PHYSICAL, CHEMICAL AND BIOLOGICAL DYNAMICS WITHIN THE PLUNGE POINT REGION OF A SMALL STRATIFIED RESERVOIR

THESIS

Presented to the Graduate Council of
Texas State University-San Marcos
in Partial Fulfillment
of the Requirements

for the Degree

Master of Science

by

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San Marcos, Texas
December 2007

ACKNOWLEDGEMENTS

I would like to begin by thanking my mother, Cindy Horne, and her husband Larry, for motivating me to stay the course and finish the job. I would also like to express my thanks to my two sisters, Summer and Sabra Woodward, who have always been a positive encouragement in whatever endeavors I pursue.

I am extremely thankful to the members of my thesis committee. My most sincere appreciation goes out to Dr. Groeger for his patience and expertise during my process of learning. He has a genuine love for limnology and a passion for discovering the processes that shape this facet of the living world. I am indebted to Dr. Tietjen for his long distance guidance and instrumental advice along the way. Dr. Rast has been a mentor in this department and his unique background has enriched my experience on this project. Also, this project could not have been completed without the help from Dr. Weston's lab. I want to express my gratitude to all of these men for the services they have so generously lent me.

This manuscript was submitted on August 12, 2007.

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CHAPTER I

INTRODUCTION

Chlorophyll abundance, both a measure of phytoplankton biomass and lake trophic status of lakes, can be influenced by many physical, chemical and biological factors: nutrient limitation (Hodgson 2005), zooplankton grazing (Thingstad et al. 1999, Vadstein et al. 1999), temperature (Currie 1990), hydrology (Carmack et al. 1986, Wetzel 2001, Lopez-Archilla et al. 2004), and climate change (Sorrano et al. 1996, Baines et al. 2000) can all affect the density and make-up of phytoplankton populations within an aquatic system.

Many studies have demonstrated that flow and water residence time (WRT) can play a crucial role in shaping the growing season of phytoplankton and primary production in lentic systems (Carmack et al. 1986, Monsen et al. 2002). The tendency of a reservoir ecosystem to stratify is strongly influenced by the WRT, in addition to the temperature and hydrology of the inflowing and outflowing water. A short WRT limits the ability of a reservoir to strongly stratify or stratify at all on a seasonal basis. The stratification and mixing created by abiotic processes within a reservoir also affect the availability of nutrients to phytoplankton (Hamilton and Lewis 1987).

A better knowledge of reservoir transport mechanisms is critical to understanding reservoir ecosystems (Thornton et al. 1990). Along the horizontal axis of the reservoir, vertical stratification is initiated at the plunge point. Thornton et al. (1990) describe reservoir systems by separating the longitudinal axis of the reservoir into three zones: the riverine zone, the transition zone and the lacustrine zone. The riverine zone most clearly mimics the inflowing river. The transition zone starts directly downstream of the riverine zone, and is wider with much less current velocity. The lacustrine zone is the final downstream zone, ending at the dam, and most resembles a lake ecosystem. The plunge point is the location in a reservoir where the inflowing, denser water flows under warmer downstream surface waters, and is in the transition zone of a reservoir.

Within the area of a plunge point, density differences (gravity) force cooler water downstream beneath warmer surface water, and the convective forces caused by shear motion simultaneously pull the warm water back upstream into the plunge point. There is some water exchange between the density differences. This process provides an environment conducive to both phytoplankton and microbial growth. These convective forces make the plunge point a very productive area in a reservoir system (Thorton, et al. 1990, Groeger and Martin 2001).

Water density is the product of temperature, suspended solids (SS), and total dissolved solids (TDS). Suspended solids most influence water densities during flood events, where the concentrations are higher. The TDS basically defines the specific conductivity of the water (Ford and Johnson 1983). Different water densities can be used to distinguish layers of stratification within a water body.

In the Czech Republic's stratified Orlik Reservoir (WRT ~23 days), primary production, bacterial abundance, and bacterial production were highest near the inflow, and gradually decreased downstream (Masin et al. 2003). The data clearly illustrate a strong linkage between high plankton biomass/growth rates (in a eutrophic reservoir) and nutrient availability at the point of inflow. The role of autotrophic algal communities on nutrient cycling and their interactions with primary productivity in reservoir ecosystems is significant in shaping the chemical and biological characteristics of the reservoir system.

Scientists have previously speculated on whether phytoplankton or heterotrophic bacterioplankton have the higher affinity for phosphorus uptake in phosphorus limited systems. Cole (1982) found relationships between algae and bacteria to be less of a competitively-structured association, and more an interaction similar to characterizing symbiotic species. He categorized many of the interactions between heterotrophic bacteria and phytoplankton as being similar to that between bacteria and higher plants. Currie and Kalff (1984) subsequently demonstrated that bacteria can play a critical role in the cycling of phosphorus in most aquatic systems, but are usually limited by organic carbon excretion from phytoplankton populations. Therefore, bacterial population dynamics are positively related to phytoplankton dynamics (they increase or decrease in direct correlation with phytoplankton) and respond, as well, to changes in the environment that limits phytoplankton production. Currie (1990) concluded that, although algae and bacteria positively influence each other's abundance, there may be a third major factor affecting the relationship (e.g., temperature; bacterivore abundance).

The abundance and frequency of zooplankton that graze upon bacterioplankton and algae can have a negative effect on the size of the community structure of these microorganisms (Thingstad et al. 1999). However, although top-down models (models that explain primary productivity and algal biomass as being controlled by the behavior of higher trophic level organisms) can explain much of the variance that is not explained by models that anticipate the bottom-up (nutrient-loading models) forcing of aquatic systems, nutrient inputs are the major controlling factor on the upper limit of primary production in an aquatic system (Hodgson 2005). In eutrophic systems with a very low WRT, zooplankton grazing usually does not have an impact that could significantly alter the biomass of algae and bacterioplankton (Kalff 2002).

Tietjen and Wetzel (2003) studied the proportions of bacterial viability and chlorophyll-α present within an aquatic system on both depth and horizontal spatial scales. They linked the distribution of viable bacteria to the abundance of dissolved organic carbon, chlorophyll-α and turbidity (caused by storm surges). One of the shortcomings of this study, from the perspective of its application to other reservoir systems, is that there was little water movement during their study period (i.e., little or no water was discharged from the reservoir during the study). A similar study with a lower WRT would facilitate research that could highlight biological interactions and their reactions to physical and chemical changes in their environment.

A better understanding of the physical and chemical factors influencing the producers and primary consumers of aquatic systems can be gained through observing the mechanisms by which they interact. The microbial assemblages in aquatic systems vary distinctly from mixed species of microbes in near proximity, to close microbial relationships involving aggregates or bioflocs. In general, frequent interactions occur within and between the autotrophic and heterotrophic components of reservoir microbial assemblages (Lanza and Silvey 1985). Therefore, studying the autotrophic components of a reservoir will allow one to make assumptions about the heterotrophic condition of a reservoir system.

The research site for this study, Lake Dunlap, is a reservoir ecosystem with a strongly-defined summer plunge point. Lake Dunlap, on the Guadalupe River, in New Braunfels, Texas (29°39'13"N, 98°04'57"W), is a uniquely structured body of water (Figure 1). The reservoir, positioned over the old Guadalupe river channel, has an extended riverine zone. Dunlap follows the old river channel for approximately 12 kilometers from inflow to dam. Dunlap has a transitional zone between 2 and 7 kilometers uplake from the dam. Groeger and Martin (2001) classified Lake Dunlap as eutrophic because of its high chlorophyll concentrations, due largely to high nutrient loading from the New Braunfels Utilities' wastewater treatment plant (WWTP). Nutrient sampling for total phosphorus, soluble reactive phosphorus (SRP), nutrient limitation bioassays and total nitrogen, identified phosphorus as the limiting nutrient of the system. The inflowing Guadalupe River has high inorganic nitrogen concentrations (originating in springs feeding the Comal River) and low phosphorus concentrations. The WWTP stimulates the productivity seen within Dunlap because of the added phosphorus from the plant.

Lake Dunlap has a short water residence time (a median of about six days), with the reservoir fed by the mixed flow from the Guadalupe and Comal Rivers. The Comal River is a very short, spring-fed river that maintains a temperature of about 23°C throughout the year. During the summer months of relatively normal flow years, from approximately mid May until early September, the cooler waters feeding Lake Dunlap plunge down into the water column, causing stratification to normally occur about 2-5 km upstream of the dam (Groeger and Martin 2001). The low flow allows for a prolonged water residence time in the near-dam water. This characteristic, along with high nutrient inputs from the WWTP, stimulates conditions conducive for optimal algae growth (Groeger 2002).

Hydrological conditions in Lake Dunlap vary on a year-to-year basis (Groeger 2002). In the 1992 "wet" summer, no stratification took place. However, the summer of 2000 was an extremely dry summer with little water inflow; the "green algal front" associated with plunge point activity moved upstream past observations prior to 2000 (i.e., as was reported by a local resident, Ray Kottler, living on the reservoir). As the inflow increases, the plunge point moves further downstream toward the dam. Wet summers can even prevent seasonal stratification. Decreasing water inflow gives the surface water a longer WRT (increasing surface temperature and allowing a greater density difference throughout the water column), moving the plunge point back up-stream from the dam.

Previous research has confirmed that there can be a large SRP concentration spike within the plunge point of a stratified reservoir (Groeger and Martin 2001). An increase in the concentration of SRP within the plunging zone is usually either the result of a marked increase in biological activity (released or leached from growing algal cells), or the result of a physical/chemical reaction triggered by hydrological dynamics.

Brunskill (1969) found that warmer water temperatures allowed the epilimnion of a study lake to supersaturate with ions, and for those ions to continuously precipitate during the summer months from late May until early August. Thus, the question arises of whether or not the area of plunge point activity in Lake Dunlap, where cooler water comes into contact with warmer water exhibits similar precipitation/disassociation reactions. Murphy et al. (1983) provide evidence suggesting coprecipitation of phosphate with calcite in a eutrophic lake system.

Temperature (water density) and flow play a major role in establishing and maintaining stratification. The plunge point is extremely mobile due to the dynamic physical nature of its environment and can move up and down the reservoir a distance of many kilometers over the course of a summer. The purpose of this study was to assess the combined effects of nutrient loading and dynamic flow on a shallow, seasonally stratified reservoir, and to relate these effects to the seasonally reoccurring changes in the chemical and biological makeup of the reservoir. Another goal was to evaluate chlorophyll dynamics from pre-stratification stages through the formation of stratification. A third objective was to determine the location of the transition zone (where chlorophyll is seasonally the highest) and to collect data linking changes in the biology of the reservoir to changes in its chemical parameters (conductivity, temperature, dissolved oxygen, pH, and alkalinity).

CHAPTER II

METHODS

The study was conducted from May 2003 to September 2006. There were five fixed study sites along the longitudinal axis of Lake Dunlap: D1 (.06 kilometers upstream from the dam), D2 (2.74 kilometers upstream from the dam), D3 (7.16 kilometers upstream from the dam), D4 (11.19 kilometers upstream from the dam), and the D5 (11.59 kilometers upstream from the dam) river inflow site (as identified on the attached Lake Dunlap map, Figure 2). Variables measured at these sites included pH, specific conductivity, dissolved oxygen, chlorophyll-α, temperature, alkalinity, turbidity, Secchi disk depth and light. Field measurements of dissolved oxygen, temperature, specific conductivity, and pH were made with a Hydrolab MiniSonde (Hydrolab 1997) at one meter intervals at each sampling station. Water samples were taken periodically for measuring concentrations of soluble reactive phosphorus (SRP) and chlorophyll-α at the surface. Total alkalinity was measured with a titration method according to Wetzel & Likens (1979). Chlorophyll-α concentrations were determined fluorometrically, according to Burnison (1980), with Turner Fluorometer Model 112. Turbidity was measured using a Fisher Scientific Turbidimeter.

During the first summer sampling season, 2004, all stations were utilized (except on dates when high flow prevented sampling at D5). However, during some of the 2005 sampling dates and all of the 2006 sampling dates, D5 measurements were not taken.

The surface samples from D4 were used to represent the inflow conditions. In addition to the five established station, several measurements were taken during 2005 and 2006 at the WWTP inflow site (9.34 kilometers upstream from the dam), and plunge-point, when observed. The sampling frequency was approximately monthly, from May until September.

Field *in vivo* fluorometric measurements were taken with a Scufa Fluorometer (Turner Designs) on two sampling events in August, and one sampling event in September, 2006. Sample runs were also made during a diurnal sampling event on 9/7/2005. The Scufa Fluorometer was attached to an Excel linked computer program (Keyspan) that took real-time readings every second. A Magellan GPS unit was used to monitor the point-by-point location of the fluorometric readings, being consistent with the incoming Scufa data. Samples were taken by running the boat down the thalweg of the reservoir from a point upstream from the plunge point to the dam site, or vice versa.

Flow data for Lake Dunlap were measured daily from two inflow points (USGS flow data 2004-2006). One inflow point was on the Guadalupe River, above the confluence of the Comal and Guadalupe rivers, and the other was located on the Comal River, above its confluence with the Guadalupe River.

Thermistors were placed throughout the reservoir, and continuously measured temperatures throughout the water column at pre-selected sites, once every 8 minutes. The 2005 thermistor data set ranges from the September 1 through September 22. During the summer of 2006, thermistor data were collected from the May 4 until the October 23. Thermistor data sets were compiled via two graphing programs, Delta Graph and Surfer

Plot. The graphs compare daily flow averages and daily temperature averages at specific sites and various depths.

In 2005 there were four sites in which thermistors were utilized along a longitudinal stretch of the reservoir: the dam site, D1 (.06 km upstream from the dam); the downstream stump site (approximately 3.35 km upstream from the dam); Kottler's place (approximately 5.1 km upstream from the dam) and at the D4 site (11.19 km upstream from the dam) (Figure 2). The same four reservoir sites were utilized during the 2006 summer season. .The dam site had eight thermistors strung on a vertical line, in 2005, anchored to the bottom of the reservoir. The dam site was located at the GPS coordinates 2939.271N and 9804.010W. The downstream stump site had four thermistors strung on a vertical line, in 2005, anchored to the bottom of the reservoir. The downstream stump site was located at the GPS coordinates 2940.766N and 9804.099W. The Kottler's site had two thermistors strung on a vertical line, 2005, anchored to the bottom of the reservoir (Figure 5). The Kottler's site was located at the GPS coordinates 2940.474N and 9804.790W.

The dam site had nine thermistors strung on a vertical line, in 2006, anchored to the bottom of the reservoir. The dam site was located on the same GPS coordinates as the previous summer. The downstream stump site had six thermistors strung on a vertical line, in 2006, anchored to the bottom of the reservoir, also located on the same GPS coordinates as the previous summer. The Kottler's site had three thermistors strung on a vertical line, in 2006, anchored to the bottom of the reservoir (Figure 8), on the same GPS coordinates as the previous summer. Water density data were calculated from each of the thermistor sites in both years of thermistor study (Chen and Millero 1986).

Ten remote multiprobe sondes were set in Dunlap, in 2006, at various sites from August 8 through August 13. At site D1, a surface sonde was placed 0.65 m below the surface, a mid depth sonde 1.21 m below the surface, and a deep sonde 3.77 m below the surface. At the downstream stump site, a surface sonde was placed 0.76 m below the surface, a mid depth sonde 2.36 m below the surface, and a deep sonde 3.81 m below the surface. At Kottler's site, a surface sonde was placed 0.8 m below the surface, and a bottom sonde 1.55 m below the surface. At a site (GPS: N29 40.213 W98 05.134) approximately 6.0 km upstream from the dam, a surface sonde was placed 0.28 m below the surface. At site D3, a surface sonde was placed 0.7 m below the surface. All multiprobe sondes took temperature (°C), specific conductivity (µs/cm), dissolved oxygen (mg/L), pH, and percent dissolved oxygen measurements.

Soluble reactive phosphorus (SRP) in the water column was sampled frequently according to Wetzel and Likens (1991). I used a 60 ml syringe to pump water samples through 25 mm GFF Whatman glass fiber filters. The filtered water was then frozen and determined by the SRP procedure.

Two diurnal studies were conducted (one beginning on 9/7/2005 and another on 7/11/2006), utilizing all previously-mentioned sampling procedures on a diurnal time scale. During the night hours of the 2006 diel study, plunge point area sampling was performed at the My Casa site (approximately 4.1 km upstream of the dam) due to dangerously foggy conditions on the lake that night (Figure 2).

CHAPTER III

RESULTS

The summer season flows were higher in 2004 than the median value for the past 73 years, resulting in a short WRT (Figure 3), averaging between one and three days (Table 1). Comparatively, for the summer season of 2005, the WRT averaged between three and six days, closely representative of median values for the last 73 years of flow data. Alternately, the 2006 summer season was an extremely dry summer, and the WRT was much greater, averaging approximately eight days.

At site D1, flow increased on September 4, 2005, by approximately 2 cubic meters per second (cms), to 21 cms; then slowly tapered off to approximately 16 cms on September 21. Thermistor temperatures and temperature differences between depths decreased during September 8-13. At the Downstream Stump site, the thermistor data exhibited patterns similar to the dam site. Further upstream, at Kottler's site, the two temperature measurements remained nearly identical throughout the month in 2005. At Kottler's site, the thermistor data exhibited patterns similar to the dam and stump sites (Figure 4).

