

Seasonal Patterns of Stratification, Nutrient Concentrations, and Chlorophyll in a
Shallow Mid-Atlantic Pond

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of
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ABSTRACT

SEASONAL PATTERNS OF STRATIFICATION, NUTRIENT CONCENTRATION, AND CHLOROPHYLL IN A SHALLOW MID-ATLANTIC POND

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Polymictic lakes are shallow, wind exposed lakes in warmer regions. Stratification in polymictic lakes can be established and destroyed repeatedly by daily temperature variations or episodic storm events. The temperature changes are often influenced more by cooling of the surface at night and warming during the day rather than by distinctive seasonal changes.

Patterns of stratification, hypoxia, nutrient concentrations, and chlorophyll were examined in a small polymictic pond on the campus of the NASA Goddard Space Flight Center in Greenbelt, MD. Thermal stratification had a major impact on the depth distribution of several parameters. Dissolved oxygen was distinctly depth-stratified for much of the season. The onset of hypoxia was observed in mid-June and continued through July. Total phosphorus generally increased with depth throughout the sampling season. Soluble reactive phosphorus values reached a maximum in April and then steadily declined, resulting in undetectable levels in upper waters during August. pH was

more variable in surface than in bottom waters due to the greater variability in the photosynthetic processes compared with those of respiration.

Ammonia and nitrate nitrogen followed a seasonal pattern with a maximum in May and a decline throughout the remainder of the season. Chlorophyll *a* showed a distinct seasonal pattern in the upper waters with values below 5 ug/L in April and May increasing to approximately 200 ug/L in early June.

Continuous temperature measurements at 0.25 m intervals indicate that two patterns of mixing occurred in the pond. In the first pattern the surface water cooled to the temperature of a mid-depth or bottom layer resulting in mixing. In the second pattern mixing was induced by wind action, often following a limited degree of surface cooling. Continuous temperature profiling also reveal that changes in the lower depths are more gradual and infrequent than in upper waters. Water chemistry parameters exhibited uniform values with depth immediately following mixing events, but stratified patterns were reasserted within a matter of days following mixing.

Introduction and Literature Review

Stratification Patterns

Polymictic lakes are shallow, wind exposed lakes in warmer regions.

Stratification in polymictic lakes can be established and destroyed repeatedly by daily temperature variations or storm events. These lakes are often small, shallow and in tropical or at least warmer climates or at higher altitudes. The temperature changes are often influenced more by cooling of the surface at night and warming during the day rather than by distinctive seasonal changes (Wetzel 2001).

Thermal stratification is one of the most significant physical events in a mid-latitude lake's annual cycle. If the lake is deep enough, three distinct layers will form during stratification: the epilimnion, the metalimnion, and the hypolimnion. The breakdown and reformation of these layers and their associated nutrient concentrations has major implications for water quality and biological communities (Horne 1994). Over the years, limnologists have used vertical temperature profiles to observe changes in the summer heating periods of lakes. As the season advances, the epilimnion deepens, the metalimnion gradient becomes steeper, and the temperature increases at all depths (Bachmann and Goldman 1965).

Hambricht et al. (1994) describe the presence of a seasonal thermocline as the core of a lake's character. The depth of the thermocline and volume of the epilimnion

influence the dynamics of an energy budget, nutrient recycling, and primary production (Hambright et al. 1994, Hutchinson 1957, Wetzel 1983).

The induction of stratification in the spring is controlled by many factors. According to Wetzel (2001) small, shallow lakes, if protected by the wind like that of the lake detailed in this study, may circulate only briefly during the spring. The process often occurs only for a few days and this period of circulation may allow the temperature of the water to increase more than 10° C.

Prior to the start of thermal stratification in summer, isothermal conditions exist. This isothermal status leads to mixing and an even distribution of chemical and biological components (Nurnberg 1984). The distribution of nutrients such as carbon dioxide and oxygen provides information as to the general nature and trophic state of the lake.

Thermal lake structure influences practically all biological and chemical processes. These processes include primary and secondary production, nutrient cycling, oxygen depletion, and water movement (Mazumder and Taylor 1994, Schindler 1971, Cornett and Rigler 1980, Quay et al. 1980, Gliwicz 1980).

Stratification in temperate lakes isolates hypolimnetic water from contact with atmospheric oxygen. Biomass produced by primary productivity in the epilimnion settles into the hypolimnion and decomposes, resulting in oxygen depletion. Since hypolimnetic water is no longer in contact with the atmosphere and is below the photic zone, oxygen is rapidly depleted causing hypoxia or anoxia. These anoxic conditions at the sediment-water interface cause a release of phosphate, ammonia, and metal components from sediments (Schladow and Fishcer 1995).

