daily flow data from the Upper Newell Creek gage between September 2002 and October 2002, which represents flow from the Newell Creek mainstem. Flow data for the North and South Newell Creek tributaries also exist from 2010 to 2012. Data for the Newell Creek Reservoir outflow are sparse in our database but include data for several days between 1961 and 1966 and monthly data from 1971 to 1986. Additional outflow data can be found at SCWD. Flow data for water pumped from the San Lorenzo River to the Newell Creek Reservoir via the Felton Diversion Facility is also available from 1976 to present.

To quantify the majority of precipitation and discharge to the Newell Creek Reservoir and to demonstrate influences on reservoir elevation, we graphed daily precipitation data from the Newell Creek watershed, daily flow data for the Newell Creek mainstem and elevation data for the Newell Creek Reservoir from 2003 to 2011 (Fig. 6). The figure demonstrates that as a precipitation event occurs in the Newell Creek watershed, the flow of water from the Newell Creek mainstem increases, along with the elevation of the reservoir. Conversely, during periods with little precipitation, flow decreases and the reservoir elevation decreases. Specifically, Figure 6 demonstrates the effect of precipitation events during the wet season (November to March) (a) and corresponding discharge peaks on the Newell Creek mainstem (b), followed by a lagged rise in elevation near spillway capacity at the Newell Creek Reservoir (c).

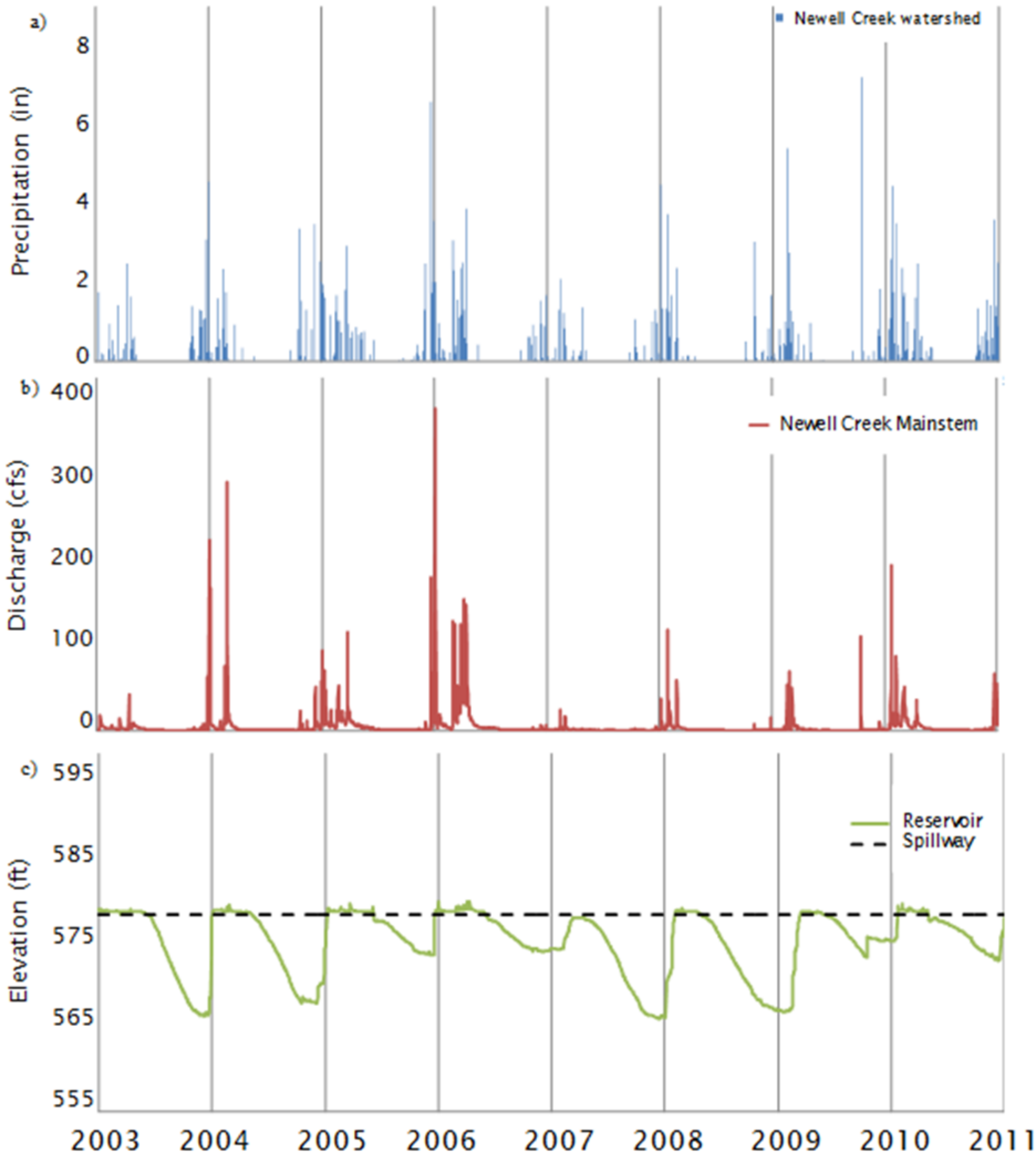

Figure 6. Daily precipitation for Newell Creek watershed (a), inflow/discharge for the Newell Creek mainstem (b) and surface elevation within the Newell Creek Reservoir (c).

4 Water Quality

The SCWD has regularly sampled Newell Creek Reservoir water quality at Site 2 since 1966. However, in this report, we will only focus on water quality data collected from 2003 to 2011 due to limited digitized data at the outset of this project. We assessed a variety of water quality parameters from the Newell Creek Reservoir including color, turbidity, conductivity, pH and temperature while available data on parameters such as nitrate, phosphate, alkalinity, and hardness were also available but were excluded as the number of sampling dates was low ($n<30$). Additional water quality data at various locations are available at SCWD for further analysis, such as six consecutive years of 15-minute turbidity data from the Newell Creek mainstem.

Key water quality parameters in terms of drinking water production and recreation include color, turbidity, temperature, and dissolved oxygen (DO) (SLVWD 2010). Color is a measure of the dissolved organic matter and is important in the calculation of water disinfectant as high dissolved organic matter can result in disinfection by-products (AWWA 2010). Turbidity is the measurement of cloudiness within water. Turbidity consists of suspended silts, clays, other fine organic and inorganic particles, plankton (phytoplankton and zooplankton), and other microorganisms (Clesceri et al*.* 1998). Conductivity and pH are important in the evaluation of surface water as they are indicative of the concentration of dissolved ions/compounds and are influenced by biotic metabolism and other biochemical processes (Water Quality Assessments 1996).

Water temperature is one of the most important water quality parameters as it can directly affect mixing through establishment of a thermocline in addition to influencing other parameters such as conductivity and DO. As the lake surface warms in the late spring and early summer, a warm-water epilimnion develops, overlaying a cooler hypolimnion. The resulting difference in density between these layers prevents overall water column mixing and increases the stability of the water column near the surface (Anderson 2002). Thermoclines play a key role in lake ecology by isolating nutrients, oxygen, and various species into different habitat spaces of the water column during different times of year (Wetzel 2001). The Newell Creek Reservoir typically mixes in late autumn when precipitation and cooler weather induce mixing of the water column. Monomictic water bodies, such as the Newell Creek Reservoir, only mix once per year with stratification during the summer and turnover during autumn with the well-mixed water column typically lasting until spring (Larson et al. 2006).

We compared water quality parameters for a wet year (2010), the lowest precipitation year (2007) which represented a dry year, and an average precipitation year (2009). To visualize differences between these years, we constructed depth profile plots from an elevation of 470 feet to the surface using monthly averages for each water quality parameter, which were measured at 20-foot depth intervals (Fig. 7 – Fig. 12). The depth profiles have a rainbow color symbology for different months throughout the year. We examined the plots for patterns by depth and amongst each year. We evaluated evidence of stratification as an abrupt gradient in the parameter with depth, demonstrating an inflection point in the curve where the parameter abruptly changed from the surface condition to the bottom condition. We assessed mixing or lack of stratification as no gradient in the parameter with depth or a vertical/gradually sloped profile.

4.1 Temperature

Across study years, the water column was well-mixed in the winter months and coldest in January and February (Fig. 7). The surface temperatures also increased with season to the same maxima across all years. In 2007, the driest year, increased heating of the shallower water column was demonstrated by the faster temperature increase at the 550 elevation and the higher range of temperatures measured at 530 feet. While the water column appeared to be thermally stratified from 20 to 25 feet in September and October of all study years, the stratification started a month earlier in 2007. Following the stratification period, we saw a decrease from the surface temperature maxima as the temperatures dropped to a well-mixed water column in December.

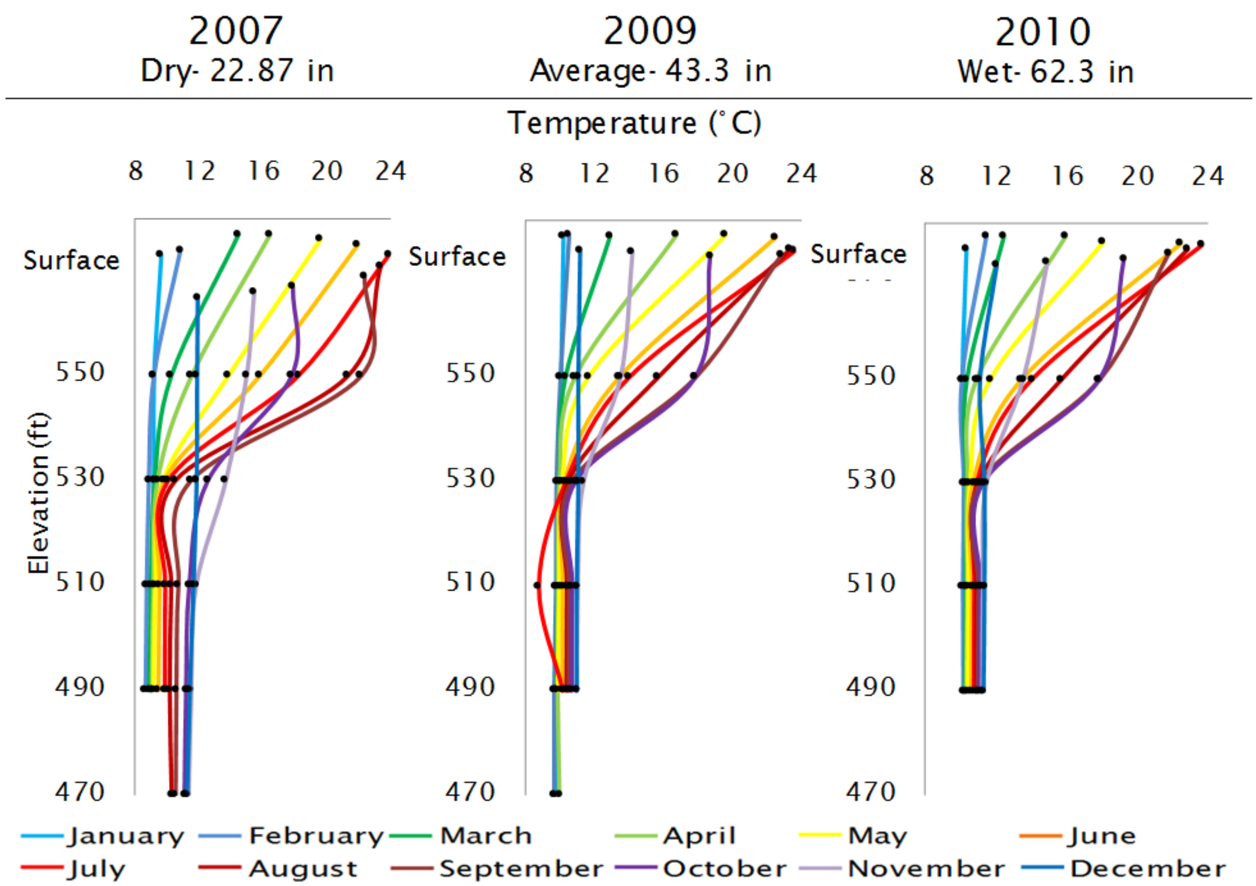

Figure 7. Temperature profiles for 2007, 2009 and 2010.