There was a sharp increase in flow during 2006 at site D1, caused by a storm surge at the beginning of July, followed by a distinct decrease. Thermistor temperatures from the various depths decreased, beginning in early September, and their range was compressed. The same phenomenon was observed for the downstream stump data, and

Kottler's site (Figure 5). The temperature differences as they relate to depth at site D1 can be more clearly observed in Figure 6. The highest average temperature at all sites occurred during the mid-summer months of June, July and August. The temperatures from thermistors at site D1 and the downstream stump site are similar throughout most of the sampling period. However, at Kottler's site, the range between the temperatures at the three various depths become condensed sooner in September than for similar depths at the other two sites (Figure 5).

Water density data were also calculated for each thermistor site in 2005 and 2006. Water densities decreased at site D1 during the summer months of 2006 as the water column warmed before becoming homogeneous (they all became closer to the same temperature), and increasing in late September. The water density data at the downstream stump site, during 2006, exhibit much the same trend as at the D1 site (Figure 7).

The water density data at site D1 for 2005 (Figure 8) are grouped as one large clump of continuous thermistor data, instead of daily thermistor means. Although there is a slight daily fluctuation in the data, the trends remain similar to the downstream stump data from 2005.

Figure 9 represents sampling dates for the 2004 sampling season, and illustrates the isothermal properties of the reservoir during the high flow summer season. In May, 2005 (Figure 10), before seasonal stratification and underflow has been established, isothermal properties of the reservoir and diurnal heat storage near the dam are clear. In contrast, the June and July 2005 data exhibit a clear plunge point effect in the temperature data (Figure 11) from the reservoir. The same is true for the June 2006 sampling date (Figure 12).

The lowest concentrations of chlorophyll-α were measured for the 2004 summer season. The 2004 chlorophyll data show the highest chlorophyll-α levels (1.2 ug/L) within the reservoir came from the river D5 site (Figure 13).

In the averaged chlorophyll data for 2005 (Figure 14), there were low chlorophyll-α concentrations between sites D4 and D3. At the plunge point, however, there was a chlorophyll-α spike (averaging ~15 ug/L). During the majority of the 2005 summer sampling season, the plunge point area was approximately 3.24 km upstream from the dam (between sites D2 and D3). Averaged chlorophyll-α concentrations at sites D2 and D1 were also higher than the other sites sampled along the length of the reservoir (between 3 and 6 ug/L).

Several *in vivo* fluorescence sampling trips along the surface of Lake Dunlap, during 2006, were performed in August and September. On August 8-9, the chlorophyll fluorescence increased in a direct relationship with an increase in temperature (Figure 15). Four more sampling runs were performed on August 23 (Figures 16 and 17). Although conducted at four different times over the course of a day, all sampling trip results indicated the same paired response of fluorescence and temperature (with a peak temperature near 34 °C). All four trips also show the plunge point to be located very close to site D3. Two more sampling trips were performed on September 14, 2006 (Figures 18), indicating a more gradual increase in temperature from uplake to downlake, with a lower peak temperature than previous sample dates (approximately 30 °C on sampling run 2). The peak fluorometric data were obtained directly upstream of My Casa (approximately 200 m). Splotchy areas of soupy water, along the sides of the reservoir were observed as far uplake as site D3.

The SRP concentrations during 2005 exhibited a change between the time before thermal stratification to the time that stratification became established. Before stratification occurred low phosphorus levels were detected upstream of the WWTP. A high concentration was also observed at the WWTP site, followed by a gradual decrease in concentrations as one moved toward the D1 site (Figure 19). After stratification, the 2005 June sampling date exhibited a SRP spike at the plunge point (Figure 20).

Diel sampling on 7/11/2006 and 7/12/2006 indicated higher chlorophyll-α concentrations at site D1 and the plunge point site than at Kottler's site. Temperature differences were greater during the day. The SRP concentrations decreased during the night at all three sites (Table 2). The surface concentrations of SRP at Kottler's site are higher than at site D1, but lower than at the plunge point site. The temperatures throughout the water column of the reservoir began to cool at night, but the thermocline rose from a depth of 4-5 m to approximately 3 m. Kottler's site exhibited little to no stratification. The chlorophyll-α concentrations are also lower at Kottler's site than at the other two sites. The thermocline became stronger at night; there was a larger temperature difference between the two depths separating the night thermocline than between the depths separating the daytime thermocline.

The diel sampling on 9/7/2005 was conducted and partially measured for soluble reactive phosphorus (Table 3). The results only comprise samples taken at 0800 and 2100 hours.

The alkalinity data collected for each sampling trip throughout the study period did not substantially change across the longitudinal axis of the reservoir. Averaged seasonally, however, there is a difference between the 2004 and 2005 summer season

(Figure 21). In 2004, the alkalinity measurements averaged approximately 4 meq/L, while they increase to approximately 4.5 meq/L in 2005. The alkalinity averages in the 2006 season were not taken sufficiently frequently to graph, although the collected data appeared similar to the 2005 data.

The average 2004 turbidity measurements increased from sites D5 to D1. Site D3 was slightly more turbid in 2005 than at all other sites (Figure 22). The averaged plunge point measurements was not included, because the plunge point area was not consistently sampled every trip.

The average conductivity (μS/cm) was lowest in the 2004 sampling season, (between 414 and 449). Higher conductivity concentrations were observed in 2005 (between 488 and 504). The 2006 sites exhibited the highest conductivity concentrations, (between 486 and 520) (Table 4).

The data from remote mulitprobe sondes placed at various sites in Lake Dunlap on August 8, 2006, illustrate an inverse relationship between temperature and specific conductance, and a direct relationship between temperature and dissolved oxygen. The D1 site shows a large difference between the peak surface measurements of specific conductivity (approximately 512) and the peak mid depth measurements (approximately 410) (Figures 23 and 24). However, the downstream stump site exhibited the opposite relationship between surface and mid depth peak conductivity measurements. Further upstream, the surface and bottom depths, at Kottler's site, exhibited the same conductivity pattern as the downstream stump site (Figures 23 and 24).

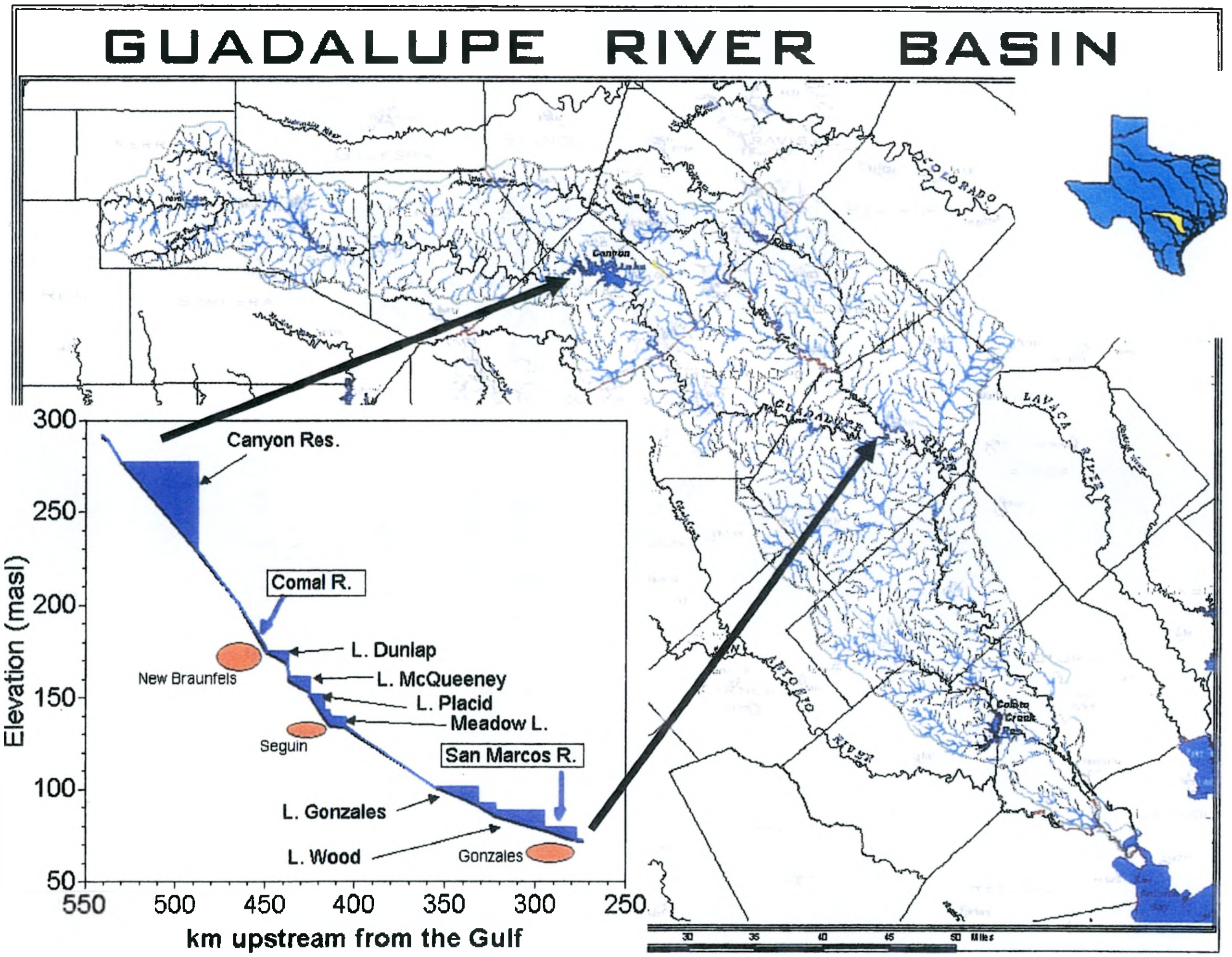


Figure 1: Map of Guadalupe River Basin (Groeger, unpublished manuscript).

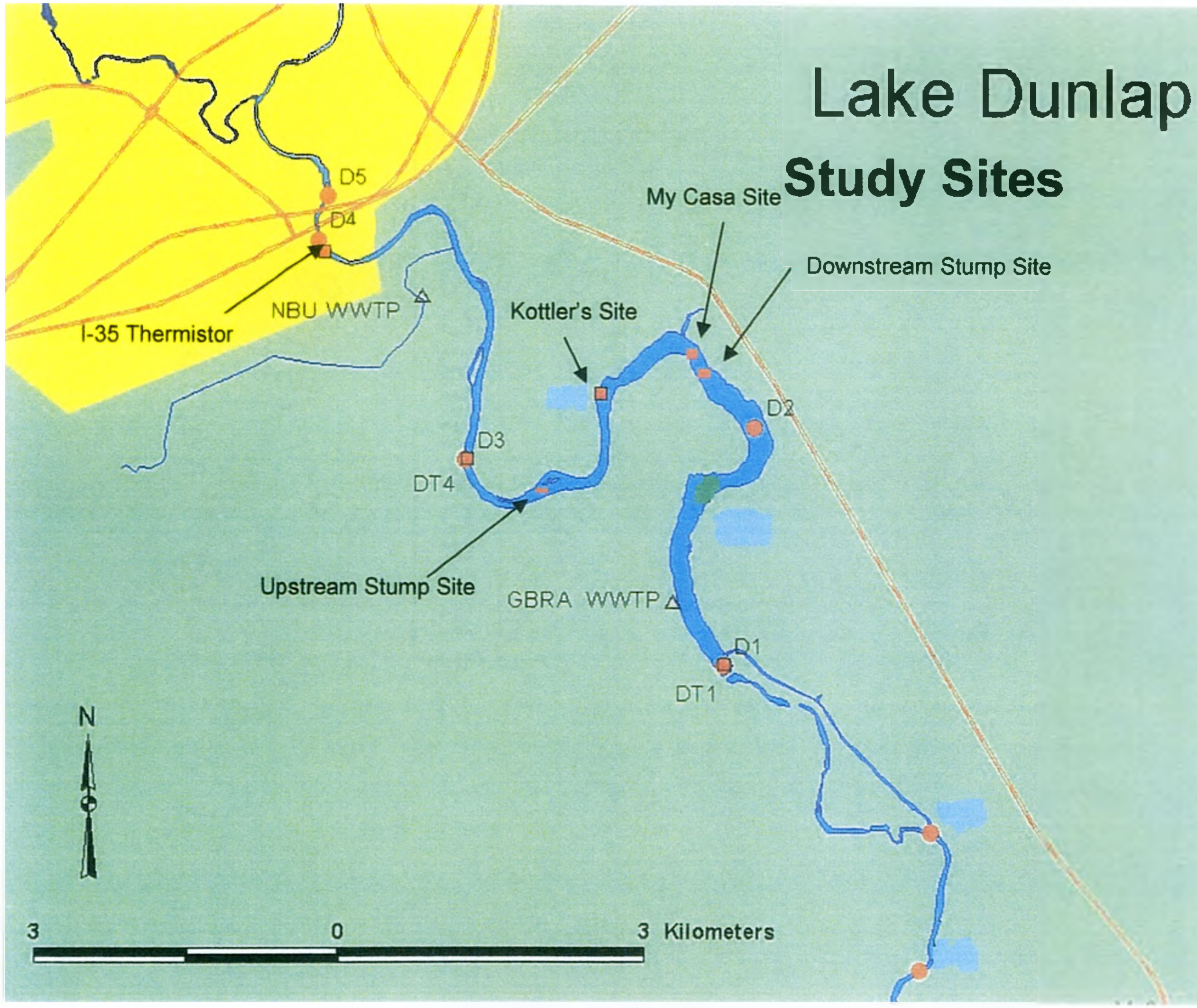


Figure 2: Map of Lake Dunlap Study Sites (Groeger 2002).

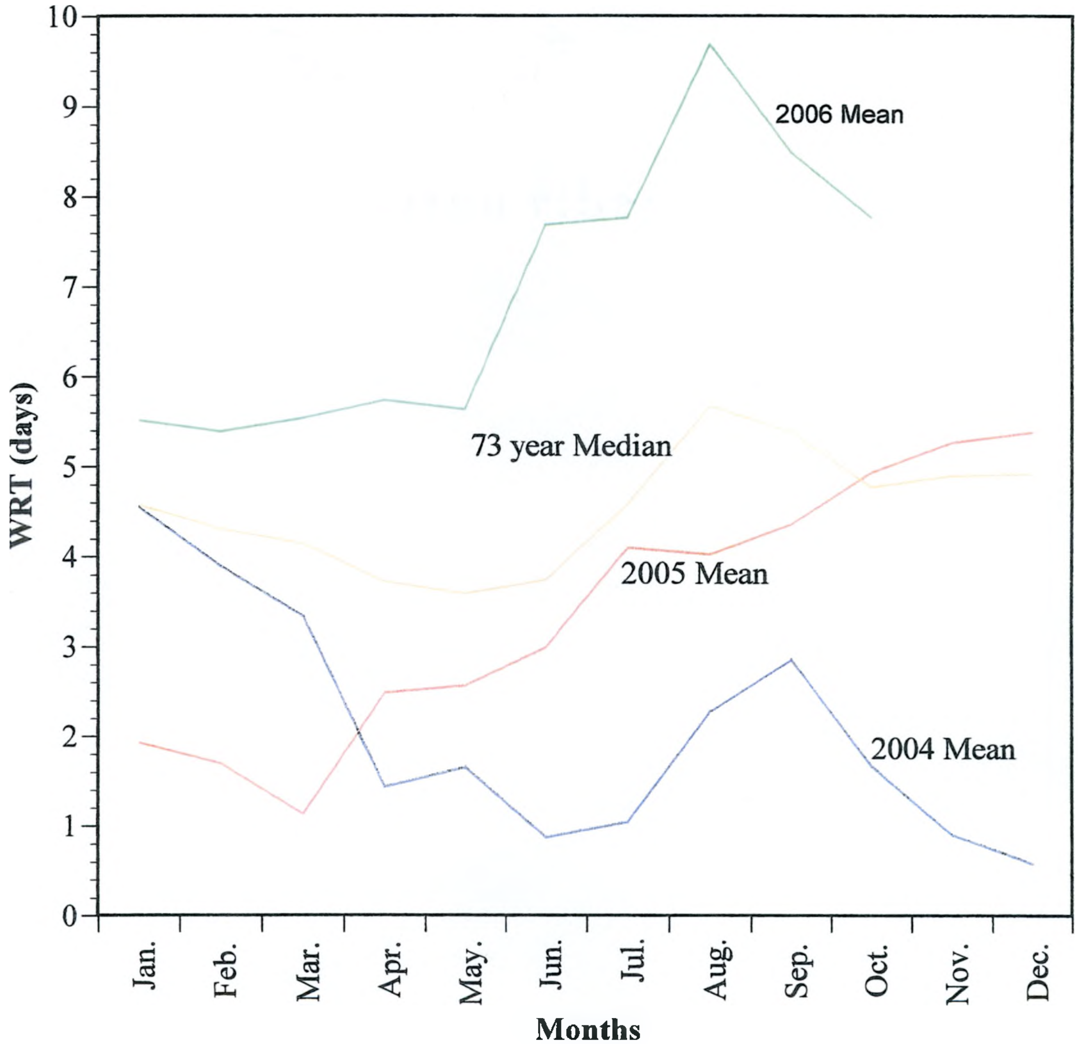


Figure 3: This graph represents the annual water residence times (measured in days) of three consecutive years (2004, 2005, and 2006) measured in monthly averages. The 73 year median represents the median monthly values from cumulative years (1933-2006) (Groeger Unpublished).

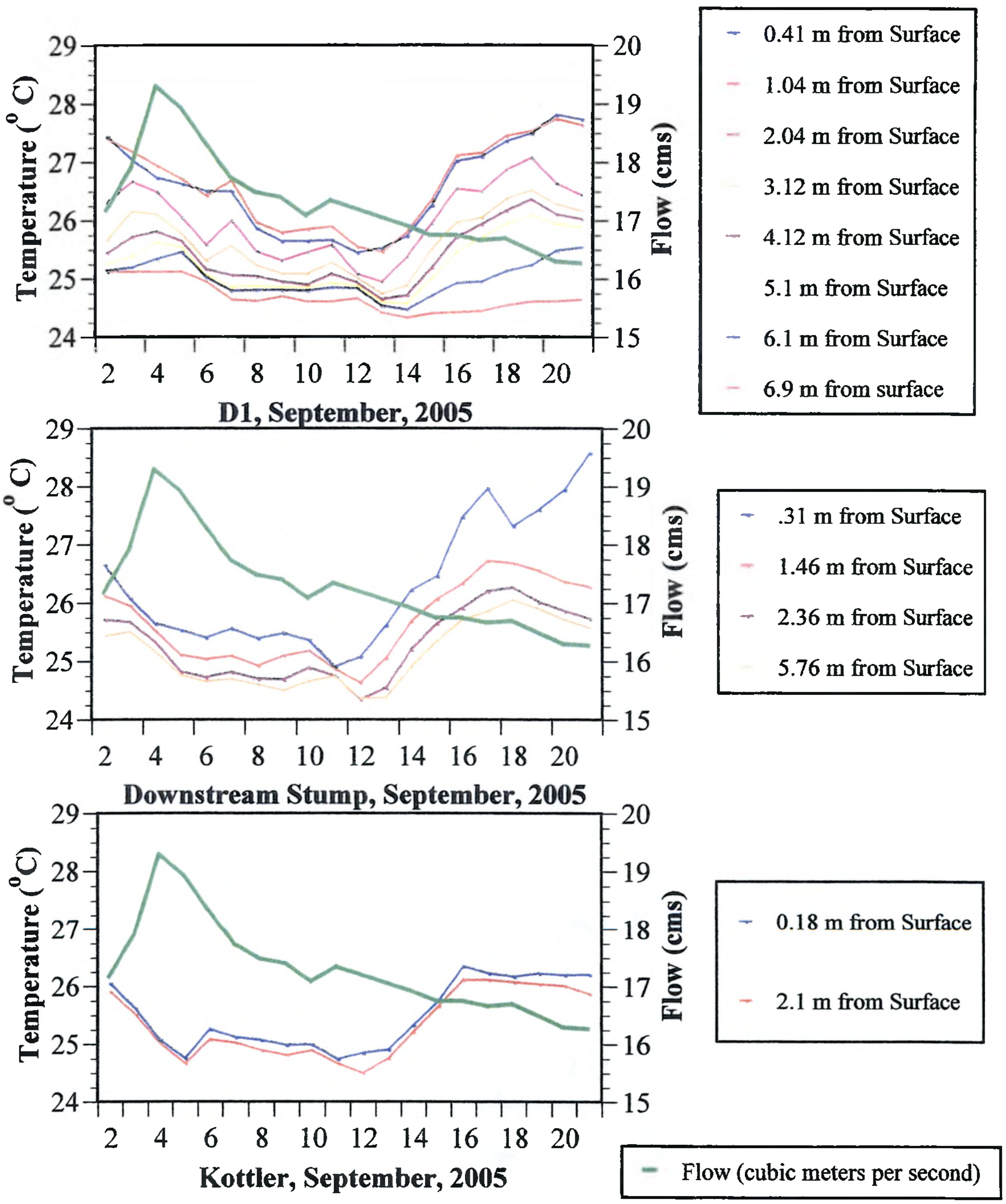


Figure 4: September, 2005, Temperature (°C) and Flow (cubic meters per second) at three locations (D1, the Downstream Stump, and Kottler's) on Lake Dunlap. The x-axis identifies days of the month in September (2005).

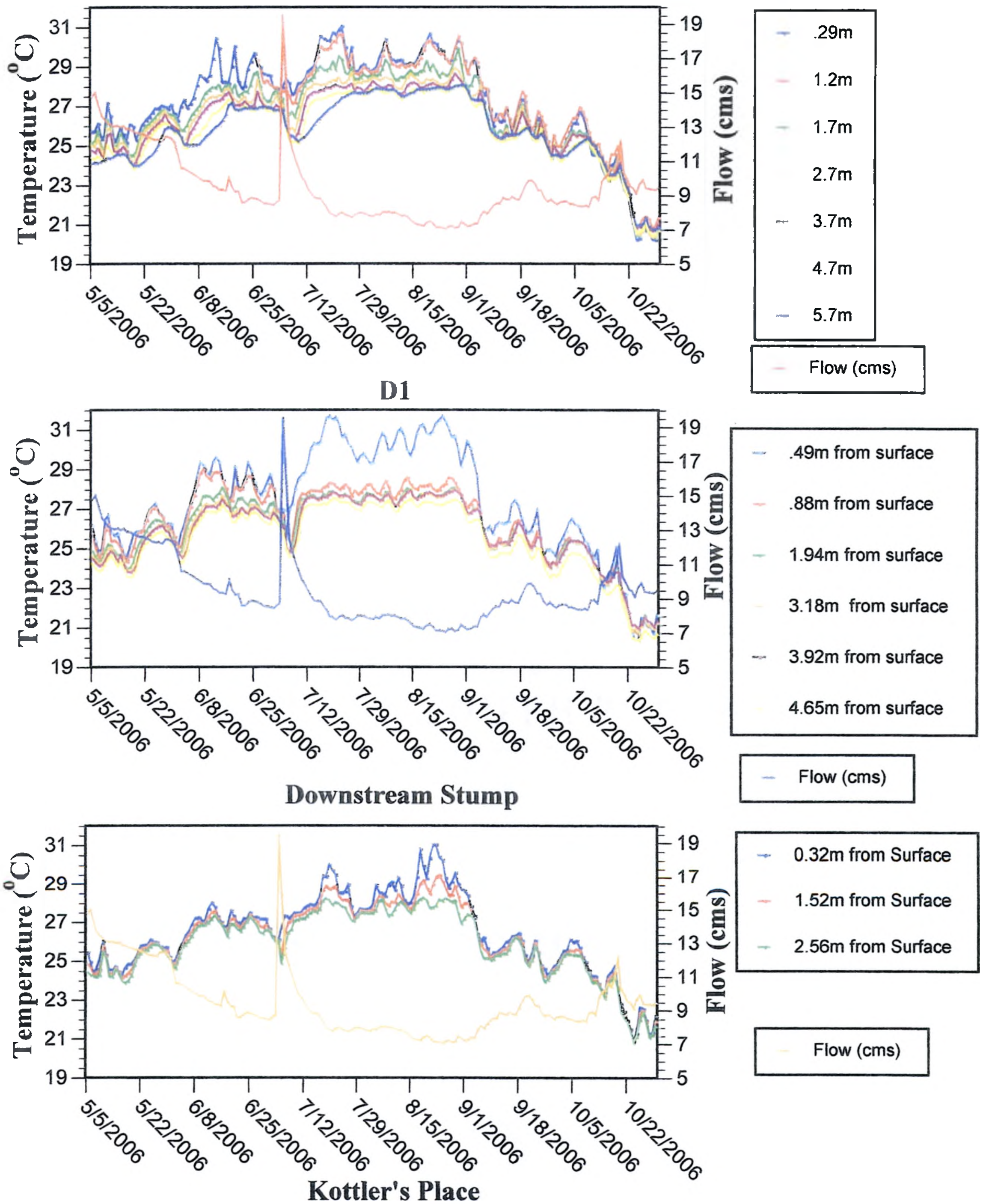
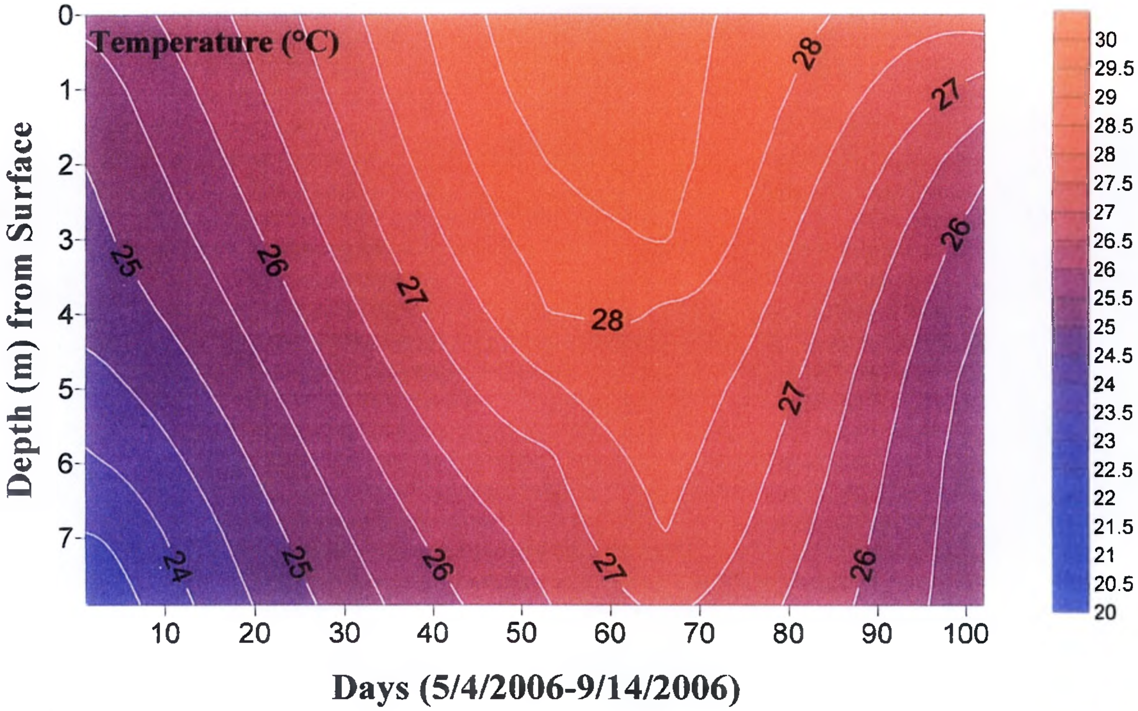


Figure 5: May-October, 2006, Temperature (°C) and Flow (cubic meters per second) at three locations (D1, the Downstream Stump, and Kottler's) on Lake Dunlap. The x-axis identifies dates (May-October, 2006).



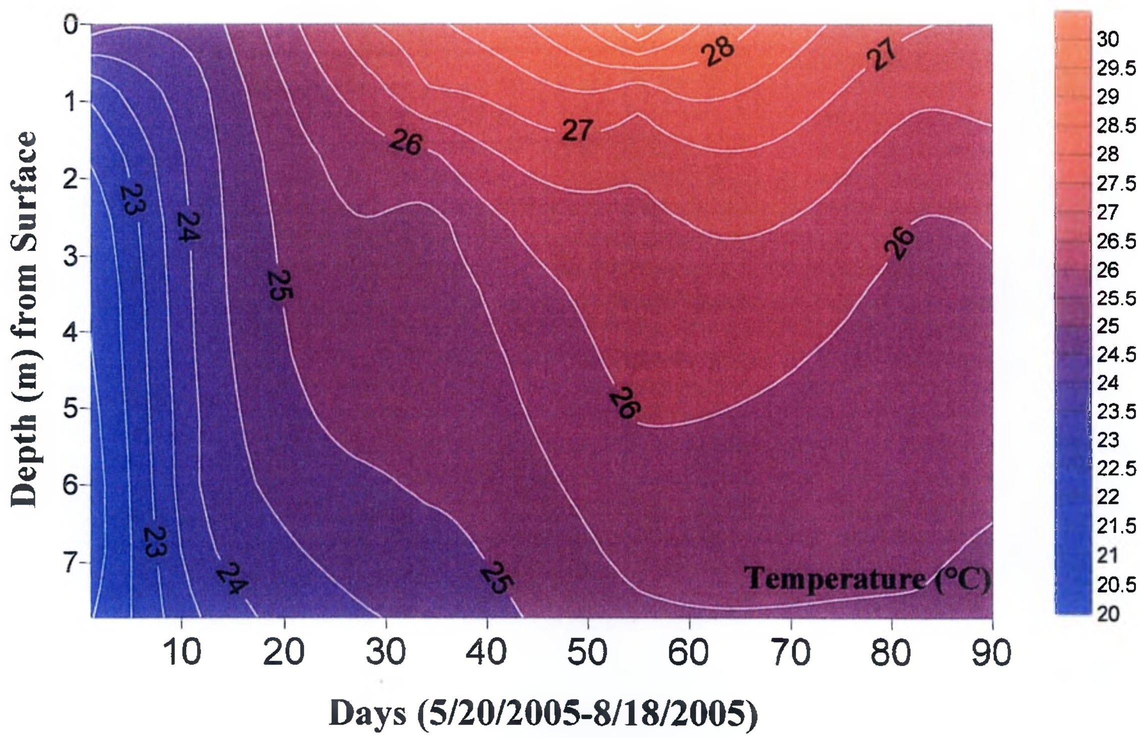
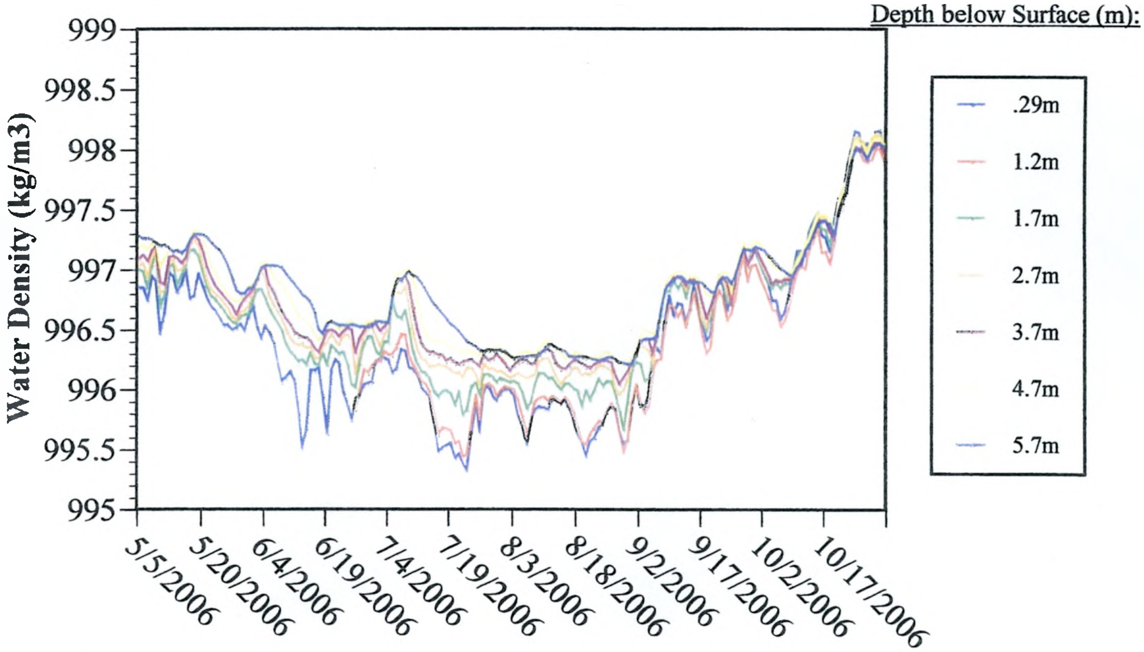
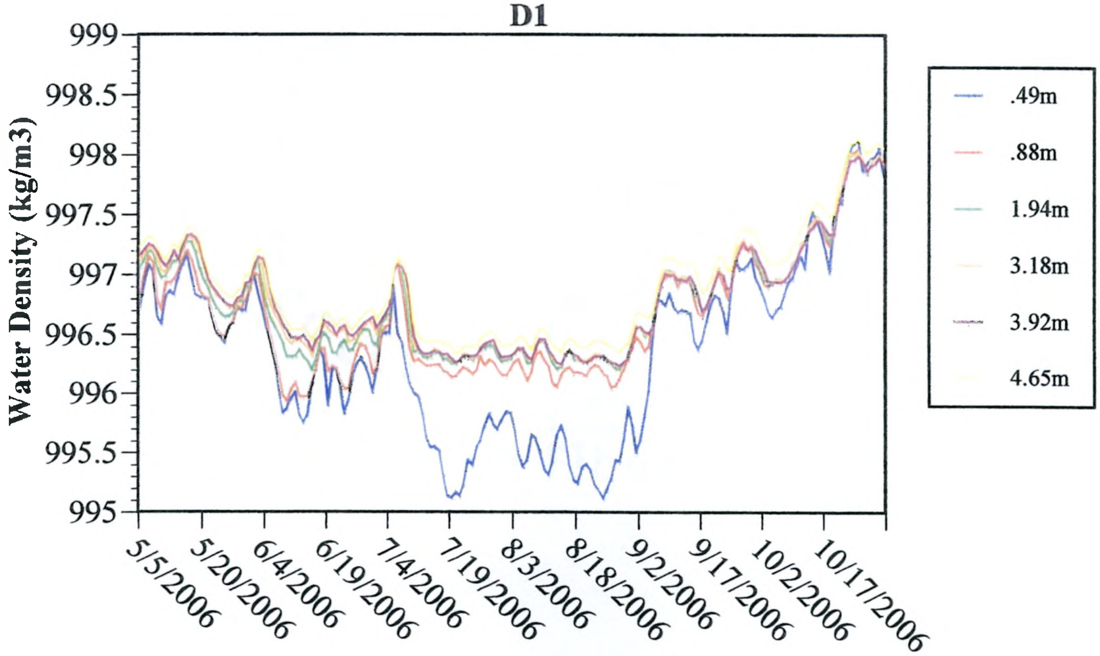


Figure 6: Lake Dunlap, Site D1, Isotherms for the 2006 and 2005 summer seasons.