4.2 Dissolved Oxygen

For 2007 and 2010, the surface water DO was highest at the beginning of the year when mixing is the highest and temperatures are the lowest (Fig. 8). In 2009, the average precipitation year, the highest DO appears in July, which may correspond to increased photosynthesis. Periods of substantial DO stratification are apparent in 2009 and 2010, but to a lesser extent in 2007. In 2010, the reservoir appears to be DO stratified from January to May. There was a sudden drop of DO to nearly zero at the 550 foot elevation in the summer months of 2009 and 2010. This may be evidence of an area of increased respiration due to decomposition of bloom biomass following algaecide treatment. To further confirm this observation, we cross-checked DO with odor and discovered that a spike in odor occurred in September of both years, suggesting higher decomposition at the time.

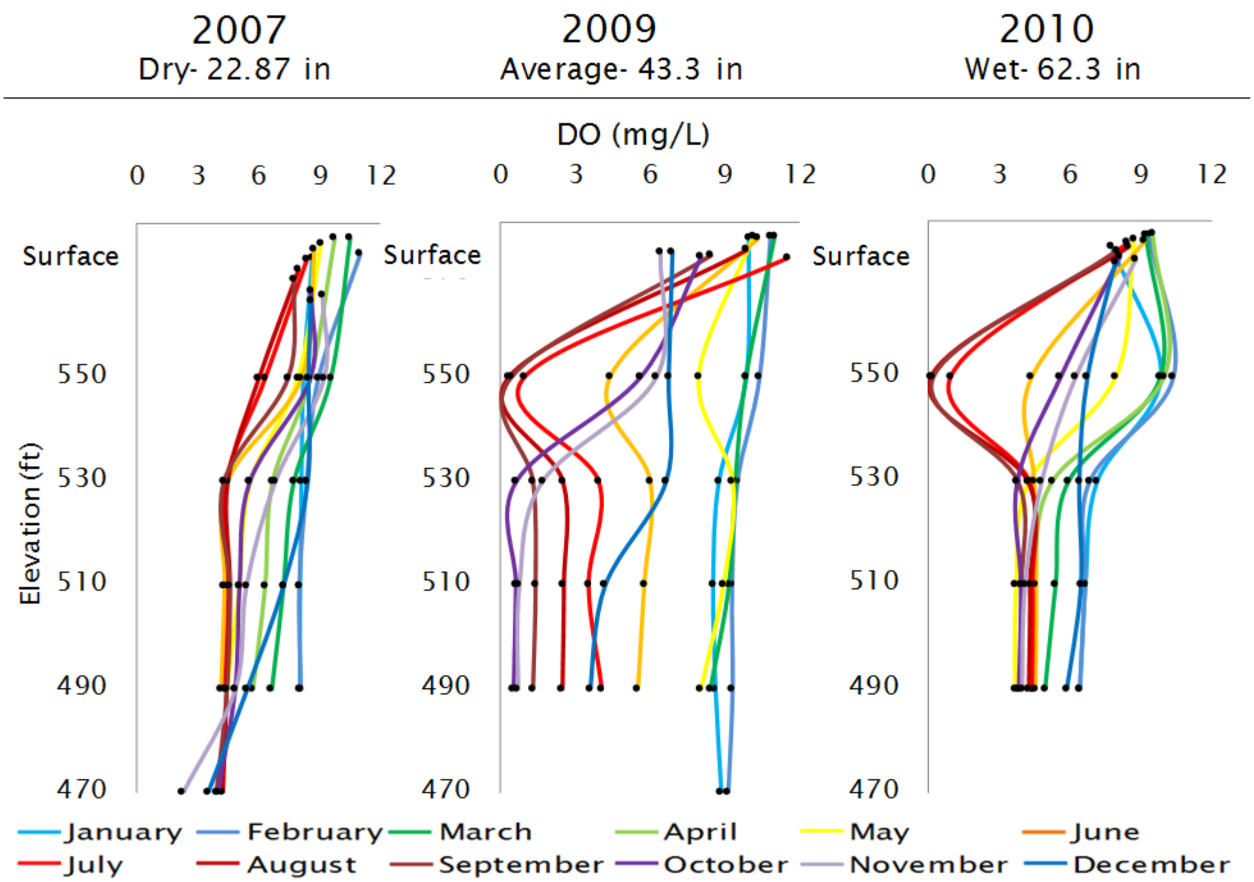

Figure 8. Dissolved oxygen profiles for 2007, 2009 and 2010.

4.3 Water Clarity

We examined two metrics of water clarity: laboratory determined turbidity (NTU) and field measured Secchi depths. In the dry year (2007), turbidity was consistently low throughout the water column (Fig. 9). In contrast, surface water turbidity in 2009 (the average year) was considerably higher in summer and autumn months than the rest of the year. In July, turbidity was higher throughout the water column. The higher overall turbidity in 2009 may be reflective of bio-turbidity from that year's cyanobacteria bloom, which included taxa capable of producing particularly turbid conditions (T. Tompkins, SCWD, pers. comm. 2012). In contrast, 2010 (the wet year) demonstrated the highest surface turbidity in January and February, perhaps in correlation with increased turbidity from increased runoff. The 2010 turbidity profile also demonstrated higher turbidity than previous years at the 530 foot elevation and below, perhaps also indicative of the increased seasonal runoff and mixing during that period. Secchi depth over the three years followed the same general pattern of lower water clarity in winter and summer (corresponding to increased winter runoff and summer bio-turbidity from blooms), and higher water clarity in the spring and fall.

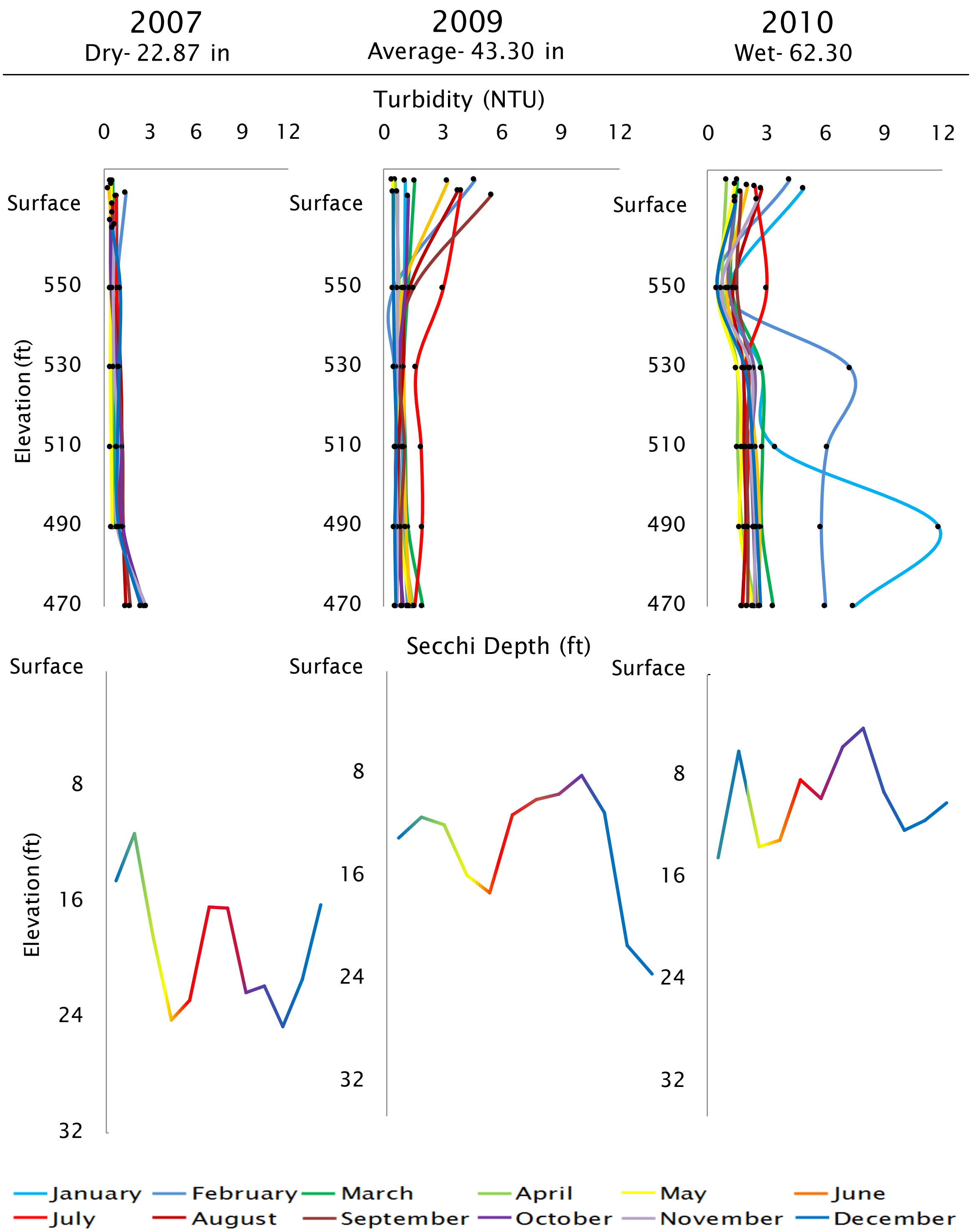

Figure 9. Turbidity and Secchi profiles for 2007, 2009 and 2010.

4.4 Water Color

Across all years, the water color was highest in the winter and spring months, at the surface, which is most likely reflective of the higher levels of suspended matter corresponding with increased winter runoff (Fig. 10). Otherwise, the color throughout the water column was relatively well mixed throughout the years.

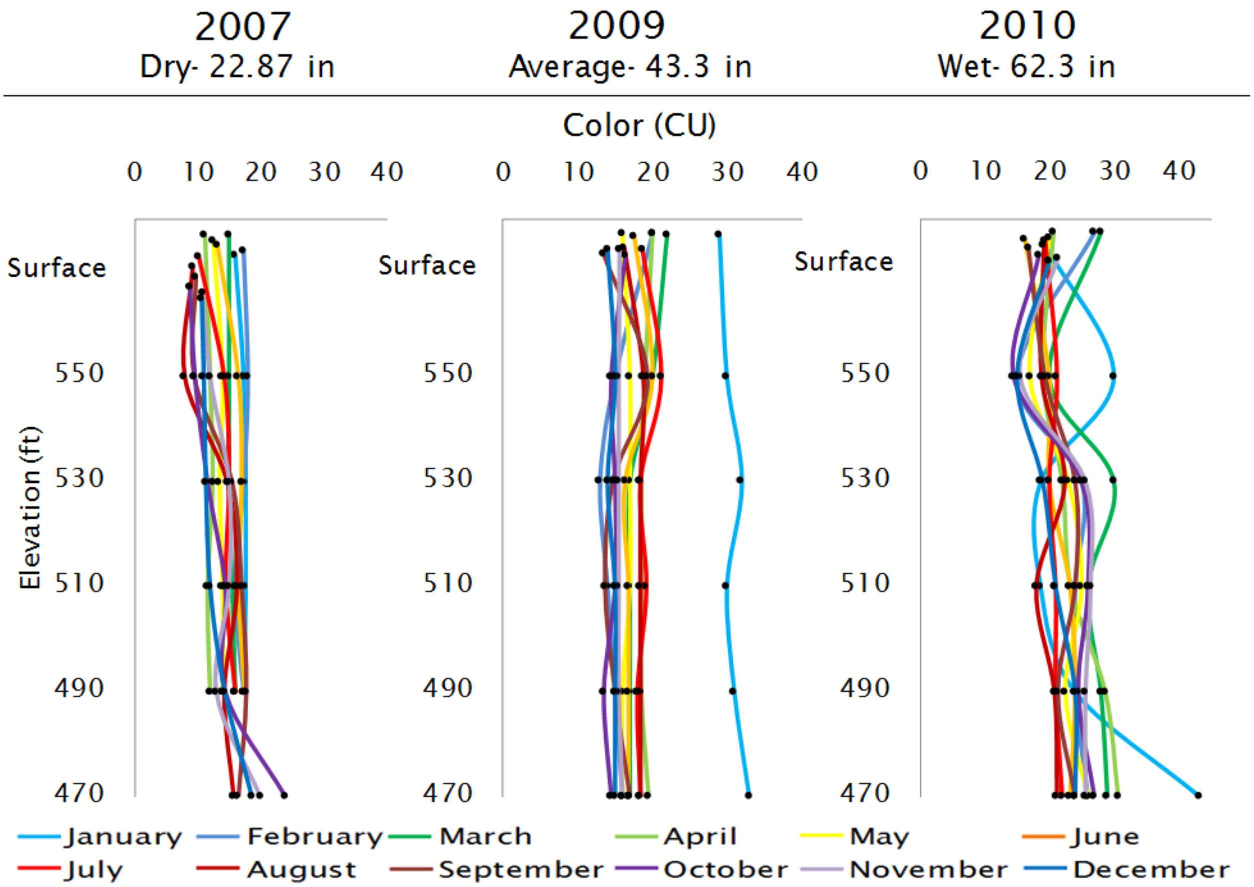

Figure 10. Water color profiles for 2007, 2009 and 2010.

4.5 pH

Across all years, there are distinct patterns between surface and subsurface pH (Fig. 11). The surface water pH increased through the spring and into the summer, likely as phytoplankton blooms developed. This increase in surface water pH is particularly evident in 2009, when an unusually dense cyanobacteria bloom developed (T. Tompkins, SCWD, pers. comm. 2012). Below the surface, seasonal progression corresponded with a decrease in pH throughout the year, which reflects an increase in microbial activity as surface water organisms and nutrients sink into the deeper, darker water (Wetzel 2001).

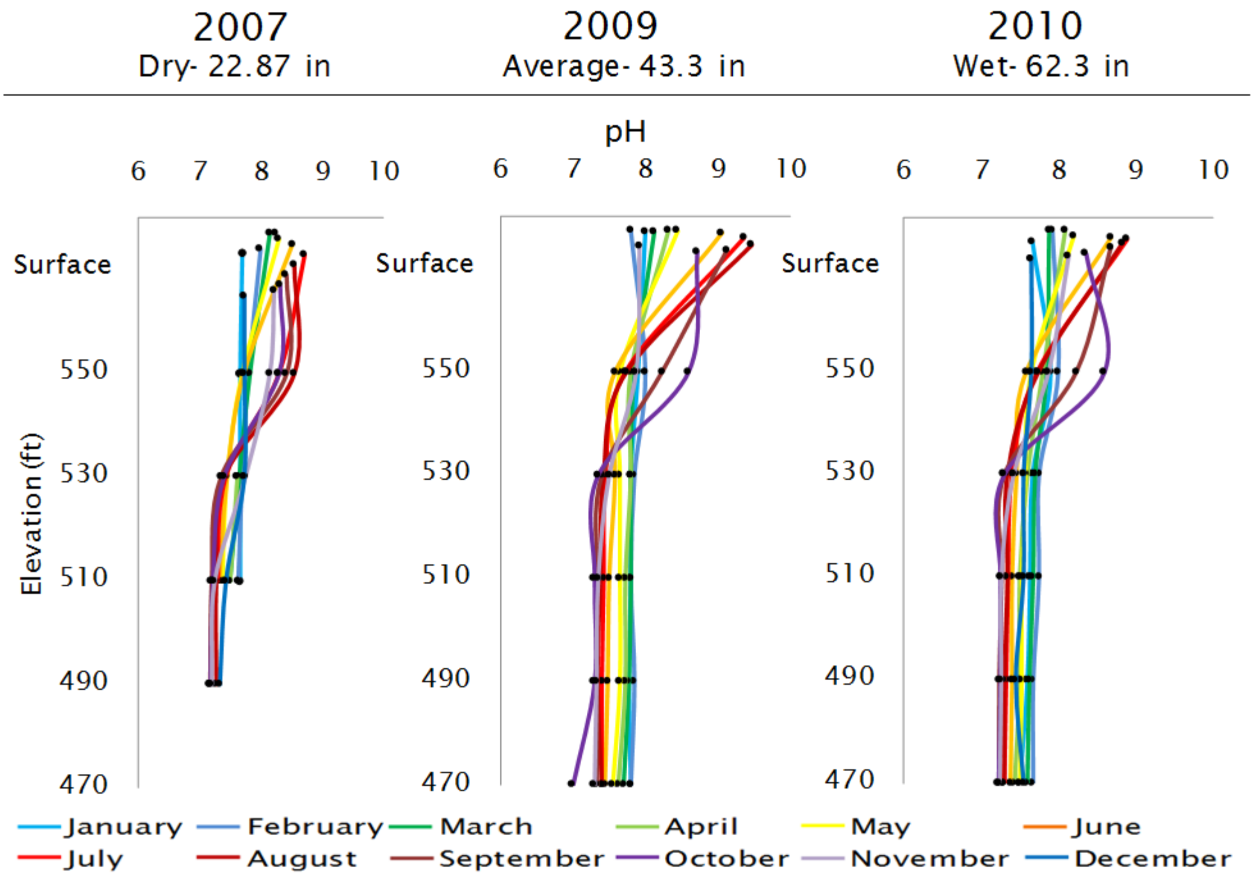

Figure 11. Depth profiles of pH for 2007, 2009 and 2010. Disclaimer: Data from the 530 foot elevation to the 550 foot elevation for all three years was not available to include in our analysis at the time of this report but exists on file with SCWD.

4.6 Conductivity

Conductivity tended to increase with seasonal increases in temperature, as these factors are inextricably linked (Fig.12). The correlation between increased water temperature and conductivity was exemplified in the summer through autumn months of 2007 and 2010 when the high surface conductivity paralleled with increased water temperature which increased with depth to the thermocline.

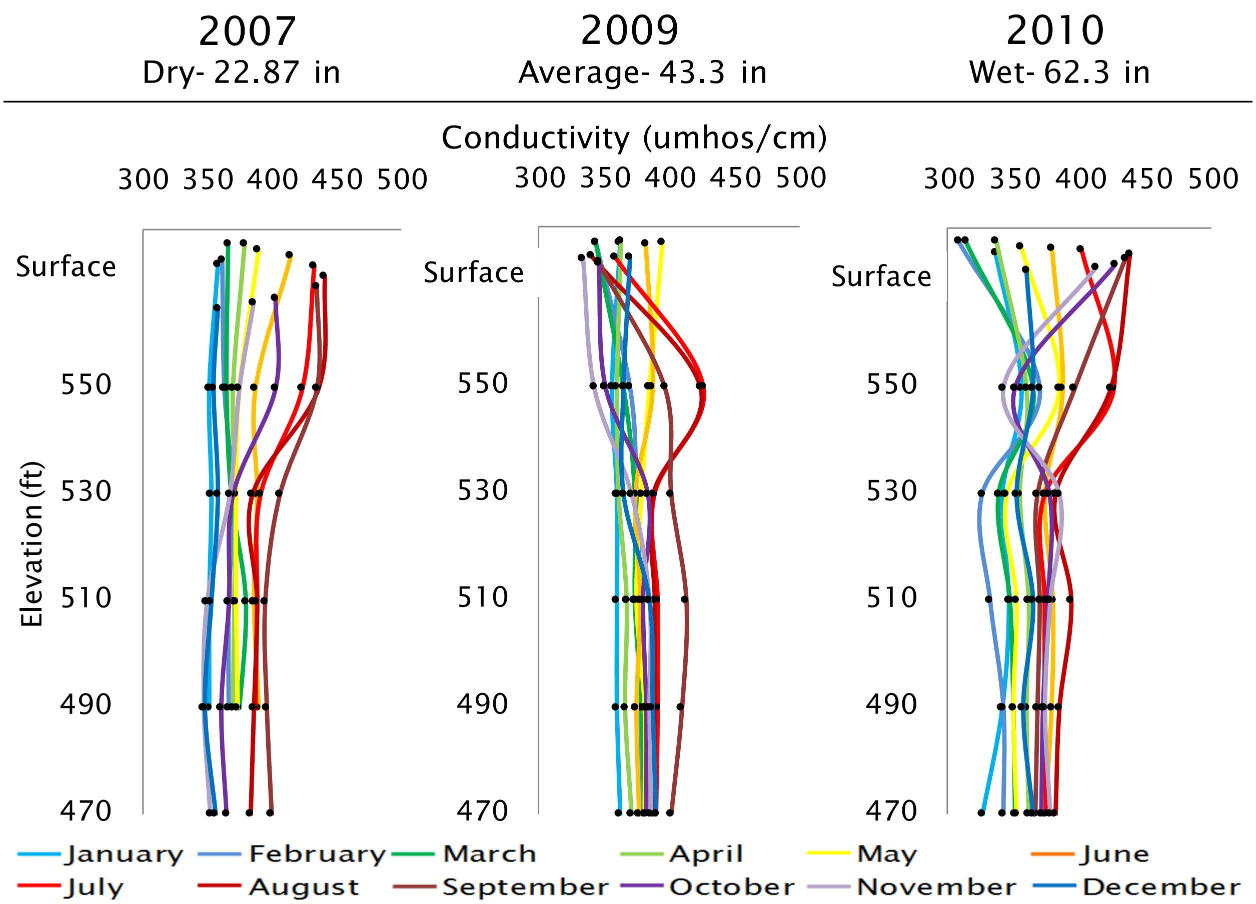

Figure 12. Conductivity profile for 2007, 2009 and 2010.

5 Phytoplankton Dynamics

Phytoplankton are free-floating, microscopic organisms that photosynthesize to produce chemical energy. Phytoplankton are critical sources of primary production in aquatic ecosystems and heavily influence nutrient cycling and food web dynamics (Dawes 1998). Phytoplankton taxa that are historically present within the Newell Creek Reservoir were separated into the following groups for analysis of phytoplankton dynamics: algae, cyanobacteria and flagellates.

We summarized phytoplankton data between 2003 and 2012 at Sites 2 and 4 of the Newell Creek Reservoir due to limited digitized phytoplankton data at the outset of the project, and the absence of phytoplankton data at other sampling sites. The SCWD performed phytoplankton cell counts by examining one milliliter (mL) samples from ten mL concentrates. For each microscope field, they wrote the number of occurrences/frequency of observed phytoplankton to the highest order of taxonomic resolution and used a system of multipliers to get the natural unit count (NU/mL) where the resulting number of each taxa per slide was multiplied by eight. Natural unit counts can include cells, colonies and filaments as opposed to counting each phytoplankton cell individually. Table 1 lists all phytoplankton taxa recorded in the Newell Creek Reservoir between 2003 and 2012.

Table 1. Phytoplankton taxa recorded at Newell Creek Reservoir between 2003 and 2012.

Algae		Cyanobacteria	Flagellate
Diatom	**Green Algae**	*Agmenellum*	*Chrysochromulina*
Asterionella	*Ankistrodesmus*	*Anabaena*	*Phytoconis*
Cyclotella	*Ankyra*	*Anacystis*	Unknown Flagellates
Cymbella	*Chlamydomonas*	*Aphanizomenon*	**Dinoflagellate**
Fragilaria	*Chlorella*	*Aphanizomenon gracile*	*Ceratium*
Melosira	*Chlorococcum*	*Lyngbya*	*Peridinium*
Navicula	*Closterium*	*Microcystis*	**Euglenoid**
Nitzschia	*Coelastrum*	*Oscillatoria*	*Trachelomonas*
Pennate Diatom	*Eudorina*	*Phormidium*	*Euglena*
Stephanodiscus	*Golenkinia*	*Planktolyngbya*	
Synedra	*Monoraphidium*	*Pseudo Anabaena*	
Tabellaria	*Oocystis*	*Woronichinia*	
Unknown Diatom	*Palmella*		
Cryptomonad	*Palmellopsis*		
Cryptomonas	*Pediastrum*		
Cryptophyte	*Phytoconis*		
Golden Algae	*Scenedesmus*		
Chrysococcus	*Sphaerocystis*		
Dinobryon	*Staurastrum*		
Mallamonas	*Volvox*		
Synura			

Algae can be classified as large, autotrophic organisms that have a high growth rates. Algae consist of many smaller groups such as diatoms, cryptomonads, green algae and golden algae, each of which play a different role within a given ecosystem. Many lakes experience green algae and diatom blooms during periods of cool water and high dissolved nitrogen levels, oftentimes in the spring. Cyanobacteria are archaic, prokaryotic organisms that are often able to outcompete algae due to characteristics such as the ability to fix nitrogen (Ferber et al. 2004). Flagellates are organisms with appendages called flagella that allow for slight locomotion throughout the water column. Flagellates include colonial, free-living and parasitic species as well as the dinoflagellates which are known for producing “red tide” during a bloom (UCB 2006). Potential detrimental effects of the phytoplankton groups within Newell Creek Reservoir are as follows (NHMRC and NRMMC 2011):

Algae

- Decreased DO due to decomposition
- Diminished aesthetics
- Undesirable, color, odor and taste

Cyanobacteria

- Same as algae
- Can be pathogenic
- Toxin production (e.g. *Microcystis*)
- Human health effects (skin rashes, eye irritation)

Flagellates

- Neurotoxin production

We also visualized phytoplankton data between 2003 and 2012 by plotting: relative abundance at various water elevations, relative abundance over time, relative abundance in relation to chlorophyll and algaecide, and relative abundance of specific taxa within each group. These analyses were performed to determine if seasonal patterns existed among phytoplankton blooms at various sites and elevations, and to visualize correlations between phytoplankton, chlorophyll, and algaecide.