D1



Downtstream Stump

Figure 7: Two graphs of Water Density (kg/m3) at two sites in Lake Dunlap, along the x-axis of time (May-October, 2006); D1 and Downstream Stump.

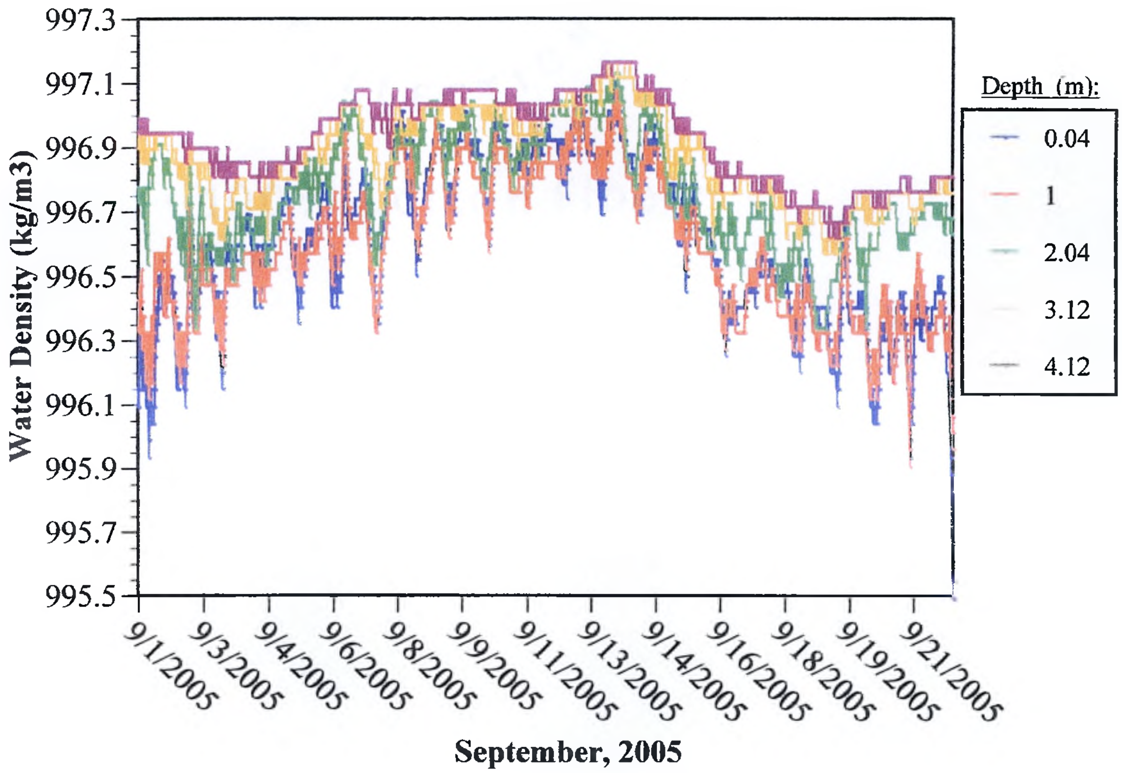


Figure 8: Site D1 water density data (kg/m3), September, 2005. A reading was taken every three seconds and imported into the graph from the the listed depths (meters below the surface).

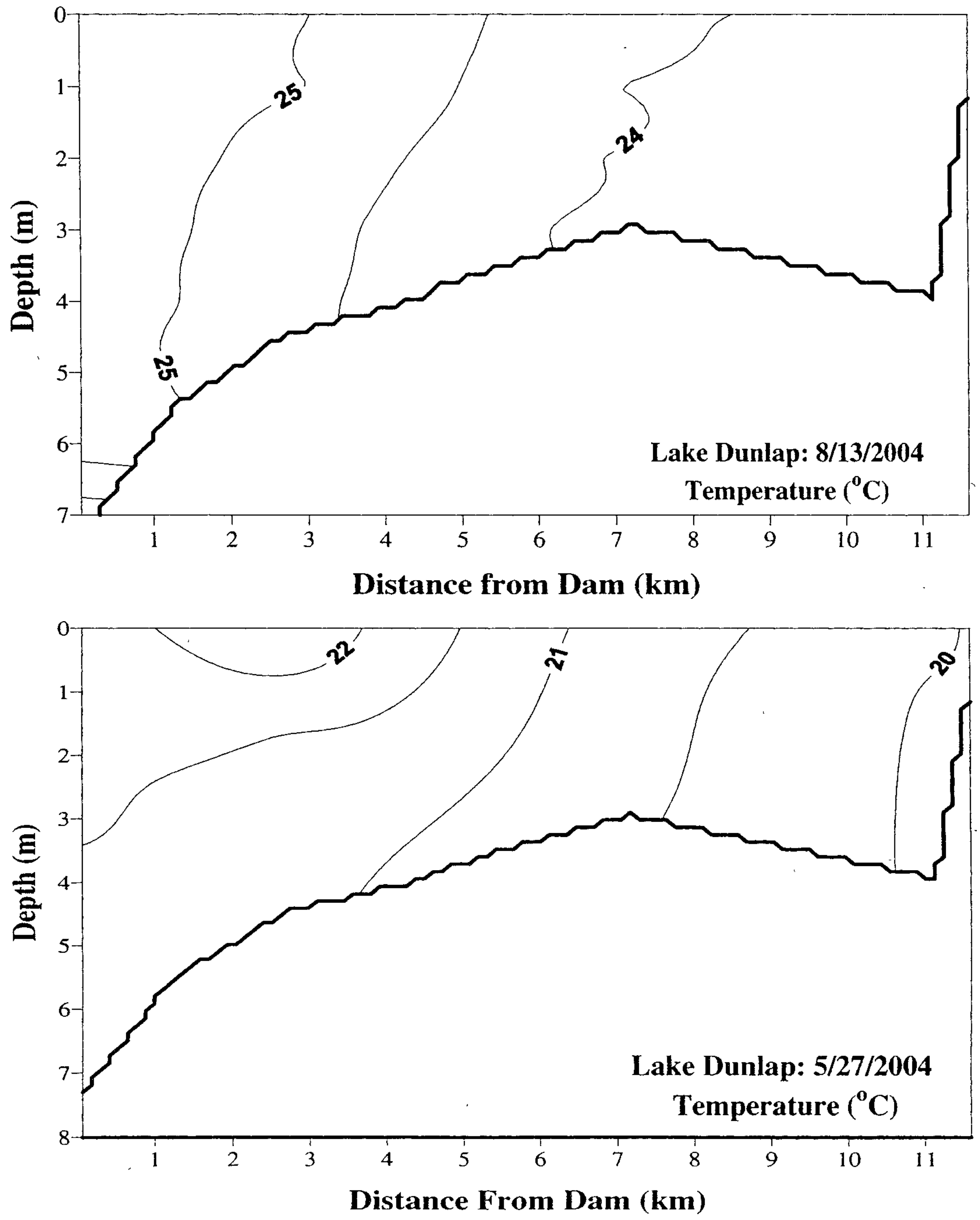


Figure 9: Isotherms from two sampling dates (Summer of 2004). Each light line represents Temperature (°C). The river inflow is located at ~11 km, and the dam is located at 0 km. The dark line represents the bottom of Lake Dunlap.

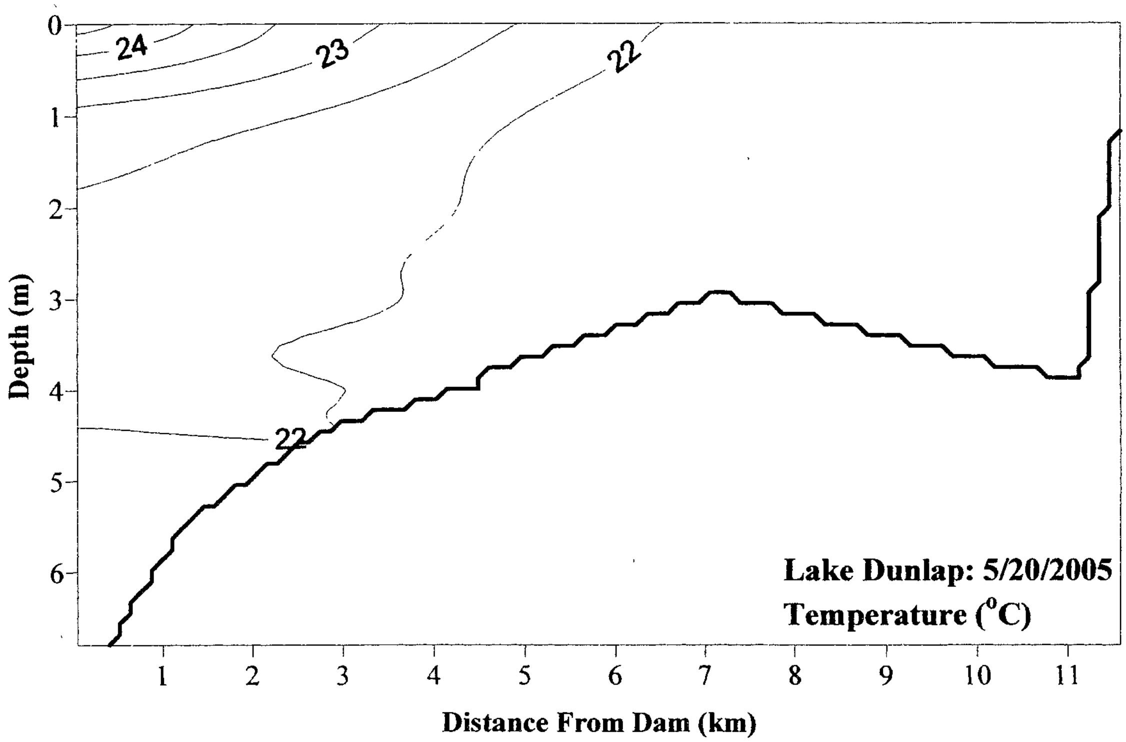


Figure 10: Isotherm of pre-stratification period (May 20, 2005). Each light line represents Temperature (°C). The river inflow is located at ~11 km, and the dam is located at 0 km. The dark line represents the bottom of Lake Dunlap.

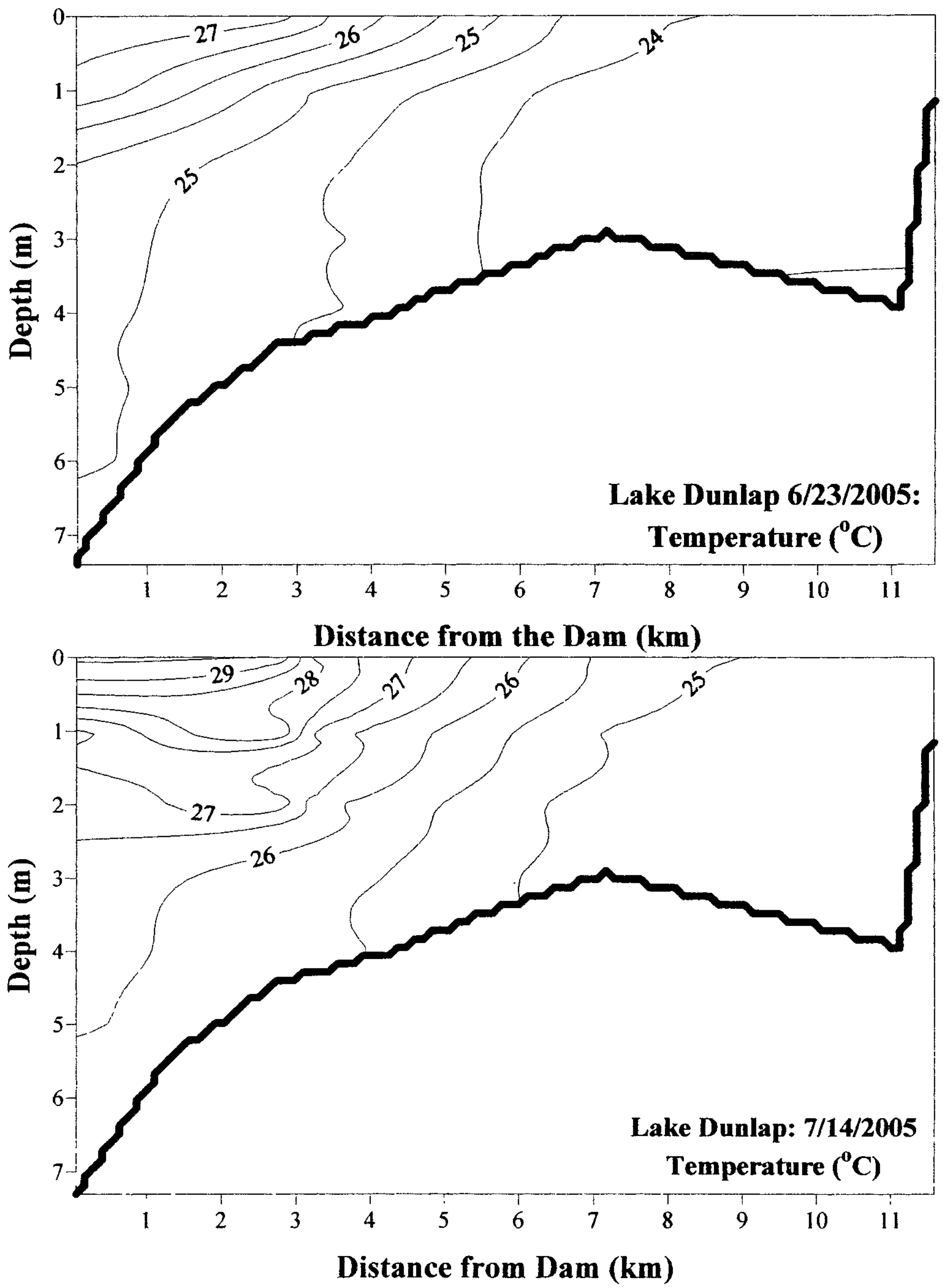


Figure 11: Isotherms of stratification (Summer of 2005). Each light line represents Temperature (°C). The river inflow is located at ~11 km, and the dam is located at 0 km. The dark line represents the bottom of Lake Dunlap.

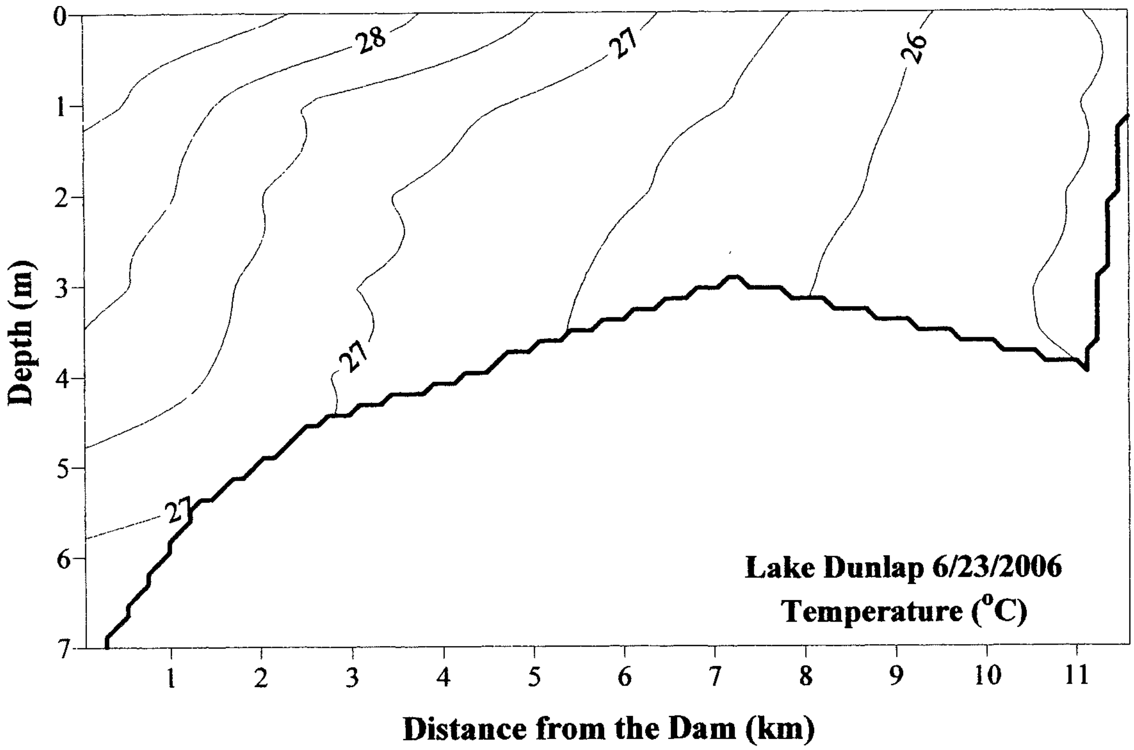


Figure 12: Isotherm of stratification (Summer of 2006). Each light line represents Temperature (°C). The river inflow is located at ~11 km, and the dam is located at 0 km. The dark line represents the bottom of Lake Dunlap.

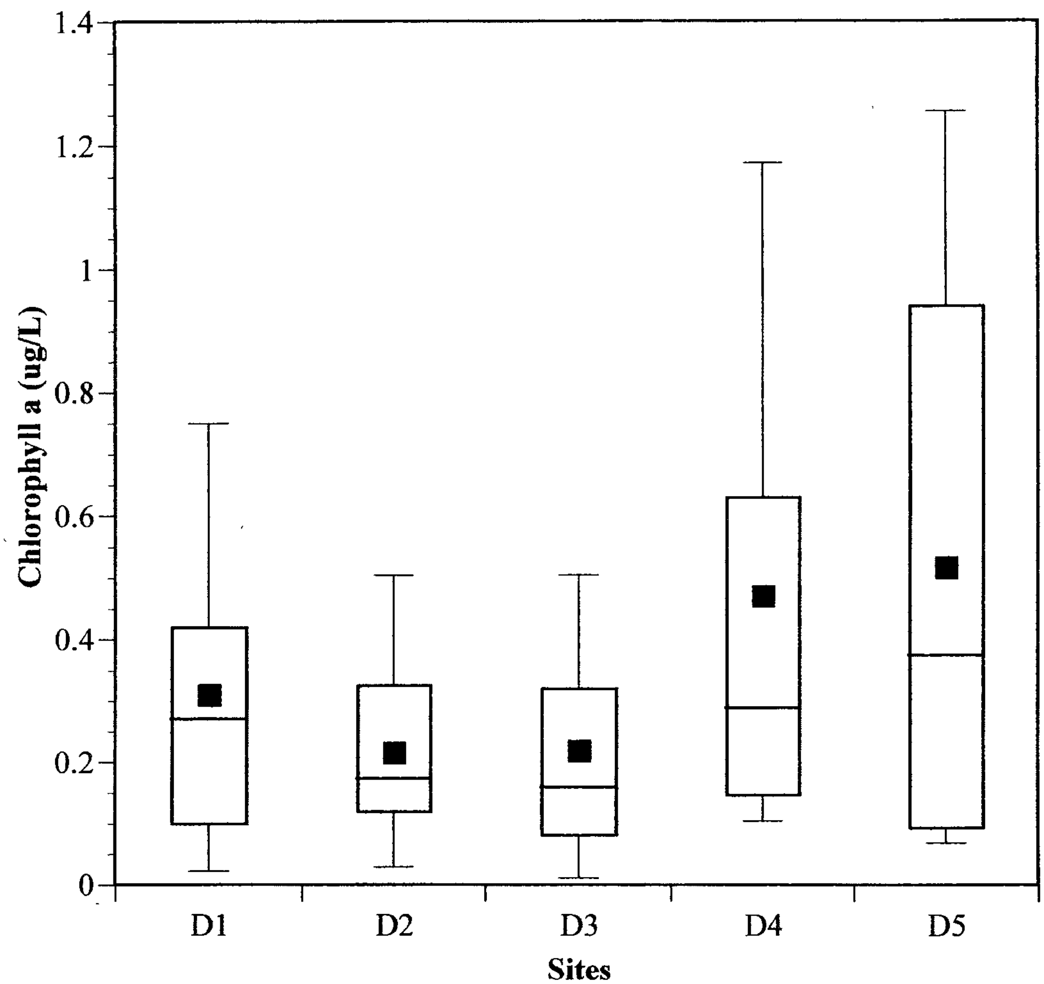


Figure 13: Averaged chlorophyll-a concentrations (ug/L), from sampling events spanning May-October (2004), the x-axis represents five sites on Lake Dunlap.

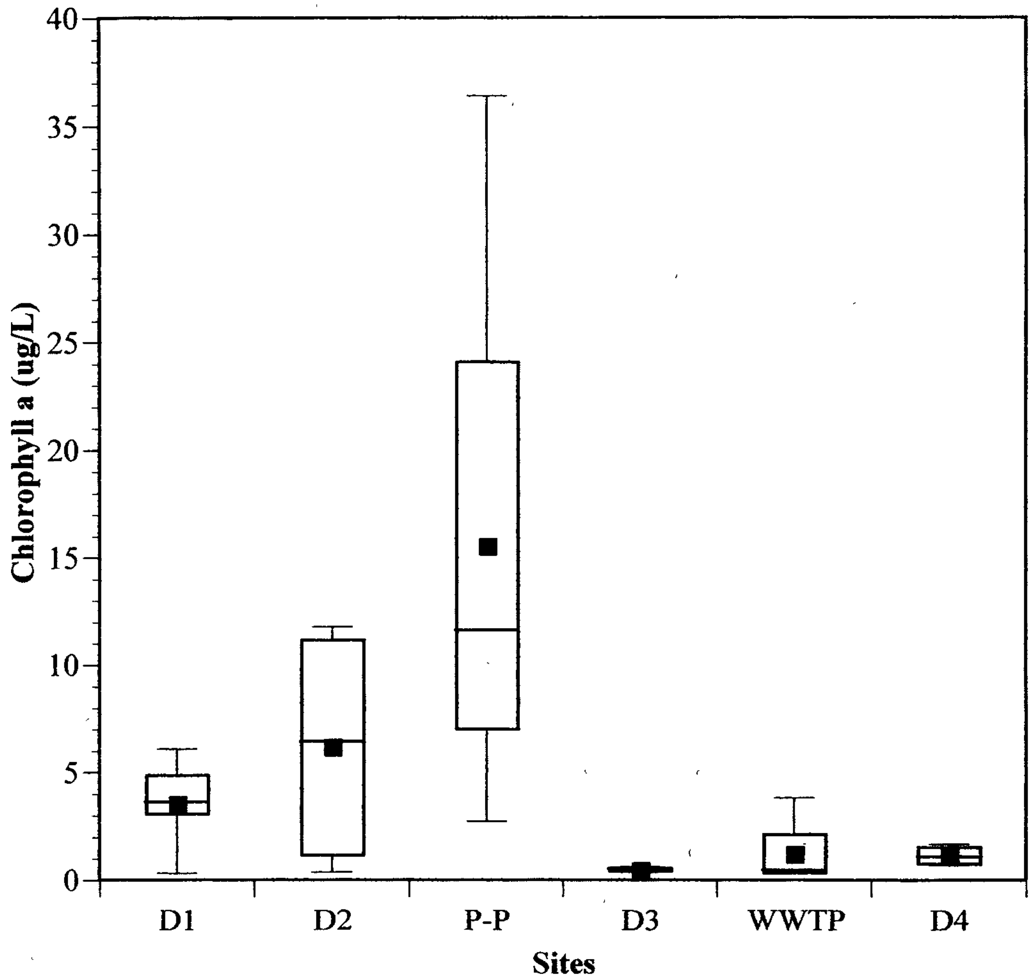


Figure 14: Averaged chlorophyll-a concentrations (ug/L), May-October (2005), from three sites on Lake Dunlap. The P-P column represents the averaged chlorophyll-a concentrations at the plunge point area (generally located between stations D2 and D3). The WWTP column represents the averaged chlorophyll-a concentrations at the outflow of the New Braunfels Utilities' Waste Water Treatment Plant.

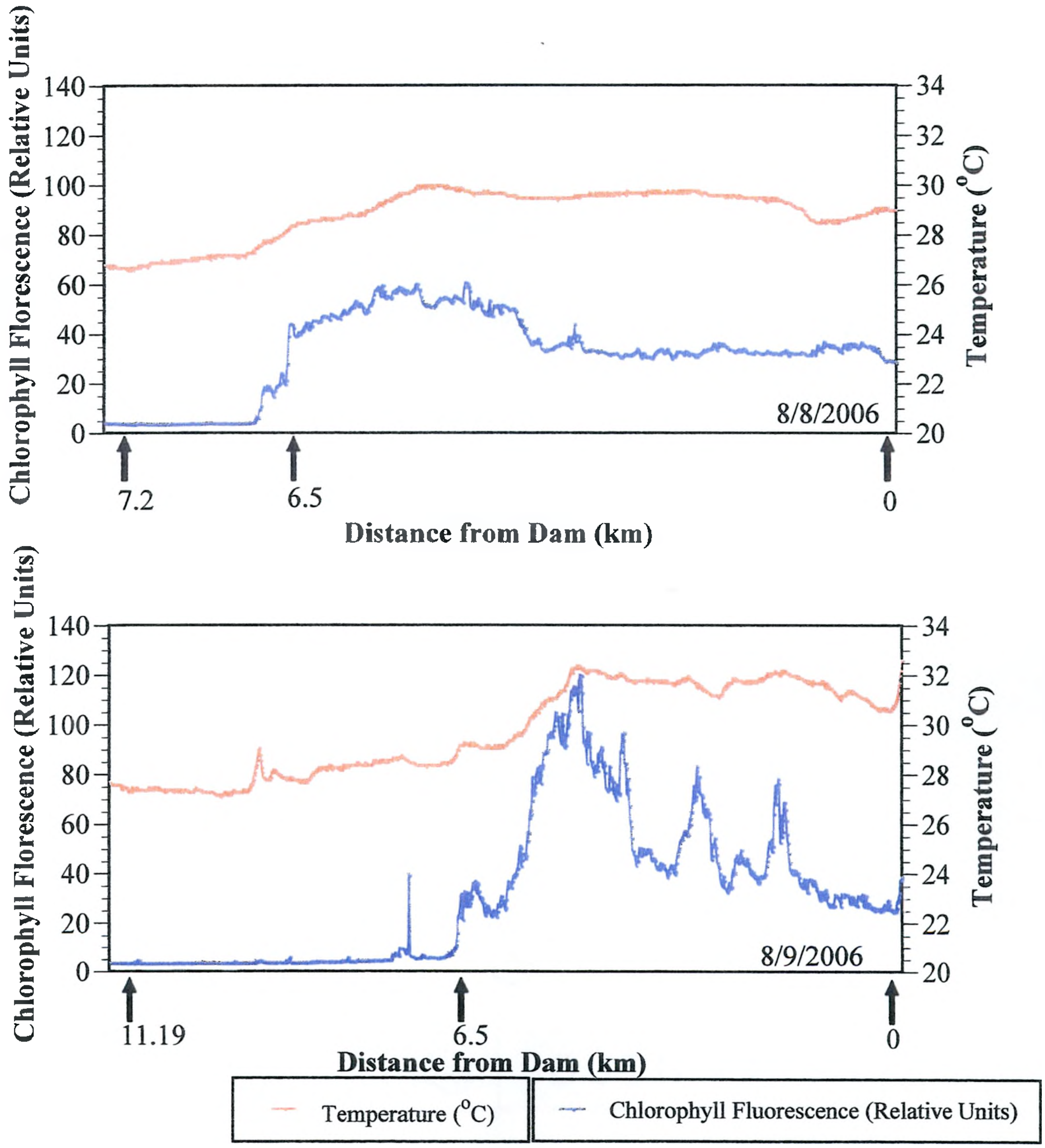


Figure 15: Top graph (8/8/2006) represents *in vivo* fluorescence (IVF) and temperature following the thalweg of the reservoir; measurements (one reading per second) were taken at surface depths from the dam, 0 km, through the plunge point, ~6.5 km, and to an upstream ending point at D3, ~7.2 km. The bottom graph (8/9/2006) represents the same parameters with the same plunge point location, ~6.5 km, and an alternate upstream ending point, D4, ~11.19 km. Sampling times were mid-day.

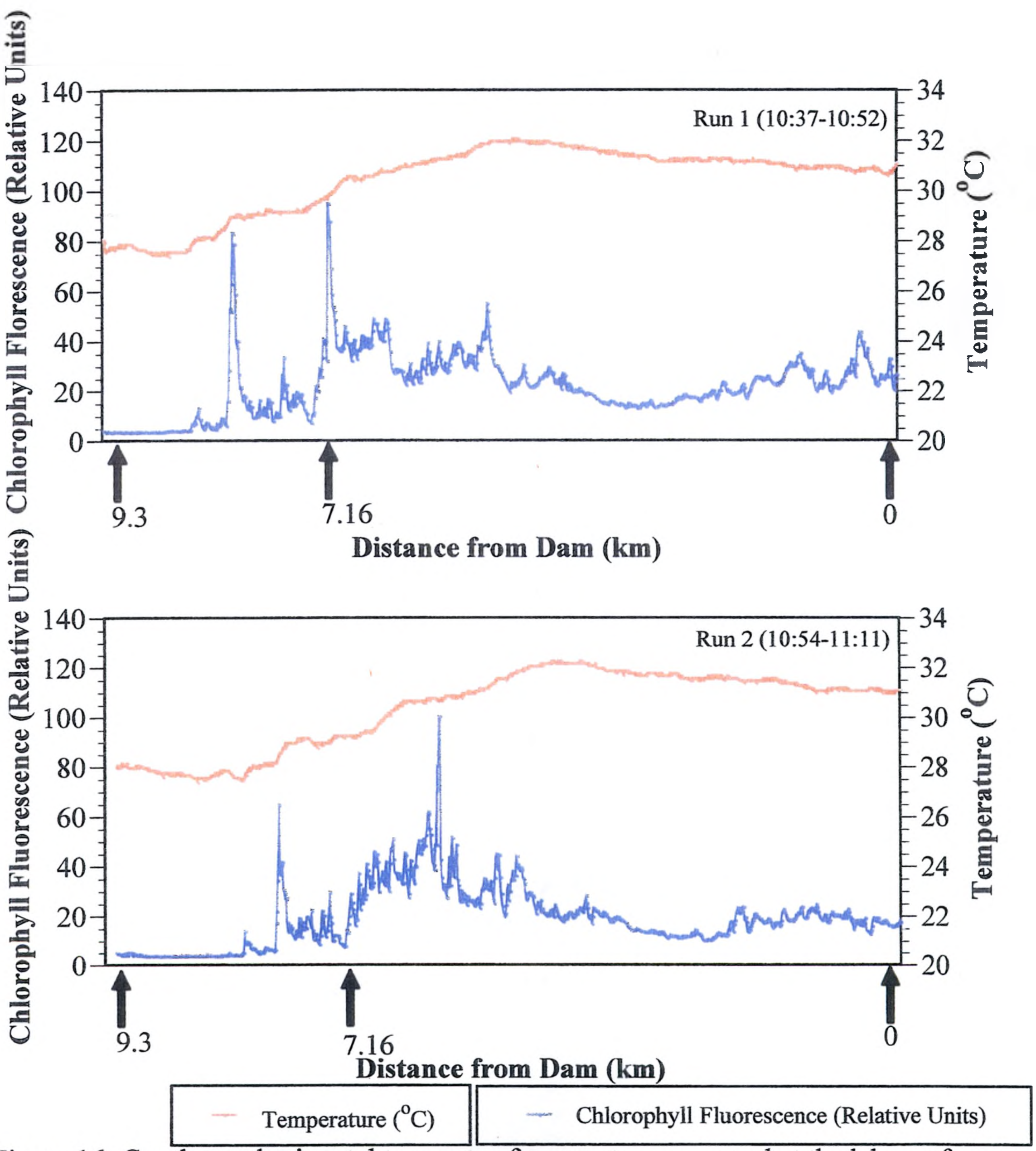


Figure 16: Graphs are horizontal transects of parameters measured at the lake surface on 8/23/2006. Top graph (Run 1) represents *in vivo* fluorescence (IVF) and temperature following the thalweg of the reservoir; data were processed once per second. Measurements begin at dam, 0 km, continue through the plunge point, ~7.16 km, and end just before the WWTP, ~9.3 km. The bottom graph (Run 2) represents the same parameters with the same plunge point location, ~7.16 km, and the same ending point, WWTP, ~9.3 km.

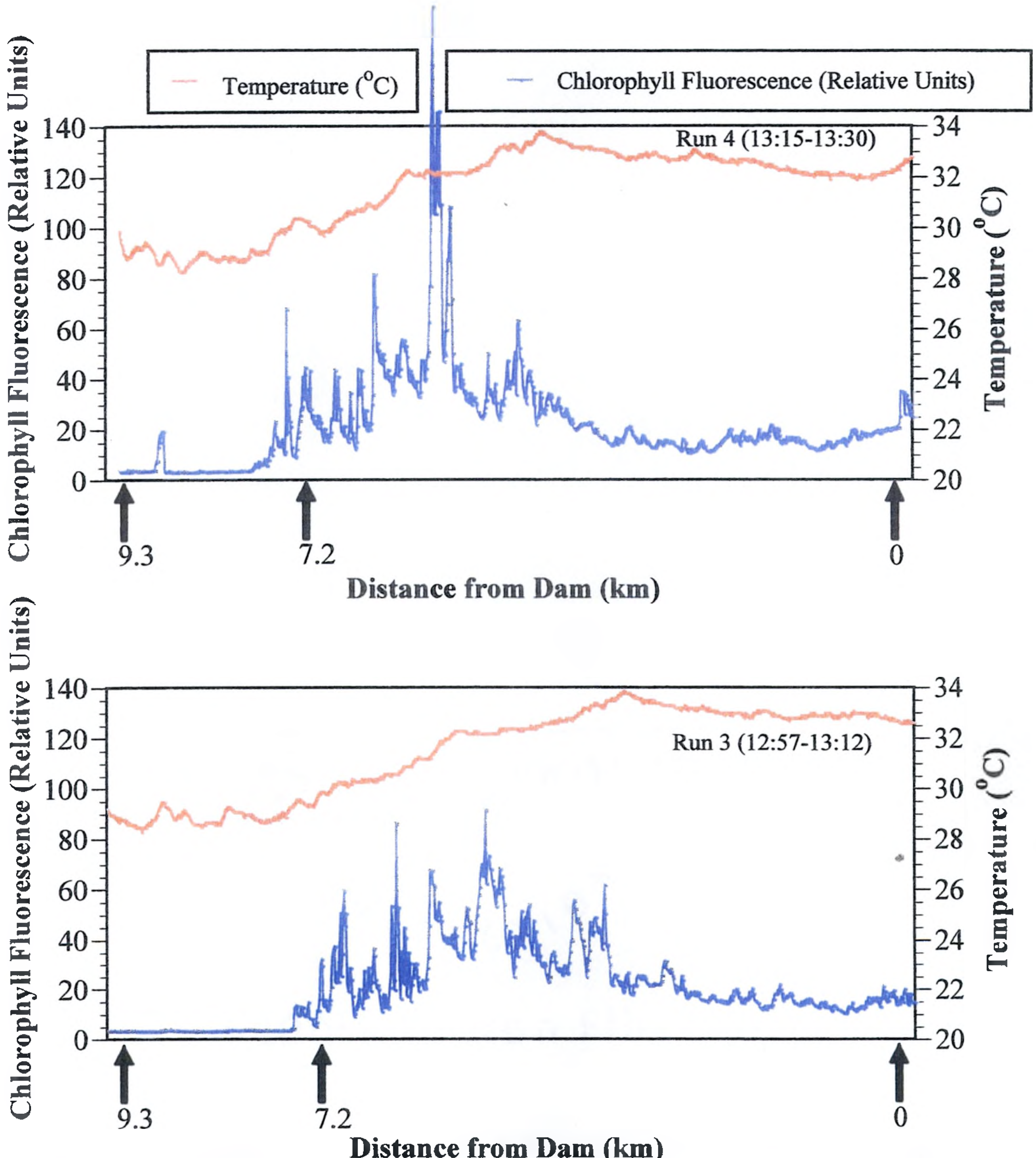


Figure 17: Graphs are horizontal transects of parameters measured at the lake surface on 8/23/2006. Top graph (Run 4) represents *in vivo* fluorescence (IVF) and temperature following the thalweg of the reservoir; data were processed once per second. Measurements begin at dam, 0 km, continue through the plunge point, ~7.2 km, and end just before the WWTP, ~9.3 km. The bottom graph (Run 3) represents the same parameters with the same plunge point location, ~7.2 km, and the same ending point, WWTP, ~9.3 km.