As expected, phytoplankton blooms were generally found at the surface and followed a strong seasonal pattern. For example, blooms at Site 2 mainly occurred at the surface in the summer and did not reach deeper depths (Fig. 13). When blooms were found at deeper depths they appear to have occurred during the fall/winter months when the lake was isothermal and thus relatively well-mixed. Specifically, cyanobacteria blooms dominated in the summer, around July, typically persisting or recurring over a period of one or two months punctuated by treatments, while green algae appeared in smaller abundances throughout the year. Cyanobacteria and algae blooms also made up the majority of blooms at the surface of Site 4 during the summer months, with cyanobacteria dominating (Fig. 14). Comparison of the two sites indicated that Site 4, which is located in shallow waters, had less bloom activity than Site 2, which is near the dam at the deepest part of the lake.

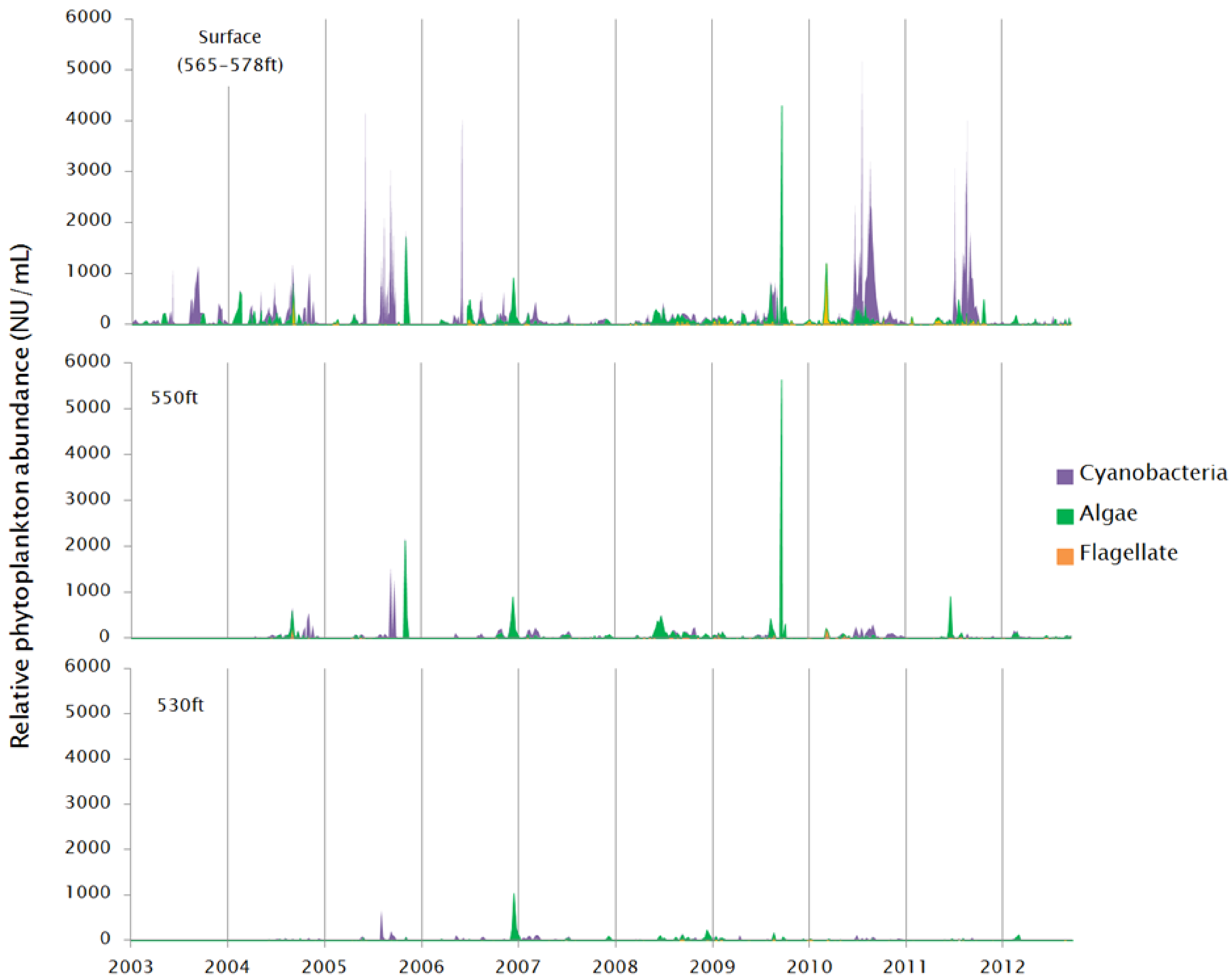

Figure 13. Relative phytoplankton abundance at the surface, and at elevations of 550 ft and 530 ft, at Site 2 of the Newell Creek Reservoir. The plot is a "stacked area" plot; the total height reflects the total count, and the colors reflect the contribution of each taxonomic group to that total.

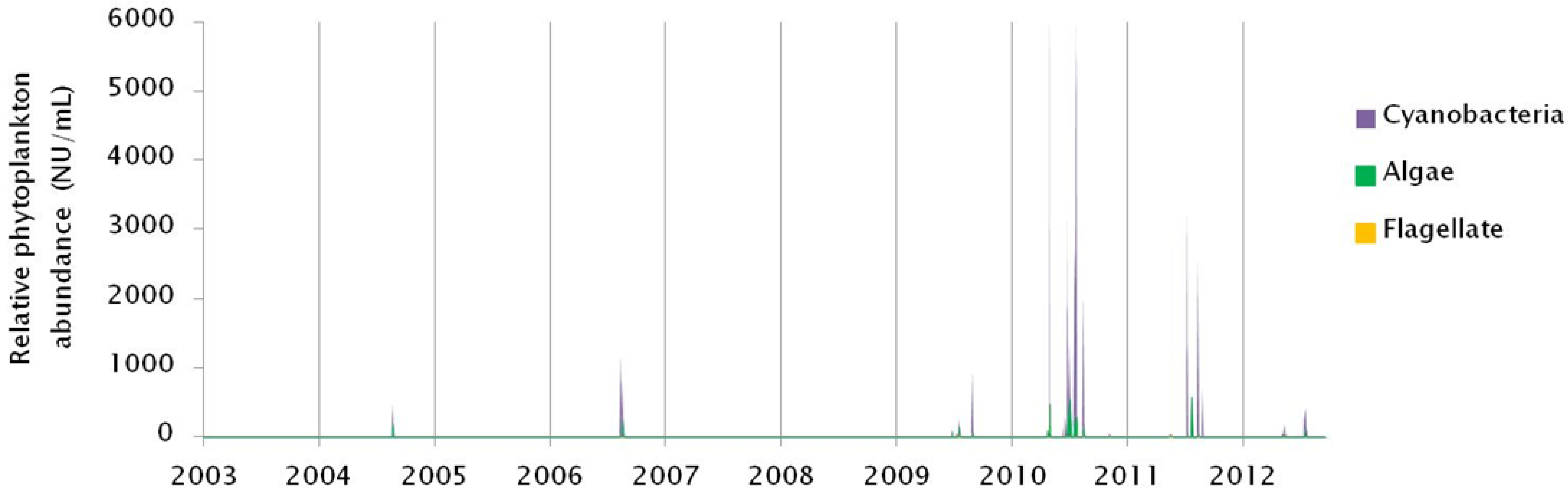

Figure 14. Relative phytoplankton abundance at the surface of Site 4 of the Newell Creek Reservoir. Flagellates were present, but due to their low abundance (480 maximum count), counts cannot be seen on the graph.

Analysis of the relationship between phytoplankton, chlorophyll, and algaecide applications indicated that chlorophyll concentrations generally corresponded with phytoplankton blooms, while both decreased following algaecide applications (Fig. 15). This alignment indicates that the NU count methodology was fairly accurate and that algaecide treatments corresponded to reduced bloom counts, suggesting that this management practice is effective. This concept was demonstrated especially well in 2009 at Site 4 as substantial reductions in phytoplankton counts can be seen following algaecide application (Fig. 16).

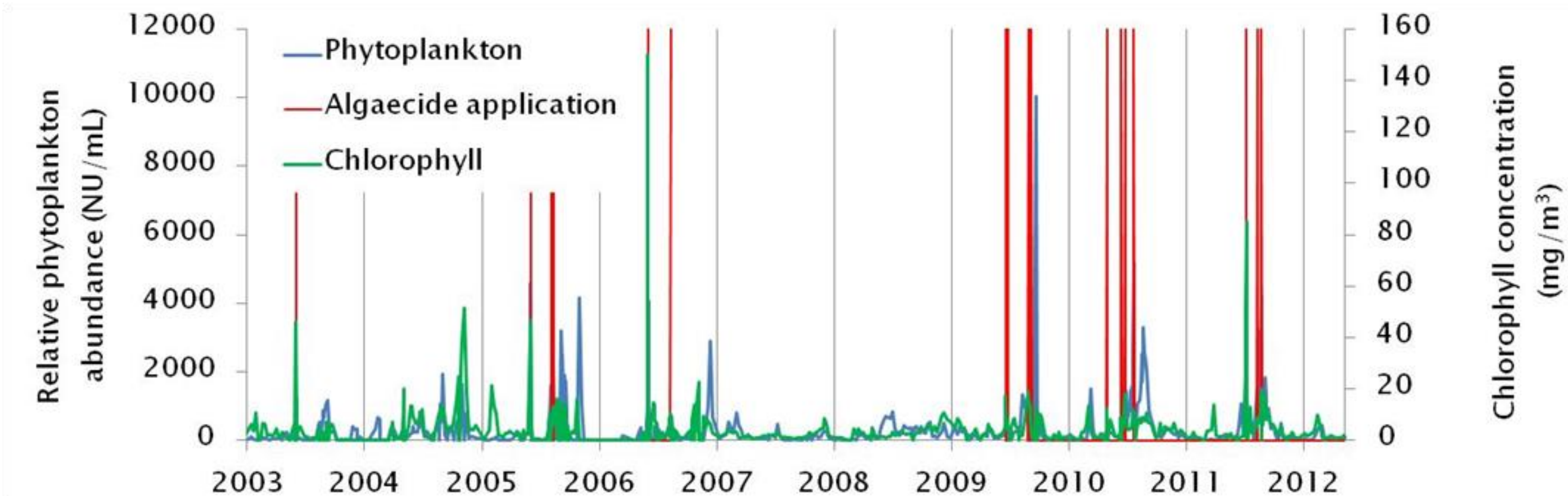

Figure 15. Total relative phytoplankton abundance and chlorophyll concentration with algaecide applications at Site 2 of Newell Creek Reservoir.

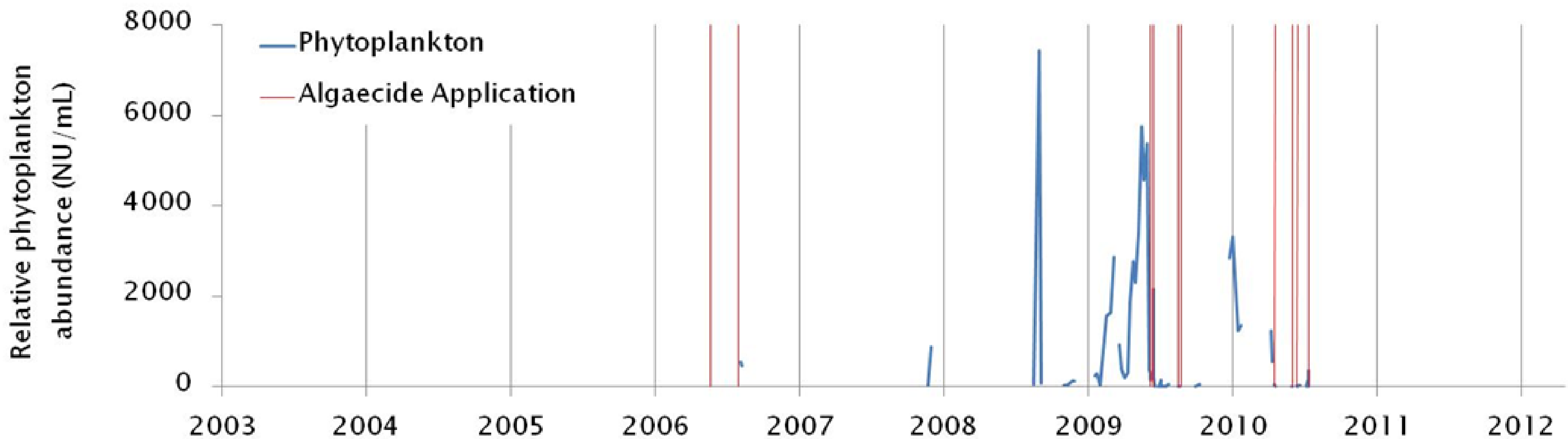

Figure 16. Total relative phytoplankton abundance with algaecide applications at Site 4 of Newell Creek Reservoir. Chlorophyll concentration was not added due to lack of data and the fact that phytoplankton data are sparse for the given years.