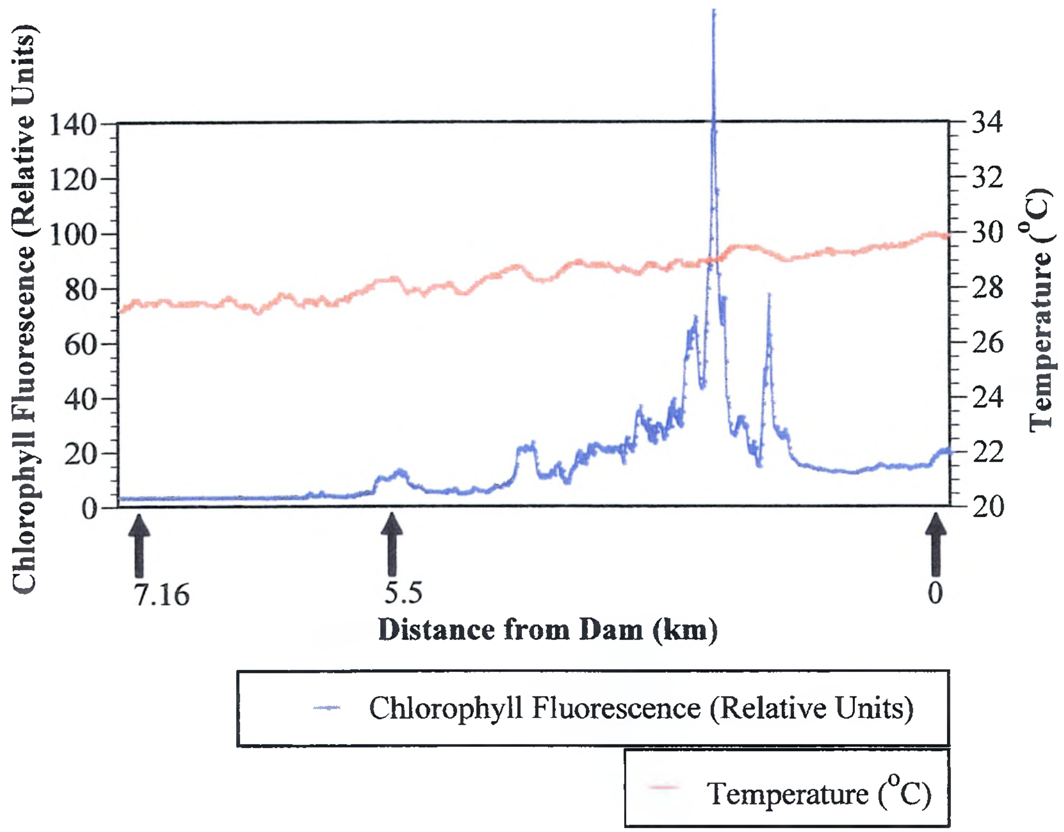


Figure 18: The graph is a horizontal transect of parameters measured at the surface of Lake Dunlap on 9/14/2006. The parameters represented are *in vivo* fluorescence (IVF) and temperature. The horizontal transect follows the thalweg of the reservoir. One data point was processed every second from when the data run began (13:31), at the dam, through the plunge point, ~5.5 km upstream of the dam, and to the ending point (13:48) just downstream of D3, ~7.16.

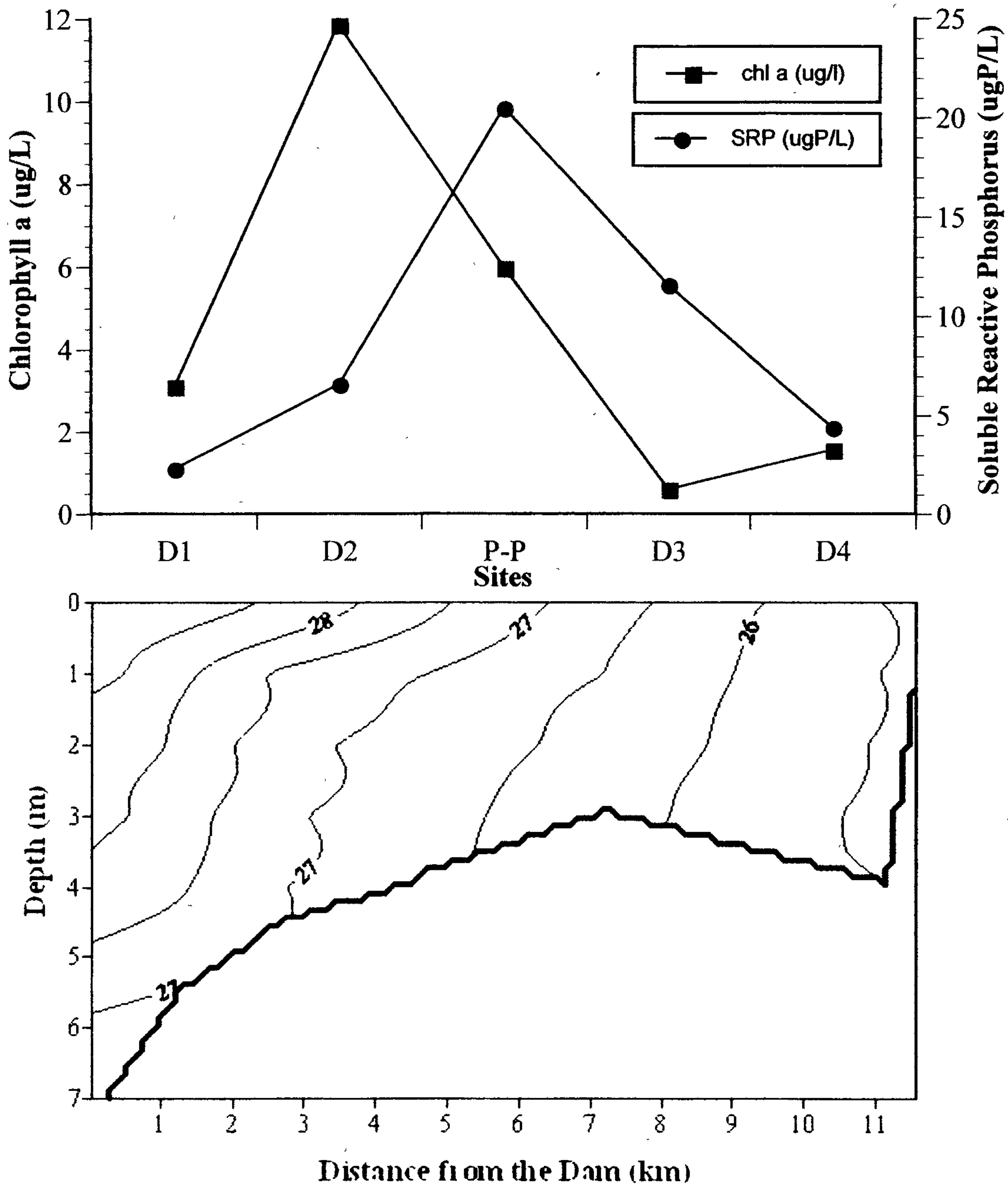


Figure 19: The top graph illustrates soluble reactive phosphorus (ugP/L), the right y-axis, and chlorophyll-a concentrations (ug/L), the left y-axis (6/23/2005). The sites along the x-axis move from the dam (D1) upstream to the inflow area (D4). The bottom graph illustrates a similar x-axis, measured in kilometers. The dam is located at 0 km, the inflow is located just past 11 km; the bold line represents the lake bottom.

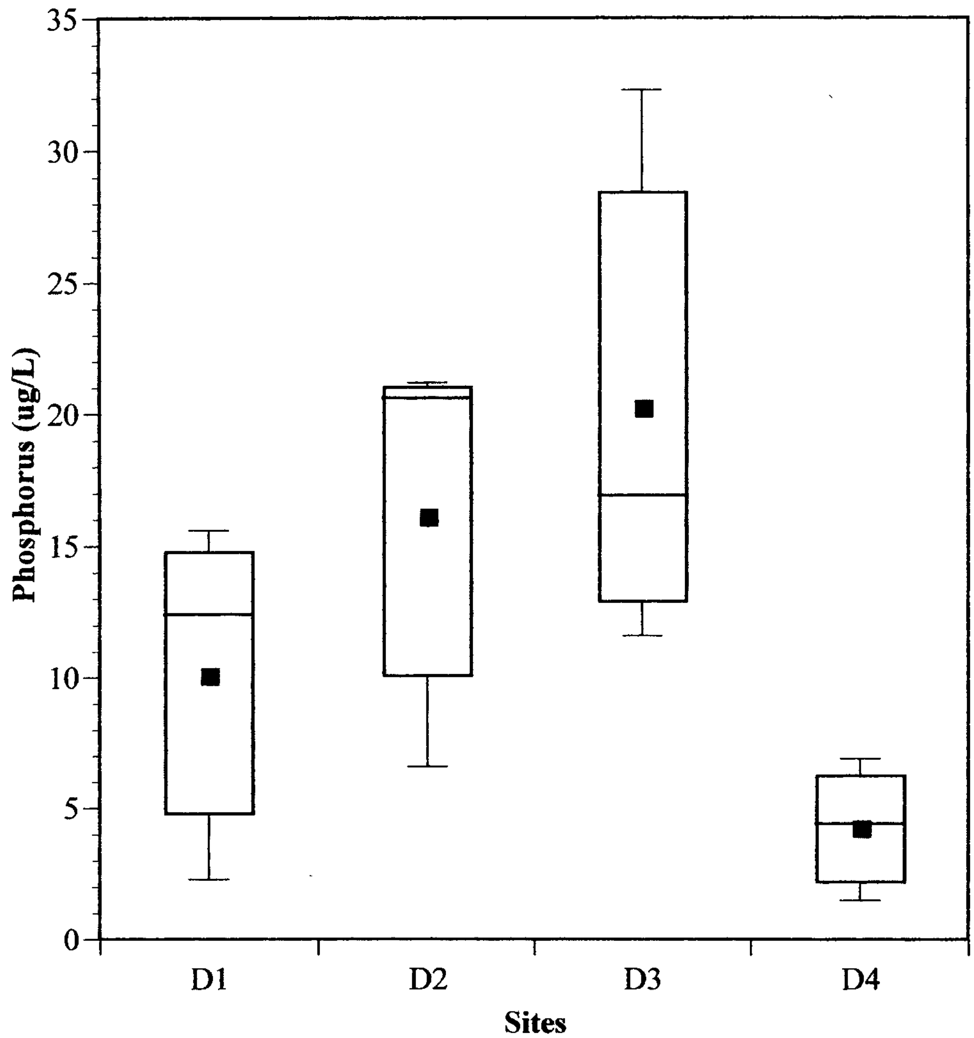
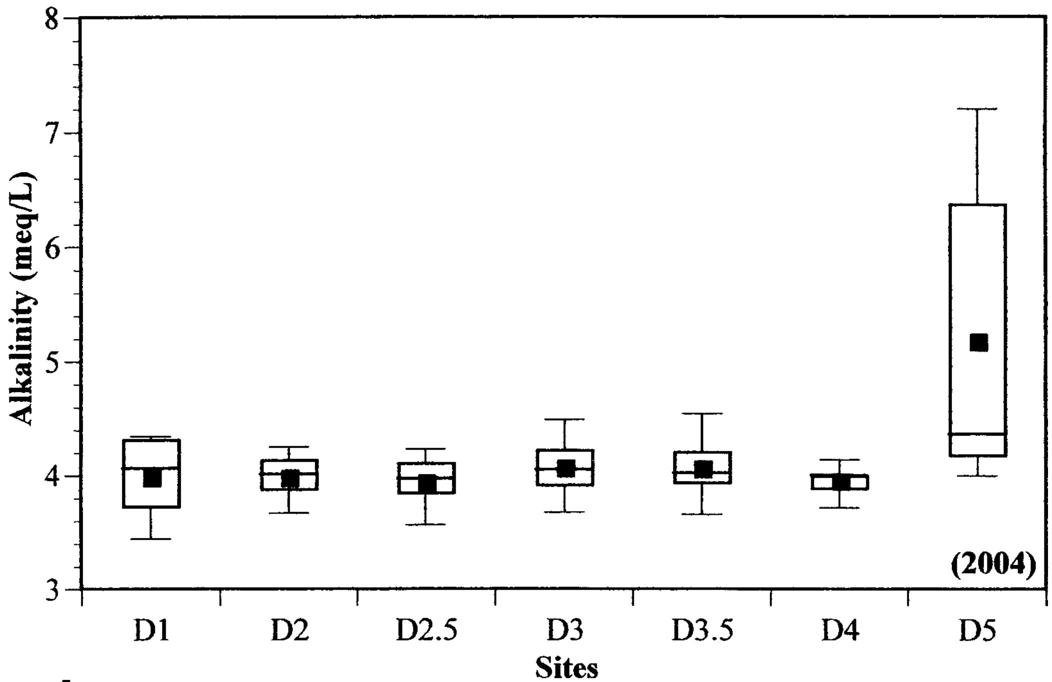


Figure 20: Graph of pre-stratification period, May of 2005. Each of four sites show average soluble reactive phosphorus concentrations (ug/L) from 2005 data. The D4 site is near inflow. The WWTP is located between D4 and D3. The D1 site is the dam site.



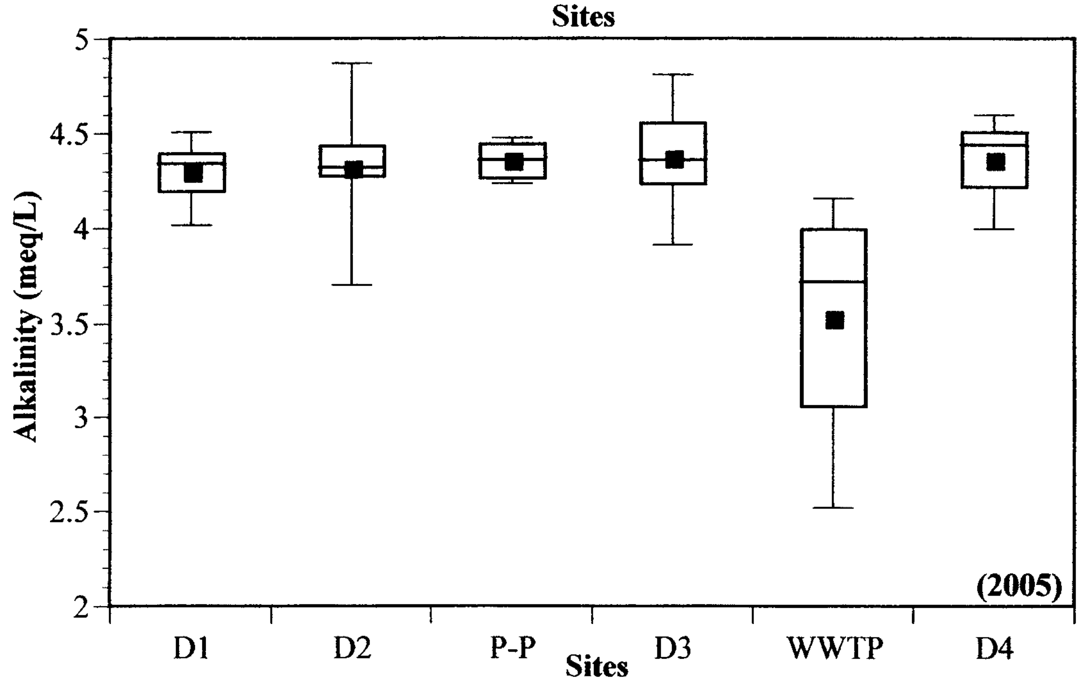


Figure 21: The graphs represent average Alkalinity concentrations (meq/L) over two (2004 and 2005) summer sampling seasons (May-September). The x-axis consists of site locations on Lake Dunlap. P-P represents data collected from the plunge point (exact location varied), the WWTP is the New Braunfels Utilities Waste Water Treatment Plant.

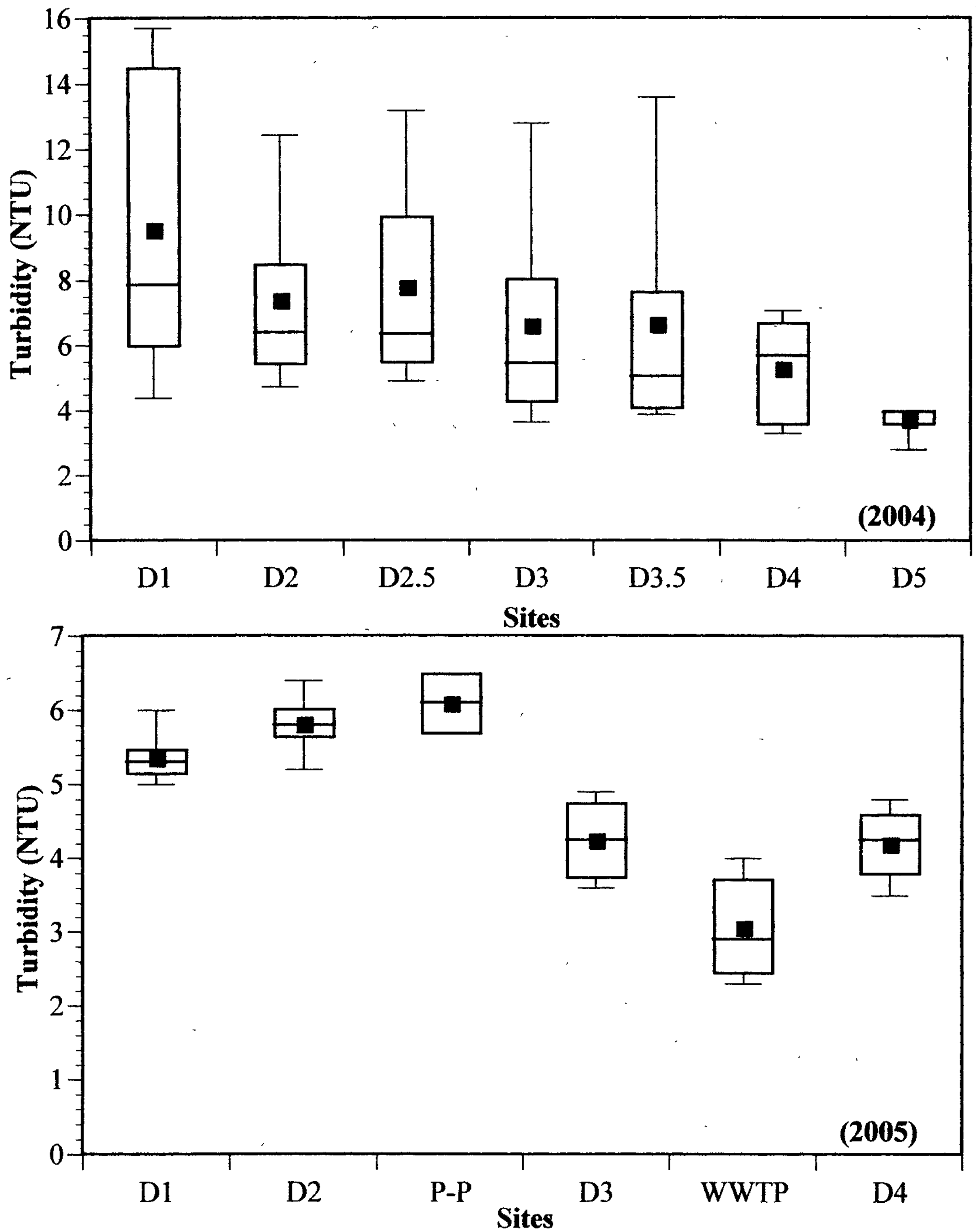


Figure 22: Turbidity measurements (nephelometric units) from (May-September) two summer sampling seasons (2004 and 2005). The x-axis consists of site locations on Lake Dunlap. P-P represents data collected from the plunge point (exact location varied), the WWTP is the New Braunfels Utilities Waste Water Treatment Plant.

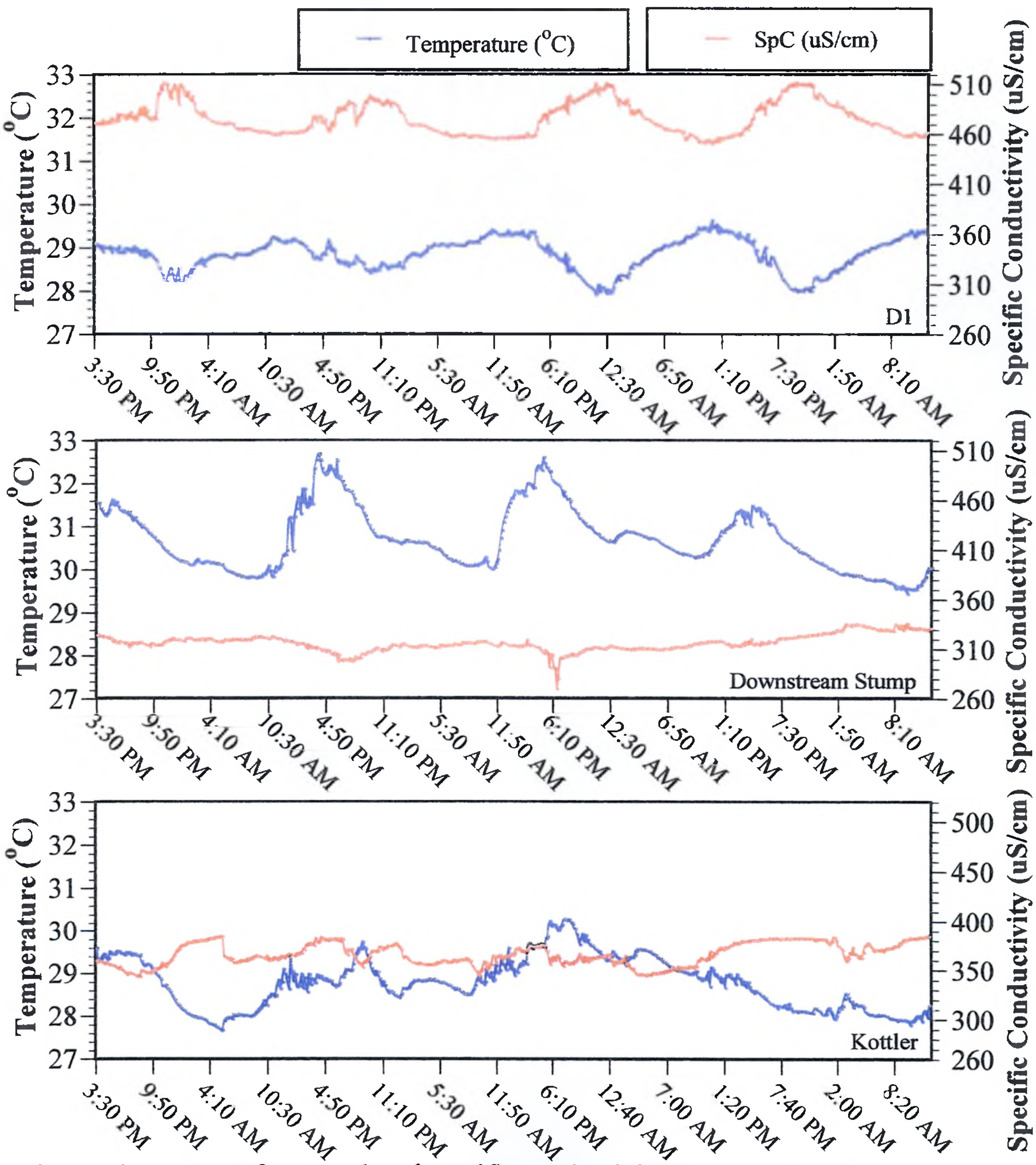


Figure 23: Near surface graphs of specific conductivity (µS/cm) and temperature (°C) from three separate sites on Lake Dunlap (August 8-13, 2006). The top graph represents data from D1 at a depth of ~1.0 meters below the surface. The middle graph represents data from the Downstream Stump site at a depth of ~.76 meters below the surface. The bottom graph represents data from the Kottler site at a depth of ~.8 meters below the surface. The x-axis references diurnal time from August 8-13.

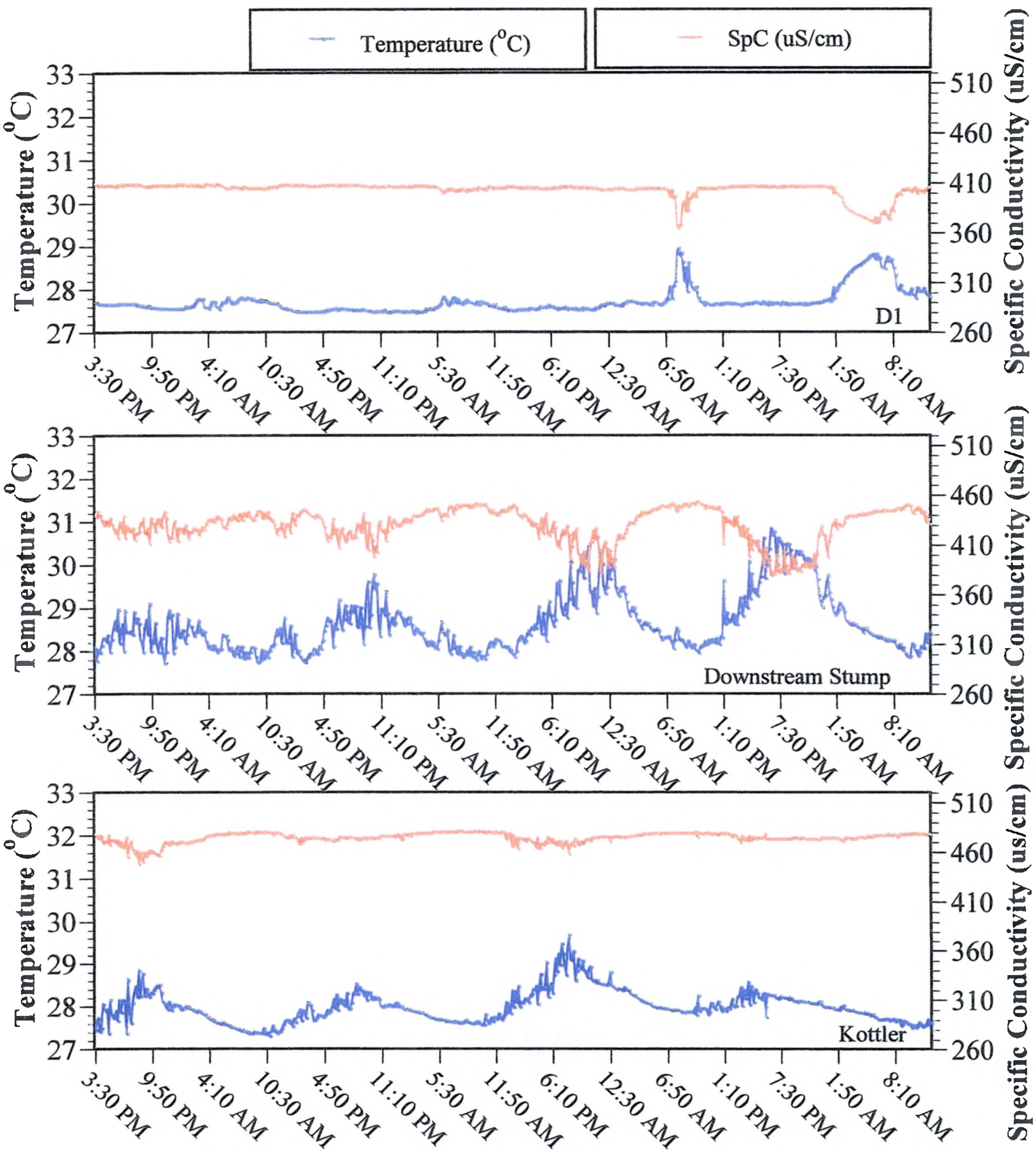


Figure 24: Mid-depth graphs of specific conductivity (μS/cm) and temperature (°C) from three separate sites on Lake Dunlap (August 8-13, 2006). The top graph represents data from D1 at a depth of ~4.0 meters below the surface. The middle graph represents the Downstream Stump site at a depth of ~2.36 meters below the surface. The bottom graph represents data from the Kottler site at a depth of ~1.55 meters below the surface. The x-axis references diurnal time from August 8-13.

Table 1: Table 1(A) represents average monthly flow (cubic meters per second) from the combined flows of the Guadalupe and Comal Rivers into Lake Dunlap (Groeger Unpublished). Table 1(B) represents average monthly water retention times (days) from the combined flows of the Guadalupe and Comal Rivers into Lake Dunlap (Groeger Unpublished). The 73 year median represents the mean monthly average from the years of 1933-2006. Each section of the table contains data from three consecutive years (2004, 2005, and 2006), as well as the 73 year median.

Flow (cms)	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Average**
2004	*16*	*19*	*22*	*51*	*44*	*84*	*70*	*32*	*26*	*44*	*81*	*126*	*51*
2005	*38*	*43*	*65*	*29*	*29*	*24*	*18*	*18*	*17*	*15*	*14*	*14*	*27*
2006	*13*	*14*	*13*	*13*	*13*	*10*	*9*	*8*	*9*	*9*			
73 Year Median	*16*	*17*	*18*	*20*	*21*	*20*	*16*	*13*	*14*	*15*	*15*	*15*	*21*

WRT (days)	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Average**
2004	*5*	*4*	*3*	*1*	*2*	*1*	*1*	*2*	*3*	*2*	*1*	*1*	*1*
2005	*2*	*2*	*1*	*2*	*3*	*3*	*4*	*4*	*4*	*5*	*5*	*5*	*3*
2006	*6*	*5*	*6*	*6*	*6*	*8*	*8*	*10*	*8*	*8*			
73 Year Median	*5*	*4*	*4*	*4*	*4*	*4*	*5*	*6*	*5*	*5*	*5*	*5*	*3*

Table 2: The table represents soluble reactive phosphorus concentrations (ugP/L) collected during the diurnal sampling event beginning on 7/11/2006 and concluding on 7/12/2006. The data were collected from three separate site locations (D1, the Plunge Point, and Kottler). Data are labeled in columns depicting approximate sampling times over the span of the two-day sampling event. The N/A designations signify that the analytical results were flawed and data is not available for the selected time and site. The D1 and Plunge Point sites were analyzed at two depths (1 and 3 meters) as illustrated on the far right column of the table.

	Time (7/11/2006-7/12/2006):					
	12:22	16:30	22:26	2:06	6:30	
Sites:			***SRP ugP/L:***			***Depth (m):***
D1	*6.1*	*N/A*	*4.6*	*3.6*	*3.1*	***1***
	N/A	*64.6*	*129.7*	*15.9*	*3.1*	***3***
Plunge Point	*N/A*	*51.9*	*15.1*	*11.4*	*39.6*	***1***
	51.8	*47.6*	*37.9*	*38.9*	*N/A*	***3***
Kottler	*56.7*	*34.5*	*N/A*	*N/A*	*29.1*	***1***

Table 3: The table represents soluble reactive phosphorus concentrations (ugP/L) collected during the diurnal sampling event beginning on 9/7/2005. The data were collected from three separate site locations (D1, the Plunge Point, and My Casa). Data are labeled in columns depicting approximate sampling times over the span of the two-day sampling event. The N/A designations signify that the analytical results were flawed and data is not available for the selected time and site.

	Time (7/7/2005):				
	8:30	11:00	17:00	21:30	
Sites:		***SRP ugP/L:***			***Depth (m):***
D1	*5.3*	*3.8*	*2.8*	*6.3*	*1*
Plunge Point	*19.9*	*19.3*	*15.8*	*N/A*	*1*
My Casa	*23.1*	*28.6*	*28.3*	*N/A*	*1*

Table 4: Values represent average conductivity concentrations (uS/cm) for the months of May-September of three consecutive years, 2004-2006. The site P-P represents average conductivity concentrations collected at the plunge point.

2004 (May-September)		**2005** (May-September)		**2006** (May-September)	
Sites:	Avg. Conductivity	Sites:	Avg. Conductivity	Sites:	Avg. Conductivity
D1	*449 uS/cm*	D1	*495 uS/cm*	D1	*486 uS/cm*
D2	*445 uS/cm*	D2	*489 uS/cm*	D2	*510 uS/cm*
D3	*443 uS/cm*	P-P	*505 uS/cm*	D3	*520 uS/cm*
D4	*449 uS/cm*	D3	*489 uS/cm*	D4	*515 uS/cm*
D5	*415 uS/cm*	D4	*488 uS/cm*		

Table 5: Values represent monthly averages of Comal River inflows as percentages (%) of total inflow into Lake Dunlap. The 73 year median represents median values from 1933-2006 (Groeger Unpublished).