When phytoplankton groups were broken down into more specific taxa, the most abundant taxa between 2003 and 2012 were cyanobacteria, diatoms, flagellates, and green algae (Fig. 17). There does not appear to be a specific correspondence based on seasonality. However, it appears that both algae groups (diatoms and green algae) occurred around the same time throughout the study period and during the few periods when cyanobacteria were not present. Flagellates appear to occur throughout the year but have increased substantially in recent years. The highest recorded count was cyanobacteria in July 2010 with a maximum count of 4,897 NU/mL. The maximum diatom count was 4,264 NU/mL in September 2009, the maximum flagellate count was 1,192 NU/mL in May 2010, while the maximum green algae count was 984 NU/mL in October 2005. Overall, cyanobacteria had the highest total count followed by diatoms, green algae, and flagellates.

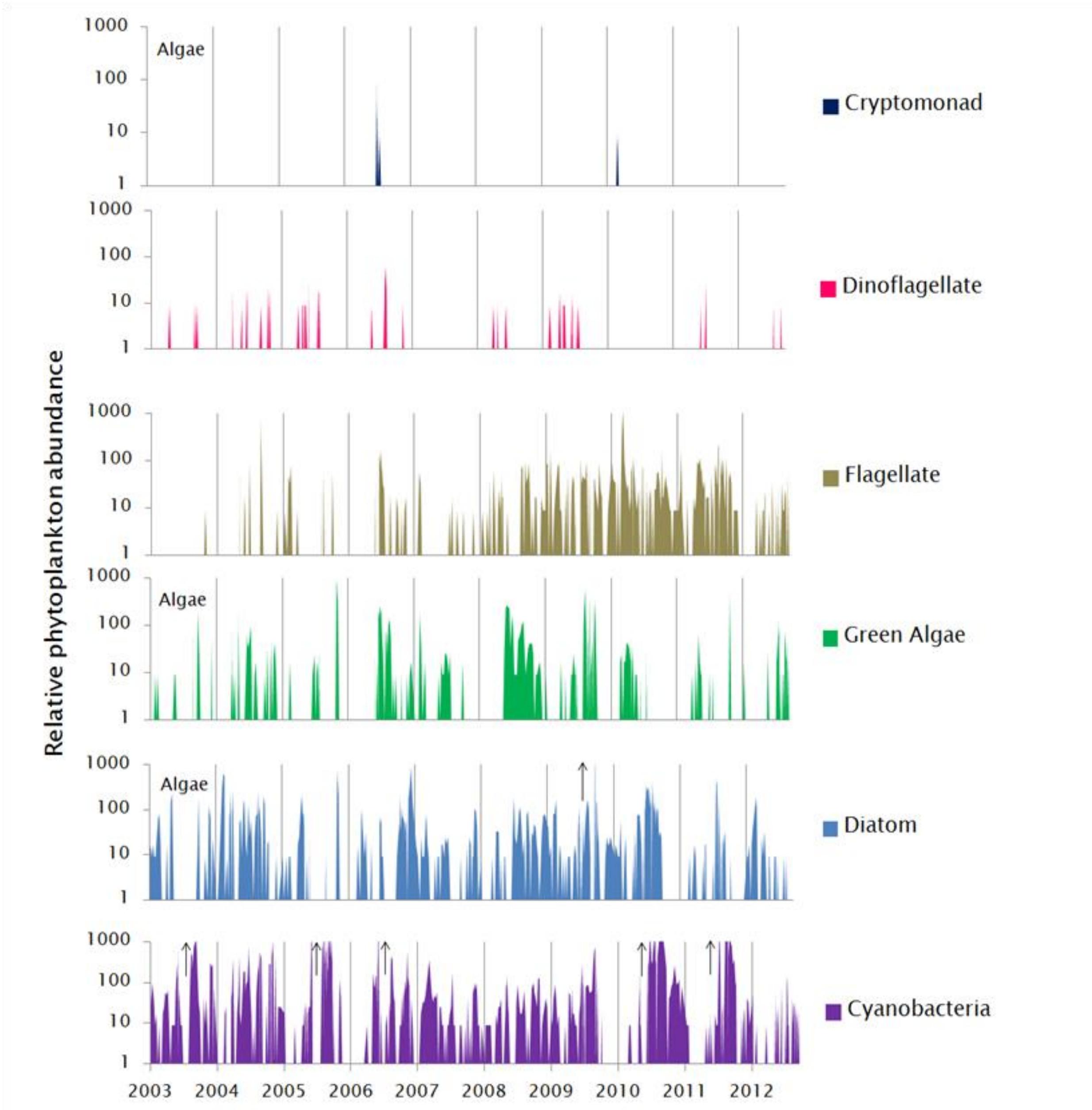

Figure 17. Relative phytoplankton taxa abundance at the surface of Site 2 at Newell Creek Reservoir. The plotted counts are actual counts + 1, to avoid log-plotting errors. The y-axis maximum is 1,000 NU/ml, but maximum counts for some taxa exceed this, which is indicated by an arrow.

We further examined the most abundant phytoplankton groups by identifying specific genera of perceived management importance. This was accomplished by selecting genera with natural unit (NU) counts greater than or equal to 200 NU/mL (Table 2). The 200 NU/mL cut-off was approximately the lowest level at which phytoplankton blooms were treated with algaecide at Newell Creek Reservoir from 2003 to 2012.

Table 2. List of genera with NU Counts greater than 200 NU/mL.

Cyanobacteria	*Anabaena*
Cyanobacteria	*Aphanizomenon*
Cyanobacteria	*Lyngbya*
Diatom	Unknown diatom
Diatom	*Nitzchia*
Diatom	*Asterionella*
Diatom	*Cyclotella*
Diatom	*Fragilaria*
Diatom	*Melosira*
Diatom	*Navicula*
Green Algae	*Ankyra*
Green Algae	*Oocystis*
Green Algae	*Palmella*
Green Algae	*Palmellopsis*
Green Algae	*Sphaerocystis*
Flagellate	*Chrysochromulina*
Flagellate	Unknown flagellate

We inferred that the genera of highest concern for management within the Newell Creek Reservoir were *Anabaena*, *Aphanizomenon*, and *Lyngbya* due to their being mentioned in algaecide application reports and as these genera were the most abundant based on total counts at the surface of both Sites 2 and 4. *Anabaena* is a filamentous cyanobacteriam and *Aphanizomenon* is a colony-forming cyanobacteriam; both are known to cause nuisance blooms in the region (SCWD 2005). *Lyngbya* is also a cyanobacteriam that can cause large blooms due to its ability to survive and grow under various ranges of temperature, light, and nutrient concentrations (Yin et al. 1997). *Anabaena, Aphanizomenon, and Lyngbya* can all produce biotoxins, cytotoxins, and saxitoxins or Paralytic Shellfish Poison (Smith 1990; Young 1992; Yin et al. 1997; Ballot et. al 2010).

A plot of these taxa over time demonstrates that *Anabaena* was the most prevalent taxon during the study period, with the largest blooms in six of the ten years (Fig 18). *Aphanizomenon* appears at high densities following *Anabaena* bloom declines in 2004, 2005, 2008, and 2011. This indicates that high densities of *Anabaena* may be competitively excluding or inhibiting *Aphanizomenon*, even though they are both nitrogen-fixing filamentous cyanobacteria (Lehman et al. 1998). This process of replacement and succession can be caused by opening of niche space and changes in nutrient composition (Lehman et al. 1998). Algaecide treatments can both open niche space and change nutrient composition as treatments are usually targeted at dominant taxa that upon eradication, release limiting nutrients through lysed cells (Elser et al*.* 1995). Fortunately, there was only slight indication of this in 2005, as *Aphanizomenen* appeared following algaecide treatment of *Anabaena. Lyngbya* was present in various years but at much lower densities and with no clear successional or seasonal patterns.

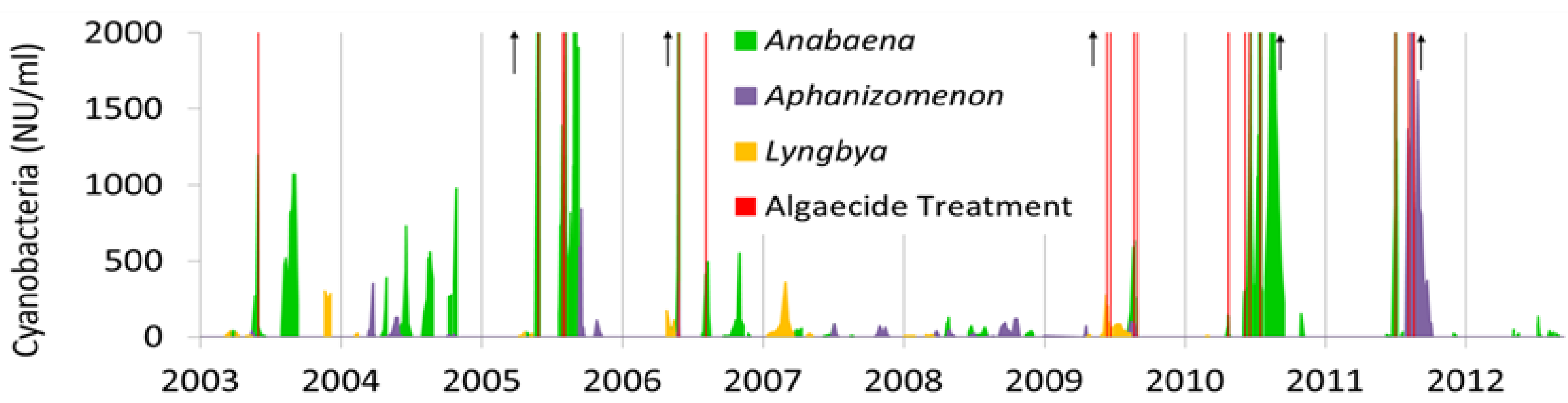

Figure 18. Relative abundance of genera of particular management concern at the surface of Site 2. The up arrows indicate that blooms exceed 2,000 NUs/mL.

6 Phytoplankton Bloom Analysis

Phytoplankton bloom intensity and frequency are dependent on a variety of environmental factors including various hydrologic and water quality parameters. These variables can be used to predict blooms, including population density, dominant taxa, and expected growth rates (Tilman 1977; Tilman 1981; Grover 1989; Jensen 1994; Huisman 1999). In this section, we assessed phytoplankton data in relation to the hydrologic and water quality data introduced earlier in this report to better understand spatial and temporal associations, and to potentially identify predictors of blooms in the Newell Creek Reservoir.

Data between January 2003 and September 2012 for Site 2 were analyzed as there was minimal phytoplankton data at Sites 1, 3, 4, and 5 and since data prior to 2003 had not been digitized at the time of the analysis. We conducted several types of analyses for the major phytoplankton groups (Cyanobacteria, Diatoms, and Green Algae) and several types of analyses for just cyanobacteria as this group was the most abundant and contains genera of management importance. Note that flagellates were not included in the major phytoplankton group analyses as the dataset only included two genera and three observations with abundances over 200 NU/mL. Analyses of the major phytoplankton groups involved a basic comparison with hydrologic and water quality data, correlation analyses between phytoplankton and these parameters, and a scatter plot to visualize a specific relationship between cyanobacteria and annual peak flow. For cyanobacteria in general, we visualized an annual *Anabaena* bloom in relation to all of the water quality and hydrologic parameters and looked at relationships of cyanobacteria with temperature through degree-day analyses.

6.1 Major Phytoplankton Groups

6.1.1 Visual Analysis

The first component of our analysis of bloom predictors was a graphical juxtaposition of the 10-year time series of phytoplankton counts and other relevant environmental factors from 2003 to 2012 (Fig. 19). It appears that relatively normal seasonal oscillations exist for each environmental parameter over the study period.

Summer surface water temperature increases corresponded temporally with the development of summer cyanobacteria blooms. Likewise, there was a seasonal increase in surface water conductivity, which was likely a result of the influence of temperature on conductivity. There also appears to be a small-scale decrease in conductivity associated with the initiation of a cyanobacteria bloom, which may be reflective of the increased uptake of ions by a developing bloom. While there does not appear to be an overarching pattern to surface DO levels, peaks in DO were associated temporally with peaks in phytoplankton abundance, probably due to photosynthesis.

Surface water pH demonstrated a regular seasonal pattern with a higher pH during the summer months. This increase in pH may be reflective of the uptake of dissolved CO_2 by cyanobacteria blooms during photosynthesis, but could also be an effect of algaecide treatments (C. Berry, SCWD, pers. comm. 2012). Turbidity and its correlate, Secchi depth, demonstrated some seasonality. The turbidity increase in the winter, indicated by Secchi depth, was likely due to increased precipitation and flow, which can carry sediment and allochthonous matter from the watershed to the reservoir. Spring and summer turbidity increases were likely due to increased bio-turbidity from phytoplankton blooms.

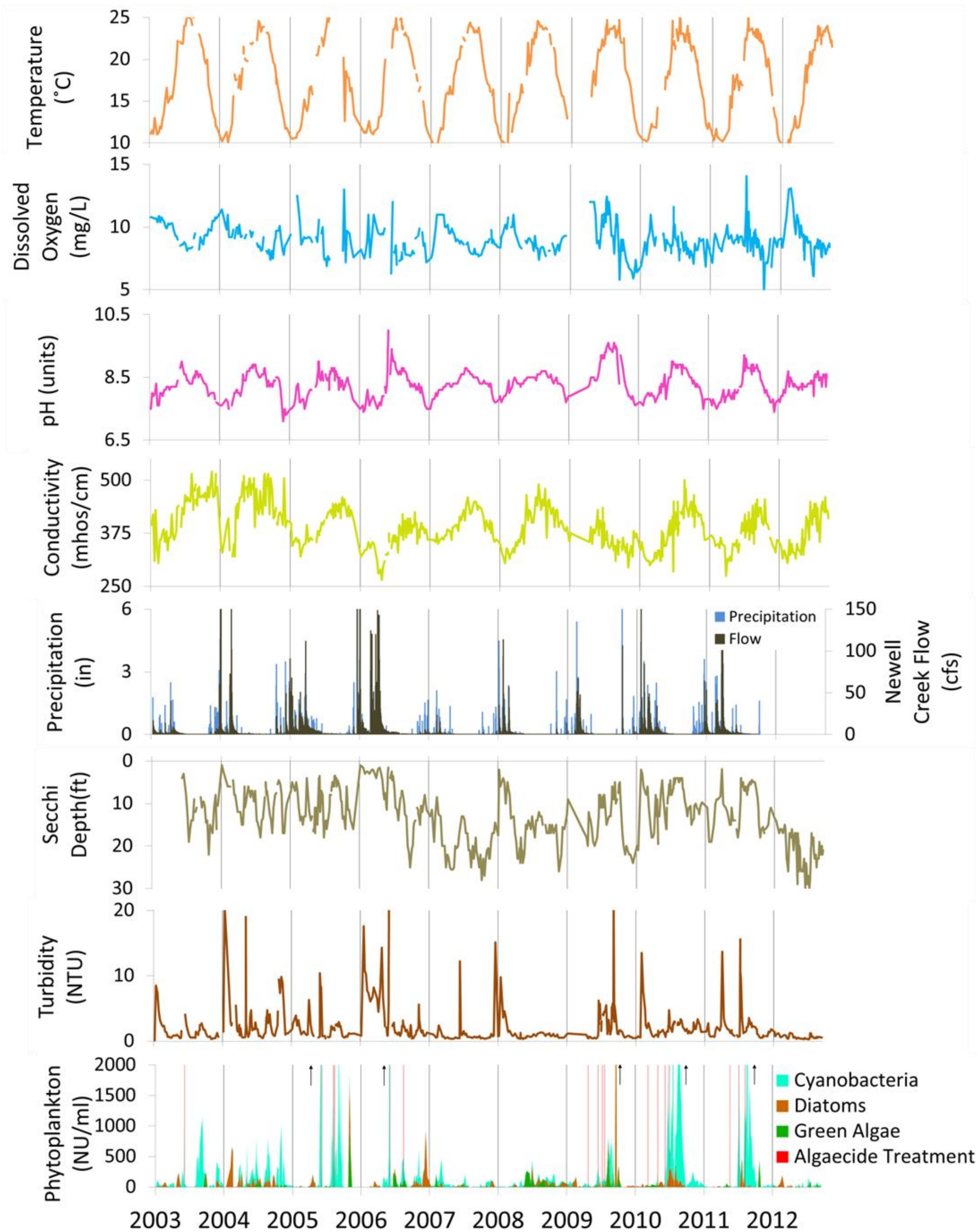

Figure 19. Newell Creek Reservoir dynamics including phytoplankton, precipitation /flow and water quality parameters. Data were recorded for the reservoir surface at Site 2. Algaecide treatment dates and the up arrows indicate that blooms exceeded 2,000 NUs/mL.

Precipitation and the resulting discharge corresponded with wet and dry seasonal patterns typical of a Mediterranean climate. The first precipitation event appeared in late fall, following decline of the remaining cyanobacteria biomass. There appears to be a temporal association between precipitation/flow and cyanobacteria blooms, as blooms seem to develop following a year with high precipitation and high flow events (Fig. 20). To examine this relationship further, we plotted peak annual discharge versus peak cyanobacteria density. There was some evidence that a predictive relationship exists, although it was not statistically significant given the nine annual data points that were considered ($R^2=0.26$, $p=0.08$). However, cyanobacteria densities may have been stunted by algaecide applications, which could have confounded results.

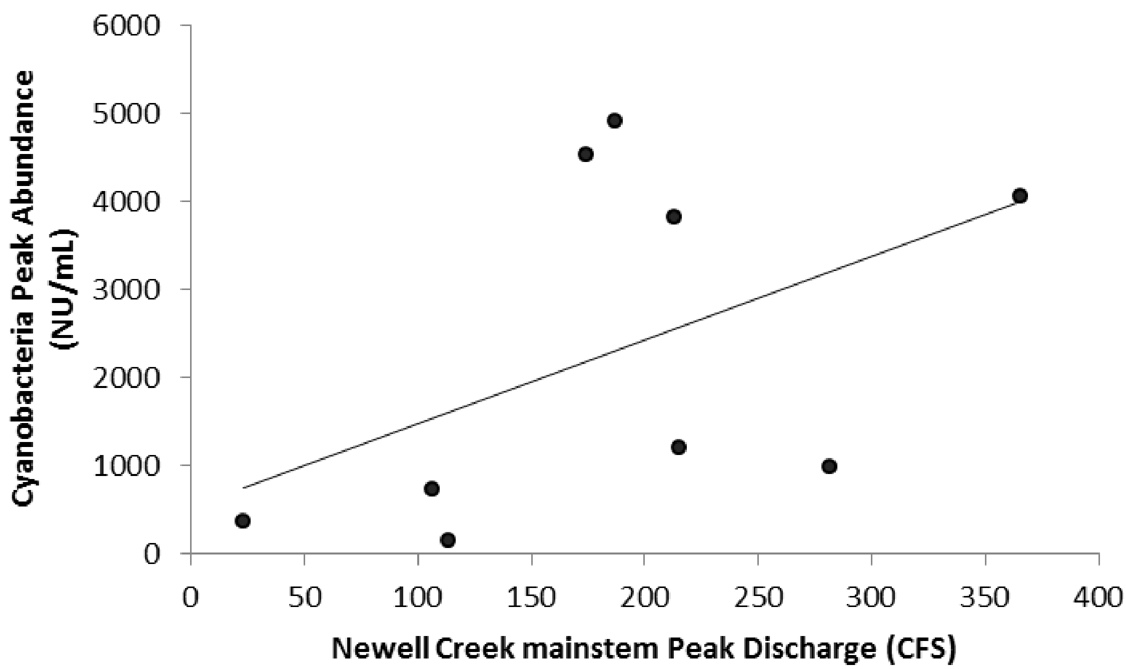

Figure 20. Linear regression showing a potential correlation between peak cyanobacteria density and annual peak discharge.

6.1.2 Correlation Analysis

Statistical correlation analyses were also performed for the dominant phytoplankton groups and the selected environmental parameters to determine if significant ecological correlations exist. These analyses were performed for the diatom and green algae data for the surface of the reservoir, while cyanobacteria analyses were conducted for the surface of the reservoir, in addition to two other depths that had count data (550 feet and 530 feet elevations). A supplemental correlation analysis of cyanobacteria was completed by looking only at the period during which blooms were observed annually (May through mid-November).

These correlation analyses were performed by means of the Spearman Rank Correlation test, a nonparametric test, in R programming language (RDCT 2012). These methods provided *p*-values and Spearman Rank Correlation coefficients (*rho*), to assess the significance and strength of correlation between phytoplankton group NU counts and environmental parameter data; thereby allowing us to isolate parameters most strongly correlated with bloom density. However, it is important to note that blooms themselves may *cause* variation within many environmental parameters (DO, pH, temperature, conductivity, turbidity).

The distribution of NU counts for all datasets was determined to be non-normal, largely due to a high number of zeros. For all analyses, missing values in the environmental parameter datasets were excluded. The number of data points (n values) for each group represented the number of phytoplankton count data that were available for analysis; however, missing environmental parameter data reduced some of these n values since only dates with both phytoplankton and environmental parameter data could be analyzed. *P*-values were considered significant at the 0.05 level, while *rho* values from 0.3 to 0.5 were considered moderate correlations and those greater than 0.5 were considered strong correlations.

The Spearman Rank test resulted in several moderate to strong correlations between bloom densities and environmental parameters (Table 3). Both the surface datasets for cyanobacteria (entire and bloom season), indicated cyanobacteria blooms having moderate to strong positive correlations with pH and turbidity. Both datasets also indicated a moderate to strong negative correlation with Secchi depth. However, turbidity and Secchi depth are related, and most likely reflect phytoplankton density, as turbidity measurements typically can't distinguish between bio-turbidity and turbidity caused by other factors such as sediment. Increases in pH were most likely an effect of blooms through photosynthesis but may have also been an effect of the chelated copper sulfate algaecide application. However, only the increased pH correlation with blooms was evident in the correlation analysis, despite applications during peak bloom periods.

Data for the other groups and for cyanobacteria below the surface indicated only significant weak correlations with certain parameters. Water temperature, conductivity, DO, precipitation, and flow had no direct correlation with any of the groups. For the green algae dataset, correlations may reflect a low volume of non-zero green algae counts (n=193) in relation to the total count versus temperature values (i.e. only 27 non-zero count dates corresponding to temperature), or due to unexplained ecological reasons.

Table 3. *P*-values and correlation coefficients (*rho*) from the Spearman Rank Correlation test. Bolded values are for environmental factors that were significant at the 0.05 level for a two-sided test and had either a moderate or strong correlation.

	Cyanobacteria (Surface)		Cyanobacteria (Surface, bloom		Cyanobacteria (550 ft elevation		Cyanobacteria (530 ft elevation)		Diatoms (Surface)		Green Algae (Surface)	
	rho	*p-value*	rho	*p-value*	rho	*p-value*	rho	*p-value*	rho	*p-value*	rho	*p-value*
Temperature	0.11	<0.01	0.24	<0.01	0.13	<0.01	-0.02	0.59	-0.7	0.12	-0.25	<0.01
Conductivity	**0.33**	**<0.01**	0.11	0.02	0.11	0.02	0.01	0.8	-0.01	0.84	0.07	0.09
DO	0.09	0.03	0.23	<0.01	-0.09	0.06	-0.04	0.37	0.12	<0.01	-0.1	0.01
pH	**0.51**	**<0.01**	**0.44**	**<0.01**	0.09	0.05					0.22	<0.01
Precipitation	-0.19	<0.01	-0.07	0.17							-0.02	0.54
Newell Creek mainstem flow	-0.23	<0.01	0.03	0.53							0.1	<0.01
Secchi depth	**-0.39**	**<0.01**	**-0.61**	**<0.01**							-0.18	<0.01
Turbidity	**0.42**	**<0.01**	**0.66**	**<0.01**	0.09	0.06	0.12	0.01			-0.03	0.37

6.2 Cyanobacteria

It is clear from the Phytoplankton Dynamics analysis that *Anabaena* had the highest relative abundance over the study period, so we performed an additional analysis on *Anabaena* to visualize annual growth/bloom formation and in relation to the selected hydrologic and water quality parameters for 2010, the wettest year during the study period (Fig. 21). The figure suggests that potential relationships exist between *Anabaena* and water temperature, conductivity, DO, and Secchi depth, while no clear associations were observed with pH and precipitation.