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Average:
2004	*62*	*54*	*46*	*21*	*23*	*19*	*16*	*33*	*40*	*29*	*30*	*10*	*24*
2005	*33*	*30*	*21*	*43*	*42*	*46*	*58*	*56*	*61*	*70*	*73*	*72*	*42*
2006	*71*	*66*	*65*	*68*	*64*	*76*	*77*	*80*	*76*	*76*			*72*
1996	*64*	*63*	*61*	*61*	*58*	*65*	*78*	*73*	*56*	*60*	*54*	*48*	*60*
73 Year Median	*55*	*52*	*49*	*47*	*45*	*45*	*53*	*59*	*52*	*55*	*54*	*55*	*44*

CHAPTER IV

DISCUSSION

The Comal River, interacting with Canyon Lake outflow (Guadalupe River), is the driving force for the stratification of Lake Dunlap. Carmack et al. (1986) show flow and WRT are important factors in determining the primary production in lake systems; the Comal and Guadalupe River confluence provides the flows that regulate primary productivity in Lake Dunlap. The Comal River is a spring fed river, controlled by an aquifer system with a relatively stable temperature and flow. The Guadalupe River flowing into Lake Dunlap is essentially the outflow of Canyon Lake. The temperature in the spring fed Comal River (approximately 23 °C) is cooler than the Dunlap reservoir water during summer months. Therefore, the water density difference between cooler inflowing Comal/Guadalupe water and the warm upper layer of reservoir water creates a stratified water column in Lake Dunlap.

Because flow and temperature are affected by season and the climate, Lake Dunlap can vary annually in its chemical and biological characteristics (Groeger and Martin 2001, Groeger 2002). Similarly, Carmack et al. (1986) conclude that a lake system with a dynamic flow may behave as a short residence-time system during one summer, and a long-residence-time system during another, even though the water residence time remains consistently short.

This study analyzed three hydrologically distinct summer seasons for this reservoir ecosystem. Stratification was observed during two seasons, 2005 and 2006. Although other studies have reported the phenomena of stratification in Lake Dunlap (Groeger and Martin 2001, Groeger 2002), the purpose of this study was to investigate the seasonal interactions between the biological and chemical components, and the main physical variables, of the reservoir. In addition to assessing of the reservoir's physical, chemical and biological characteristics on a seasonal scale, monthly and diel trends were also analyzed.

When the summer flows in Dunlap are approximately twice as high as the median flows from the past 73 years of data (Table 1), the water in the reservoir remains isothermal and mixed for the duration of the sampling season, as was observed for 2004 (Figure 9). Brown (1996) reported a similar water column structure in the "wet" 1992 summer. The 2004 high flows were not conducive to chlorophyll accumulation in the lake (Figure 13), despite the presence of the algal growth-limiting nutrient, phosphorus (Groeger and Martin 2001), added by the New Braunfels Utilities WWTP. In addition to isothermal temperatures caused by high inflows, the volume of water moving through the system dramatically decreases the WRT, as was also observed in 2004 (Table 1).

Thornton et al. (1990) illustrate that if the flushing rate (WRT) exceeds the doubling rate of phytoplankton communities, algal productivity can be limited. Lake Dunlap flushing times for 2004 were high enough to substantiate such a view (~3-6 days); however, the pre-stratification data from May, 2005 exhibit average flow volumes with low chlorophyll concentrations.

Extremely wet summers can cause the reservoir to resemble a riverine system, while dry, warm summers result in vertical stratification with vertical density zones in the water column, similar to a deep lake water column. There are multiple reasons for stratification to occur in Lake Dunlap. When there is little outflow, the surface temperature downlake greatly increases as the atmospheric temperature warms the lake surface. As long as the flow remains low, cooler Comal River water does not become diluted by the higher temperature water from the Guadalupe River. The warm surface water of the reservoir, and the cool inflow from the Comal River, causes a plunge point to occur when conditions are conducive. Further, a longer WRT can cause the plunge point distance to move up the reservoir.

Thermistor data from September, 2005 (Figure 4) illustrate how high flow can break down stratification. A high water flow (approximately 19 cms) moved through the reservoir, with it becoming less stratified, resulting in isothermal mixing in the water column. Stratification reformed one week later, and the water column densities diverged. The ability of this small reservoir to reassemble a water column structure so rapidly after being isothermal is an essential reason for the eutrophic characteristics it exhibits in warm, dry summer seasons.

Average turbidities from May to September 2004 illustrate that turbidity increased at sites from the inflow to dam during sampling events throughout the summer. The suspended solids remained in the water column because of the low WRT being higher downlake. The reservoir was less turbid in 2005 than in the previous year. The 2005 data also indicate higher average turbidity values at the plunge point, and at sites downstream of the plunge point than at the D4 and D3 upstream sites. The difference between 2004 and 2005 (Figure 22) is that turbidity in 2004 is most likely a result of inorganic solids, while the 2005 turbidity spikes were the result of phytoplankton (as reflected by the chlorophyll-α concentrations) (Figure 14). The 2004 chlorophyll-α concentration (Figure 13) is very low compared to 2005. This result of the above is a crucial difference in the chemical and biological makeup of the reservoir between stratified and non-stratified summers.

Flow into the reservoir, in 2004, was dominated by the Guadalupe River. High flows dilute the Comal River, slightly raising the temperature of the inflow to Lake Dunlap (Figure 9). The opposite effect was observed in 2006. The Guadalupe inflow in 2006 decreased, while the Comal River inflow remained relatively consistent throughout the dry summer months (Table 5). Therefore, the overall temperature flowing into Lake Dunlap was cool in 2006, despite record high seasonal temperatures. Historical flow data from 1996 exhibit a similar low flow summer season. However, as was confirmed by the personal observation by Kottler, the 1996 summer season did not produce a plunge point observed as far uplake (it did not go uplake of the Kottler site) as observed in the 2006 summer season (Groeger and Martin 2001). An explanation for the 2006 anomaly is found by comparing data from this study (the location of the plunge point in the month of August) to the USGS historical flow data. Comal River flow gauges indicated the average flow during the months from May to September, 1996, was 3.60 cms, while the same May to September average in 2006 was 7.09 cms. Both years had similar low Guadalupe River flow. The less the Comal River is diluted by the inflowing Guadalupe River, the more of an effect it has in stimulating stronger stratification in Lake Dunlap.

Another result of a Comal/Guadalupe confluence with a highly diluted Comal River is lower nitrate-nitrogen concentrations (Groeger 2002). Thus, the chlorophyll-α accumulation in 2006 was not only stimulated by stronger stratification, but nitrogen was concentrated within the system, providing additional nutrient input.

Lake Dunlap was sampled for phosphorus, its limiting nutrient (Groeger and Martin 2001) in 2005 and 2006. The phosphorus concentrations are normally predictable in pre-stratification periods and non-stratified summer seasons. The 2005 pre-stratification chlorophyll concentration averaged approximately 3 μg P/L at site D4. After receiving WWTP inputs the average concentration increased to approximately 20 μg P/L at site D3 gradually decreasing from D3 to D1, exhibiting a decreasing trend downstream from the WWTP. The results of phosphorus data from May, 2005 exhibit a gradient of nutrient concentration, decaying from the point of inflow (WWTP) to the D1 site (Figure 19). However, after the formation of the plunge point a change occurs in nutrient concentrations across the longitudinal axis of the reservoir (Figure 20). The phosphorus concentrations increase from the WWTP to the plunge point, then decrease from the plunge point to the D1 site on July 23, 2006, approximately one month after stratification began. This illustrates how simple decay models can represent nutrient processes prior to stratification (Thornton et al. 1990), but can not be applied to represent nutrient processes in summers of stratification on Lake Dunlap.

Phosphorus was observed to vary considerably over the diel period in July 2006 (SRP concentrations varied from 3 to 130 μg P/L at D1). The data collected during that diel sampling event were from three sites that bracketed the plunge point (Table 2). During the diel study the plunge point moved approximately 0.25 km over the course of one day. It moved uplake from dawn to evening as the temperatures increased. The stratification broke down at night, and the chlorophyll front diminished. Thermistor data for 2006 indicate that approximately one week prior to the diel sampling event, the stratification had been disrupted by high flows (~19 cms) (Figure 5). Though vertical stratification was observed during the diel sampling event, water density differences were not as large during the event, compared to other sampling events in 2006. This may explain some variance in the parameters analyzed.

In comparison with past data (Groeger and Martin, 2001) the SRP concentrations measured in this study were high. They decreased at night, exhibiting a direct relationship with dissolved oxygen concentrations at all three sites. However, the lower SRP concentrations observed in the early morning hours may not be a direct effect of lower chlorophyll production (Table 2). During one sampling event in the 2005 stratified sampling season (Figure 20) the chlorophyll concentrations increased across the longitudinal axis of the reservoir in delayed response to increased phosphorus concentrations. It is important to note that the trend observed on that date clearly indicate increased phosphorus concentration are not a response to increased chlorophyll concentrations.

The diel study conducted in September of 2005 illustrated a plunge point near site D2 (Table 3). The 2005 diel SRP concentrations were lower than those observed in the 2006 diel study (Tables 2 and 3). The My Casa site, uplake of the plunge point, contained the highest SRP concentrations prior to a late night sampling event. Surface warming was observed at the My Casa station, despite the absence of stratification. One interesting detail in the data was that all SRP samples were taken from the surface, and the largest divergences between surface temperatures and the temperature at the 1-m depth was at the plunge point and My Casa station. Though site D1 contained high chlorophyll concentrations, with higher temperatures, the density difference between the upper warm water and mid depth water layers was lower than the same vertical densities observed at the other two stations. The locations with the larger density differences also exhibited the highest phosphorus concentrations.

I believe the phytoplankton play a major role in processing and releasing SRP as the surface temperature of the reservoir increases throughout the day, with stratification concentrating communities within the upper boundaries of the water column. However, because Kottler's place did not exhibit high fluorescence measurements during the 2006 diel study interval, but still exhibited the same phosphorus concentration trend as downlake sites (Table 2), I do not believe the SRP concentrations were dictated by biological response. The variable SRP concentrations in this system are likely the result of chemical reactions.

Brunskill (1969) discussed the nature of precipitation/dissociation reactions of ions in the epilimnion of a supersaturated lake. Elevated conductivity and alkalinity are indications of high dissolved calcium and carbonate in Lake Dunlap (Groeger 2002). The average 2005 alkalinity data were approximately 0.5 meq l^{-1} higher than the 2004 data (Figure 21). The 2006 alkalinity was not statistically assessed because of the small number of sampling events that analyzed alkalinity; however, the inflow sites that which were sampled averaged approximately 4.4 meq l^{-1}. The 2006 data illustrate the highest conductivity concentrations of the three seasons studied. Additionally, data from July 8-13, 2006 (Figures 23 and 24), indicate the conductivity is associated with temperature in an inverse relationship (when the temperature increases the conductivity decreases). The elevated ion concentrations during 2006 are a result of the greater influence of the Comal River in 2006 (Table 5).

Murphy et al. (1983) provided evidence to suggest phosphate and calcite can coprecipitate in a eutrophic lake system. It is possible that the small size of Lake Dunlap and the concentrated inflow of calcium carbonate supersaturated the system during August 2006. Under such conditions, phosphorus may be continuously cycled through the water column in a series of precipitation/disassociation reactions. Precipitation reactions, which theoretically trap SRP within calcium-phosphate complexes, would occur more strongly in warmer periods during the day. Nonetheless, the chemical parameters in the water column, and the length of the reaction time, could possibly allow phosphorus to precipitate down through the epilimnion of Lake Dunlap and disassociate at the thermocline during the day, allowing high SRP concentrations where the warmer water meets cooler water at the thermocline. Phosphorus that precipitated out of solution may be re-precipitated under the dynamic conditions of the reservoir.

The high chlorophyll-α concentrations observed in 2005 and 2006 are a product of stratification. During the sampling year of high flow (2004), the chlorophyll-α concentrations were uniformly low across the reservoir's longitudinal axis (Figure 13). Figure 14 illustrates a higher average chlorophyll-α concentration in 2005, with the sites averaging higher concentrations being within the stratified area of the reservoir. A trend observed in 2005 was that, although the plunge point did not always contain the highest chlorophyll-α concentrations, the concentrations uplake of the plunge point never exceeded the concentrations observed in stratified areas of the reservoir.

The plunge point is not a fixed location drawn horizontally across a reservoir; rather, it can move up and down the longitudinal axis of a reservoir (Thornton et al. 1990). The *in vivo* fluorescence data from 2006 sampling dates often illustrated the location of the plunge point, by highlighting large spikes in chlorophyll fluorescence along the longitudinal axis of the reservoir. The 2006 summer season was exceptionally hot (surface temperatures consistently over 30°C), as observed in the thermistor data (Figure 7). On August 23, 2006, four sample runs were performed, recording the temperature and fluorometry of the reservoir. There was a sharp peak in both temperature and fluorometry as one moved from uplake through the plunge point (the temperature increased by 0.5-2 °C, and the fluorometry increased from 4 relative units to as much as 50 relative units). The plunge point produced correlated increases in temperature and fluorescence when stratification was observed (Figures 16 and 17).

An additional sampling observation was made for the 2006 sampling trips. During two fluorometric sampling runs on September 14 (Figure 18), the water located directly uplake (approximately 1 km) of the plunge point had pockets of high *in vivo* fluorescence normally associated with stratified water below the plunge point. However, pockets of fluorescence were observed uplake of an actual temperature break. Three days prior, the flow had increased and temperatures had dropped (Figure 5). Thus, these pockets appeared to be what remained of phytoplankton accumulations prior to the change in flow.

The effects of the plunge point on the primary productivity of Lake Dunlap illustrate the dominant physical role it plays on the reservoir ecosystem. The three zones of spatial heterogeneity in phytoplankton production along the longitudinal axis of the reservoir (i.e. riverine, transitional and lacustrine) (Kimmel and Groeger 1984) do not fit the longitudinal axis observed throughout this study on Lake Dunlap. The riverine zone dominates the system until reaching a transitional zone; the transitional zone is located at the plunge point during years of stratification. However, a system such as Lake Dunlap has no true lacustrine zone. Instead, there is an extended transitional zone reaching out from the plunge point to the dam site. Therefore, this reservoir system should be classified separately from other systems in the area (Edwards Plateau).

Lake Dunlap is unique, and the unique conditions which serve to characterize it separately from other reservoir systems also prove a challenge to manage. Groeger (2002) concluded that reducing the phosphorus concentrations coming from the New Braunfels Utilities WWTP to .5 mg/L would reduce peak chlorophyll concentration by as much as 60%. The study submitted that a tertiary waste water treatment system was a possible cost effective solution. The trend on the reservoir has continued to indicate higher concentrations of chlorophyll on years of hyper-eutrophic conditions. This study has demonstrated the mechanisms through which the physical characteristics affect the chemical and biological characteristics of the Lake Dunlap system. The variance in the physical properties of the system over the three year study illustrate the trend of increasing hyper-eutrophic conditions, as well as the need for more research assessing the chemical characteristics of phosphorus within Lake Dunlap.

CHAPTER V

CONCLUSION

This three-year study indicated that the physical ecosystem structure dominated the chemical and biological variables within Lake Dunlap. The ratio of flow from its confluent rivers and its WRT determine the location of the plunge point, and strength of stratification. The chlorophyll concentrations in the reservoir vary a great degree between drought years and high flow years. Phosphorus added into the system from the upstream WWTP is diluted and passed to reservoirs downstream of Lake Dunlap during years of high flow. However, the effects of the added nutrients can be most dramatically observed through the analysis of *in vivo* fluorescence during years of stratification, with high levels of *in vivo* fluorescence observed in the warmer months of August and September, 2006 (Figures 15-18).

Stratification within Lake Dunlap is easily weakened by changes in temperature on a diel time scale. The two diel studies conducted on the reservoir indicated that the chemistry throughout the water column varied over daily cycles. I believe, therefore, that its water chemistry is most affected by the hydrological conditions of the water densities and flow.

Theoretically, there may be a chemical/physical reaction driving the precipitation and disassociation of orthophosphate/calcium carbonate complexes in the plunge point, and perhaps even along the thermocline areas of the reservoir. Such a reaction could potentially allow for the accumulation of orthophosphate at the thermocline, so long as the feedback was continuously driven. During abnormally warm summer seasons (such as in 2006), the daily thermal heating of surface waters uplake of the observed plunge point may also prompt these chemical precipitation and disassociation reactions. However, more data are needed to test these assumptions.

Summers with continuous low flows and high temperatures will move the plunge point up the reservoir by causing portions of vertical stratification to form and dissipate over daily cycles. Therefore, the plunge point is not always present as a line transecting the reservoir and creating a phytoplankton front directly downlake. A summer of extreme heat may cause ambient air temperatures to affect the daily position of the plunge point. Another impact might be to thermally stratify eddies of surface water uplake of the plunge point, causing pockets of partially stratified water to form. These pockets will most likely be areas suitable for chemical precipitation and disassociation reactions. In addition, the conditions would be optimal for phytoplankton accumulation, which may have been partially observed in the September, 2006 sample runs. Though high fluorescence was not detected as readings were collected along the thalweg (Figure 18), areas of pea green coloration were observed along the edges of the reservoir much further uplake (approximately 1 km) than the plunge point.

The three summer seasons (2004-2006) assessed in this study provided a glimpse into one year of normal conditions (2005) and two years of extreme conditions (2004 and 2006) for Lake Dunlap. The physical chemical and biological dynamics within the plunge point area of this reservoir are difficult to pinpoint. However, trends have been observed with this study that suggests how the physical characteristics of each season can produce dynamic results in the chemical and biological characteristics of the reservoir. This may hold serious ramifications for Lake Dunlap water quality issues in the future. As the waste-water production of the surrounding New Braunfels community continue to grow, and more nutrients are released into the system, the stage is set for increasingly hyper-eutrophic conditions during summers characterized by heat and drought.

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