In July 2010, in correspondence with the initiation of an increase in *Anabaena* growth, surface water temperature exceeded 18˚C, rising over time towards optimal temperatures for growth of *Anabaena* (around 80% maximum growth rates at 18˚C). The first bloom appears to be directly associated with an increase in DO due to photosynthesis during the day when the samples were taken. Later blooms show a less clear trend, which is likely due to the confounding effects of decomposition on DO from the previous blooms. Secchi depths indicate increased water clarity right before *Anabaena* blooms in the summer months. Algaecide treatments on April 29 and June 24 showed a decrease in bio-turbidity, whereas less of an effect was seen during the June 12 treatment. Increase in available light through the water column likely facilitated the following *Anabaena* bloom in mid-June.

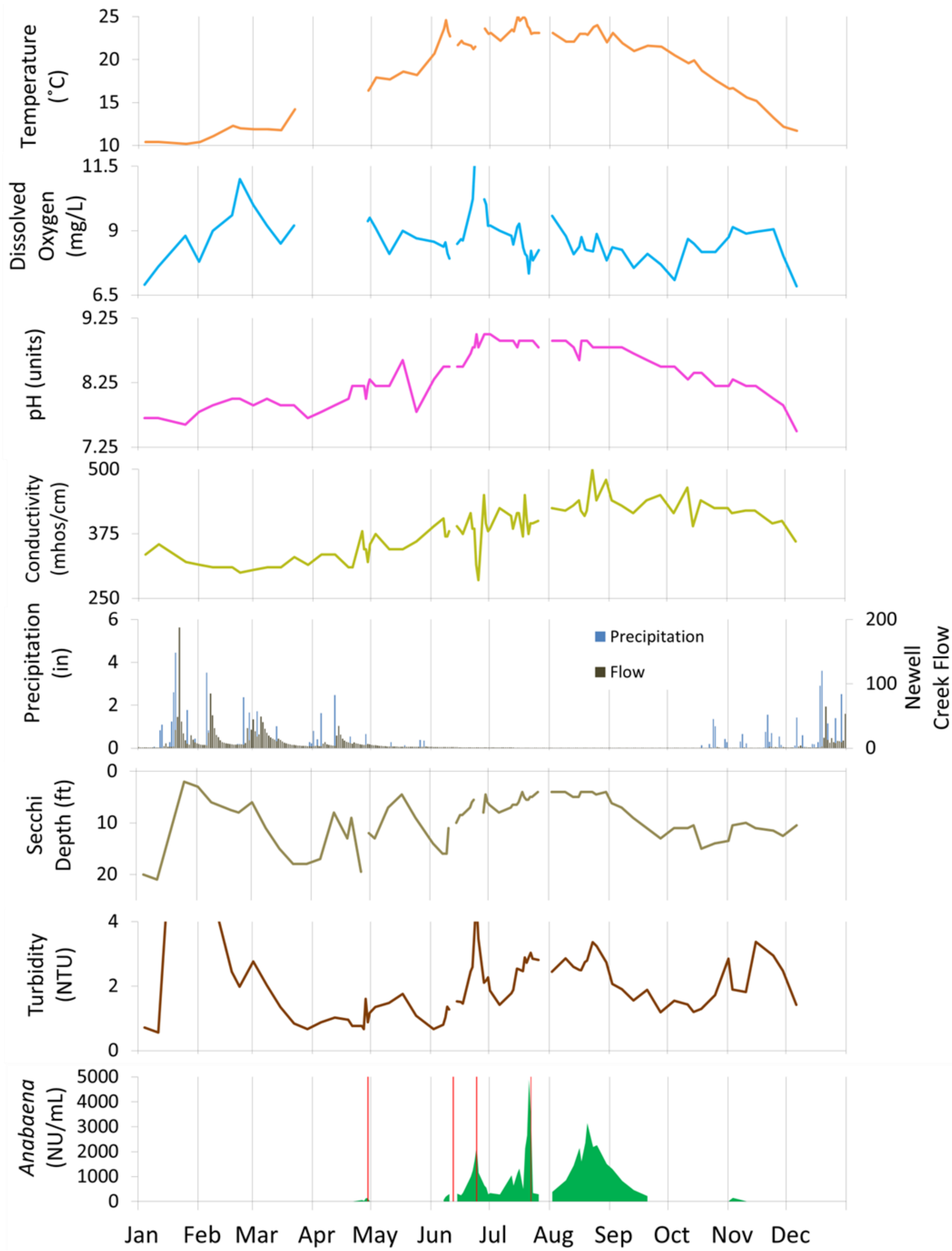

Figure 21. *Anabaena* **counts, precipitation, flow, and various water quality parameters at Site 2 for the surface of Newell Creek Reservoir in 2010.**

To further explore the relationship between temperature and cyanobacteria bloom development, we examined the relationship between cyanobacteria abundance and accumulated 'degree-days' (Kann 1998). Water temperature is often a key predictor of cyanobacteria bloom frequency and density (Cioaca et al. 2009; Paerl et al. 2011; Kosten et al. 2011), but studies have shown that basic water temperature measurements may not be sufficient to control for temporal variability in temperature. Degree-days (˚D) are an indicator of the total amount of heat required between upper and lower thresholds for photosynthetic organisms to develop (UC IPM 2012). Each degree-day is an accumulated measure of the temperature and time between upper and lower thresholds for each day. Because most photosynthetic organisms have specific heat requirements to develop, the accumulation of degree-days through the season are then calculated as an expression of the accumulation of heat over the season.

We calculated degree-days using air temperature rather than water temperature, as there was finer temporal resolution for air temperature data and a strong correlation between the two parameters. This was determined by means of a basic plot showing congruency between water temperatures measured at Newell Creek Reservoir and air temperatures measured at a representative station (the California Irrigation Management Information System De Laveaga station) (Fig. 22). We found that the air and water temperatures were strongly correlated ($r=0.72$, $p\text{-value} < 2.2e-16$).

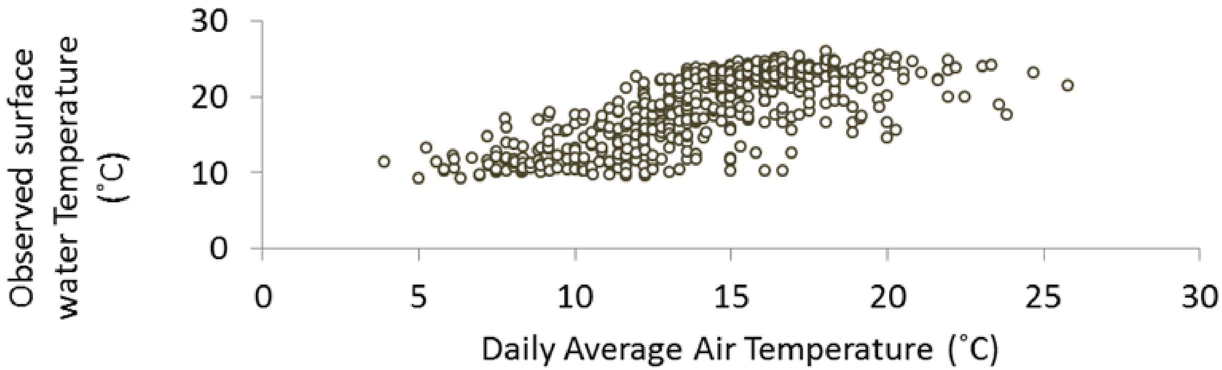

Figure 22. Relationship between average air temperature (Da Laveaga station) and surface water temperatures at Newell Creek Reservoir from 2003-2012.

Degree-days were calculated using a degree-day calculator tool available from the University of California Agriculture and Natural Resources Statewide Integrated Pest Management Program (UC IPM 2012). We used the calculator with the recommended method (UC IPM 2012) and entered the lower threshold at 16˚C and excluded an upper threshold as cyanobacteria grow faster beyond the temperature maxima for the study area (Paerl et al. 2011). The tool counted what fraction of each day was at or above a predetermined ideal minimum temperature of 16 ˚C, which corresponds to approximately 50% maximum growth rate according to cyanobacteria literature (Fig. 23).

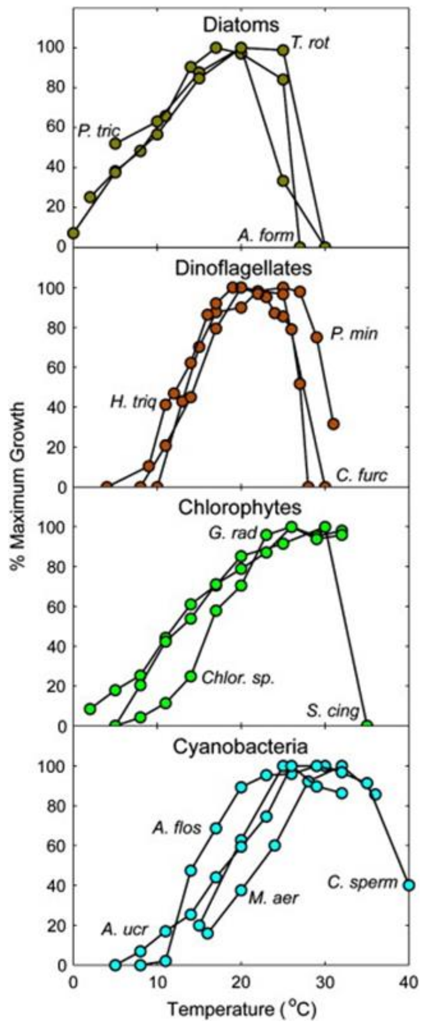

Figure 23. Temperature optima for several phytoplankton groups, including the three groups that we focused on in this report (cyanobacteria, diatoms, and green algae) (Paerl et al. 2011).

To best account for the effect of temperature on bloom appearance and development, degree-days were used for optimal temperature versus the first cyanobacteria blooms of each year (Fig. 24) (USGS 1997; USGS 2007; Dupuis et al. 2009). We used first-blooms in an attempt to discount the effect of algaecide treatments on bloom intensity, although it severely limited number and intensity of blooms covered in our analysis since all years and first-blooms except 2004, 2007, 2008 were treated with algaecide.

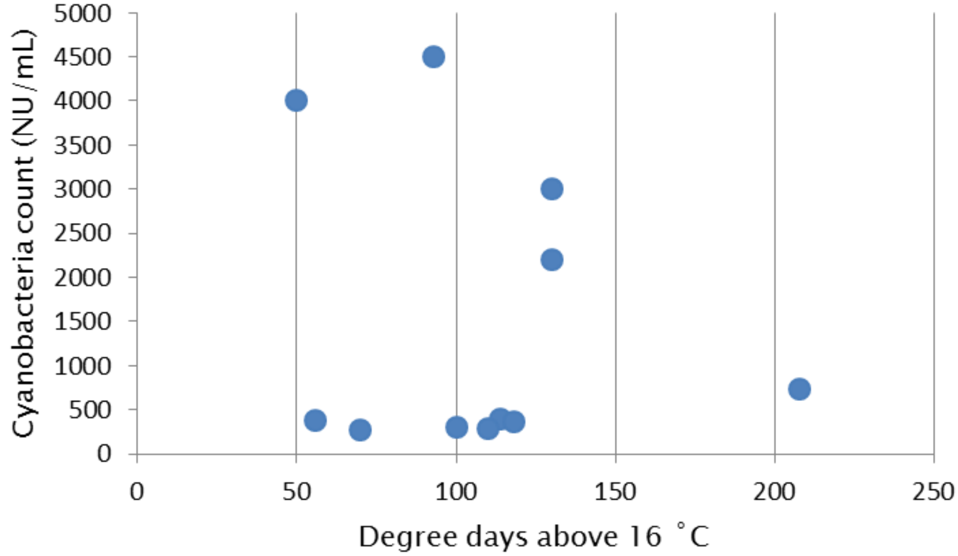

Figure 24. Plot of peak densities of cyanobacteria blooms between 2003 and 2012 occurring before the year's first algaecide treatment.

Examination of the plotted degree-day versus first-bloom does not indicate a clear correlation, which may be due to a low sample size (n=9). The second highest intensity bloom (peak=4,000 NUs) during the study period occurred after the lowest number of degree-days that year, although there may have been a short period of consecutive degree-days before that bloom that was not assessed in this broad scale analysis. The degree-day that blooms occurred varied per year with the lowest being 50 degree-days and the highest being 208 degree-days. The mean number of degree-days for the first bloom to occur in this period was 102 days and the standard deviation was 51 days.

To obtain a different perspective on degree-days, we plotted degree-days versus date for 2003 to 2011 (Fig. 25). Degree-days appear to follow a linear increasing trend by month, regardless of year, except for 2004 (orange points) which experienced temperatures above 16 ˚C earlier than other years and also showed corresponding earlier blooms. These early blooms were relatively low-intensity but above levels that were treated in other years (peaks=384,392 NUs). The earliest first-bloom during the study period occurred at the end of March, while the latest was at the end of June. This line of enquiry is not conclusive at this stage, but the analysis to date suggests that it has potential to be a fruitful way forward in the search for bloom predictors.

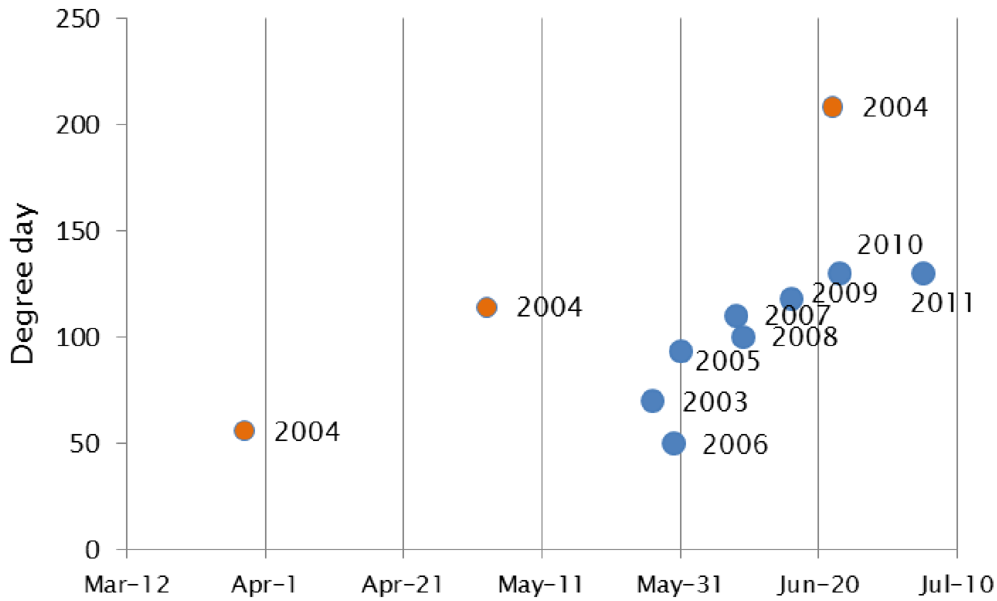

Figure 25. A linear perspective on degree-days from 2003 to 2011. There is a linear trend of degree-day versus date except for three points in 2004 (orange) that had more degree- days earlier.

7 Discussion

Our analyses resulted in several key inferences regarding phytoplankton dynamics and relationships with select hydrologic and water quality parameters that may provide insight to assist bloom mitigation at the Newell Creek Reservoir. We found that phytoplankton groups followed a strong season pattern with highest abundance in the summer, dominated by cyanobacteria, while diatoms and green algae appeared in smaller abundances throughout the year. We inferred that the genera of highest concern for management were the cyanobacteria taxa: *Anabaena*, *Aphanizomenon*, and *Lyngbya,* and that there may be successional patterns between these taxa, potentially as a result of algaecide treatment. We found preliminary support for the postulate that intensity of preceding water year discharge may influence peak densities of cyanobacteria blooms. We also found that in one year (2004), higher degree days that occurred earlier in the season (*i.e.* higher average temperatures days earlier) corresponded to an earlier, low-density bloom season.

The 10-year analysis of bloom predictors and subsequent linear regression of peak winter flow and peak cyanobacteria abundance, revealed evidence that was consistent with SCWD managers' subjective observations that peak winter flows may be a key factor governing peak blooms in the following summer. We interpret this relationship as being due to nutrients, as winter flows presumably contain higher nutrient loadings from the watershed. SCWD indicated that flows into the reservoir with high nutrients may be specifically derived from water pumped from the San Lorenzo River or from tributaries besides Newell Creek mainstem, which have contained significant concentrations of phosphorus in recent samples (T. Tompkins, SCWD, pers. comm. 2012). Therefore, winter precipitation and associated flows of high enough intensity to mobilize sediments and nutrients may be a vital predictor of bloom density in the following bloom season (Anderson and Burt 1990; Harmel et al. 2002).

Nutrients are strong drivers of phytoplankton bloom intensity and taxa composition (Pick and Lean 1987; Horne and Commins 1987; Paerl et al. 1987; Ferber et al. 2004). The lack of robust nutrient data for both the Newell Creek

Reservoir and the Newell Creek watershed was a big limitation for our analysis. We were unable to analyze and discuss specific key effects such as those of limiting nutrients on phytoplankton dynamics and bloom predictors (aside from inferring nutrient loading from winter flows). Nitrogen and phosphorus are the major limiting nutrients for phytoplankton and can be replenished by several pathways including atmospheric deposition, surface runoff, groundwater infiltration, and microbial processes at the sediment-water interface (Fisher et al. 1992; Jasby et al. 1994; Paerl 1997; Pinckney et al. 2001; Bergstrom and Jansson 2006). Of all nutrient-contributing pathways, nutrient contributions from the watershed have likely been the most widely modeled to assess and predict contributions to receiving waters (Billen et al. 1994; Newham et al. 2004).

Precipitation events and associated flow may also be able to influence phytoplankton dynamics through changes in the thermocline. Precipitation events and higher flows to the Newell Creek Reservoir result in an increased reservoir depth, as we demonstrated, which can decrease the strength and duration of thermoclines (Potter et al*.* 1982; Bouvy et al*.* 2003; Naseli-Flores and Barone 2005). Cyanobacteria are well-adapted for thriving in thermo-stratified water bodies, so high winter flows may result in a shift of the dominant phytoplankton taxa. Therefore, understanding the timing, depth, and strength of thermocline formation is vital in understanding phytoplankton population dynamics over a given season. Higher resolution measurements of thermocline data with shorter depth intervals could shed light on stratification and subsequent effects on phytoplankton dynamics and dominance of certain taxa. Interspecific dynamics such as succession are key for predicting phytoplankton blooms (Tilman 1977; Mur et al. 1978; Tilman 1981; Trochine et al. 2011) and only an initial glimpse was provided in this report.

Overall, it was challenging to identify predictors of phytoplankton blooms in a managed system. For example, installation of a SolarBee aerator, a solar-powered reservoir circulator that was installed in 2004 and removed in 2007, may have artificially impacted a variety of water quality parameters (Balance Hydrologics 2007). Algaecide applications and differences in treatment strategies may have also impacted results. For instance, cyanobacteria blooms increase pH significantly and subsequent treatment lowers pH (T. Tompkins, SCWD, pers. comm. 2012). Additionally, while algaecide applications terminate/reduce blooms, these treatments disconnect phytoplankton from factors that may naturally cause their growth or decline. While effective in the short term, algaecide treatments do not address the watershed inputs and ecosystem processes that drive bloom dynamics naturally (C. Berry, SCWD, pers. comm. 2012). Methodology limitations included phytoplankton data in the form of NU counts, which can inflate certain taxa relative to others and result in an undercounting of colonial taxa. Natural unit methods may be improved by determining a size median or average length for each taxon at the Newell Creek Reservoir in order to weight or adjust NU counts by taxa to more accurately represent their concentration in water samples.

Our analyses of ten years of hydrologic, water quality, and phytoplankton data did not reveal enough information on the interactions between phytoplankton and environmental parameters to clearly identify predictors of blooms. However, some trends were identified that can direct further analysis. In addition to the limitations identified above, our analyses were also restricted by time constraints and the availability of only ten years of digitized data at the time of our analysis. Nearly 54 years of data have since been digitized and made publically available for future analyses and more data may become available as archived records are uncovered over the next few years. Our analyses serve to provide a basis for future studies, so we have compiled an extensive list of future recommendations in the following section.

8 Future work

Future studies should account for the fact that Newell Creek Reservoir is a managed system by incorporating appropriate variables that may impact results. Analyses may therefore need to be more complex to account for compounding and unintentional effects of management practices on phytoplankton bloom dynamics. We also recommend that further analysis of the SCWD dataset focus on obtaining a deeper understanding of the methods used to collect and measure data. The following additional analyses of existing and future datasets are suggested:

- Phytoplankton
  - A correlation analysis of cyanobacteria NU counts for additional years and between depths
  - A correlation analysis between golden algae and cyanobacteria, as golden algae are known to receive benefits in the presence of cyanobacteria (Lehman et al. 2010)
  - Utilization of Bayesian model averaging to predict *Lyngbya majuscula* bloom density (Hamilton et al. 2009)
  - Collection and assessment of finer-scale count data to support more comprehensive analyses of factors contributing to bloom density
- Precipitation, Flow and Reservoir Elevation
  - An assessment of the apparent link between wet years and subsequent cyanobacteria blooms in the summer
  - An analysis that incorporates lag time between precipitation events during the wet season and blooms at the beginning of the dry season
  - A precipitation analysis that uses multiple gages, or sums daily, weekly, or monthly average rainfall in the watershed
  - An analysis of the water year and flow data versus lake level elevation
  - A time-series analysis of blooms against reservoir elevation and volume to better understand the relationship

    - Installation of monitoring wells to determine the hydraulic head and groundwater nutrient contributions to the lake
    - A discharge analysis of 'first flush' events and contribution of nutrients to the reservoir
    - An exploration of the relationship between low surface water elevation and large discharge events capable of "blowing out" upper reservoir alluvial fans. Examining this relationship further may yield some inference on bloom timing and density since these conditions can result in transport of fine sediment and nutrients to the reservoir.
- Nutrients
    - An analysis of the effect of watershed-derived nutrients on the Newell Creek reservoir, which can be determined in part by geologic substrate and organic matter composition
    - Collection and assessment of nutrient data for all contributing tributaries to the Newell Creek Reservoir
    - An assessment of nutrient contributions from the Felton Diversion Facility to determine if there is a correlation between blooms and water pumped from the San Lorenzo River
    - An investigation of nitrogen to phosphorus ratios to assess likelihood of blooms and to predict dominant taxa
    - A characterization of internal loading using sediment core collection, pore water analysis, and nutrient flux chamber installation and monitoring
    - A qualitative analysis of color as a metric for nutrient concentrations since nutrient data within the reservoir is limited. Other studies have indicated that color is often associated with nutrient content (Nürnberg 2009).
- Water Quality
    - Collection and assessment of higher resolution water quality data with shorter depth intervals to more clearly visualize trends
    - Development of simple regression models using water quality parameters as predictors (Billen et al. 1994; Pinckney et al. 1997; Scheffer 1997; Roelke et al. 1999; Downing 2001; Arquitt and Johnson 2004; Newham et al. 2004; Onderka 2007)

- An analysis of phytoplankton count data 'weighted' by water quality metrics such as turbidity (seasonally dominated bio-turbidity or suspended sediment)
- A plot of Secchi depth over time for all available data (1960s-present) to look at long-term changes in water clarity. Further research is needed to investigate the cause of increased Secchi depth within the last decade (T. Tompkins, SCWD, pers. comm. 2012).
- An analysis of radiance effects and light penetration such as Photosynthetically Active Radiation (PAR) measurements
- An analysis of the influence of parameters such as wind speed, wind direction, and solar insolation on temperature
- A study of the impact of the aerators in the reservoir on DO and temperature (thermocline disturbance)
- An analysis of population shifts in viral populations due to increased O_2 concentrations caused by a SolarBee reservoir circulator (T. Tompkins, SCWD, pers. comm. 2012). Introduced circulation may favor viruses which prefer cyanobacteria as hosts, and may shift timing of blooms (delayed onset).

9 Conclusion

SCWD provided us with 54 years of data on a variety of biological and physical parameters related to Newell Creek Reservoir, which we digitized and organized into an online public database. We analyzed the most recent ten years of data related to hydrology, water quality and phytoplankton to provide a basic assessment of phytoplankton dynamics and drivers of phytoplankton blooms in the Newell Creek Reservoir. From these analyses we made several inferences about what conditions are ideal for bloom formation and identified potential precursors to blooms such as high winter flows. However, we were not able to clearly identify specific causes of blooms in the reservoir due to the complexity of analyses required for managed water bodies in addition to time and data limitations. Overall, our study demonstrates one approach to begin comprehensively visualizing and analyzing the data and serves to provide a basis for future studies. Recommended analyses for future work focus on obtaining nutrient data and performing more specific analyses on parameters that we initially explored here to assist SCWD in predicting and mitigating phytoplankton blooms in Newell Creek Reservoir in future years.

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