As a lake mixes or destratifies, nutrients that have accumulated in the hypolimnion return to the epilimnion. This restructuring has a profound impact on nutrient concentrations and forms. For example, fixed nitrogen in freshwater is present largely as NO_3^- ions. When the hypolimnion of a eutrophic lake becomes hypoxic, bacterial nitrification of ammonia ceases. Oxidation at the water-sediment interface is also lost, reducing the absorptive capacity of the sediments for $\text{NH}_4\text{-N}$. An increase in the release of NH_4^+ from the sediments occurs and consequently the concentration of $\text{NH}_4\text{-N}$ in the hypolimnion increases (Wetzel 2001).

Water Quality Parameters

Nutrient loading to a lake includes inputs from sources such as surface runoff and precipitation. Other sources that are part of the lake's nutrient budget are dryfall (wind inputs), groundwater, and nitrogen fixation by cyanobacteria (Downing 2000).

Oxygen, or the lack thereof, is an essential element concerning biological and chemical processes in aquatic environments. The concentration of oxygen in an aquatic environment is a function of photosynthesis, respiration, water movement, and temperature (Horne 1994). Limnologists suggest that in order to fully understand a lake, knowledge of its oxygen regime is necessary (Nurnberg 1984). Dissolved oxygen (DO) is necessary for the metabolism of all aquatic organisms that have aerobic respiratory biochemistry. Its properties of solubility and distribution are essential to an understanding of the growth of aquatic organisms (Stefan et al., 1995). At low levels the

microbial community is greatly affected by small changes in dissolved oxygen which substantially alter redox conditions and associated chemical speciation.

Hypolimnetic oxygen depletion is increased by nutrient enrichment of the lake's system (Cornett 1989). Schadlow and Fischer (1995) found that extended periods of thermal stratification suppress the vertical transport of dissolved oxygen. However, sedimentation of organic production from the lake's upper layers continues. These conditions lead to anoxia in the hypolimnion and initiate serious water quality implications.

Nitrogen is a major nutrient that affects the productivity of fresh waters. In fresh waters nitrogen occurs in many forms, including molecular nitrogen (N_2), organic nitrogen, ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-). External sources of fixed nitrogen to lakes include surface land drainage, groundwater, atmospheric dry deposition, and precipitation (Wetzel 2001). Lakes play an important role as nitrogen sinks in the aquatic path from land to ocean (Bernasconi 1997, Billen et al. 1991). The most common forms of inorganic nitrogen dissolved in water are ammonium ion (NH_4^+) and nitrate ion (NO_3^-).

The distribution of ammonium in lakes varies greatly regionally, seasonally, and spatially within lakes. This distribution is mainly attributed to the level of productivity and the degree of pollution from organic matter (Wetzel 2001). Studies by Liao and Lean (1978) found that because ammonium is readily absorbed by plankton and nitrified to nitrate, concentrations in well-oxygenated zones are usually low. They also observed low ammonium concentrations in unproductive oligotrophic waters, the trophogenic zones of

most lakes, and in most lakes after periods of circulation. Additionally, they noted a marked increase of ammonium release from the sediments when the hypolimnion of eutrophic lakes becomes anoxic.

Nitrate is the most common form of inorganic nitrogen entering fresh waters from drainage basins, ground water, and precipitation. The assimilation of nitrate and its incorporation by green plants are dominant processes in the trophogenic zones of fresh waters. The ratio of $\text{NO}_3\text{-N}$ to $\text{NH}_4\text{-N}$ in lakes varies with regards to natural and polluted waters (Wetzel 2001).

Several studies have been conducted to determine the seasonal distribution of various forms of nitrogen in temperate lakes (Wetzel 2001, Domogalla et al., 1926, Domogalla and Fred 1926, Barica 1970). These studies concluded that low autumnal nitrogen concentrations in the epilimnion gradually increase in late fall and peak in late winter and summer. In the oxygenated upper waters, nitrate decreased during the spring maximum from increases in plankton production. After the onset of thermal stratification, notable decreases in nitrification were observed in the tropholytic zone due to hypoxia in the hypolimnion (Downing 2000).

Phosphorus is generally recognized as the most limiting nutrient in temperate fresh waters (Carignan and Planas 1994, Schindler 1977, 1978). Phosphorus directly limits the abundance of phytoplankton (Horne, 1994). In lakes, during seasons of active biological production, the concentration of phosphate ion often drops below the detection limit of standard methods (Guildford and Hecky 2000, Hecky et al. 1993, Meybeck, 1993). Studies of nutrient concentrations in polymictic lakes found that major storm

events resulted in high fluxes of phosphorus and sediment to the lake (Downing et al., 2000).

Lakes are often surrounded by terrestrial and urban ecosystems that introduce nutrients in fixed organic forms, either in solution or as particles (Guildford and Hecky 2000, Hecky et al. 1993, Meybeck, 1993). Furthermore, most phosphorus within lakes is tied up in biomass. As a result, limnological studies often emphasize total phosphorus (TP). TP includes dissolved organic and inorganic phosphorus plus particulate forms rather than simply inorganic forms (Guildford 2000, Vollenweder 1968, Dillon and Rigler 1974). TP concentration is used as a measure of water quality because it strongly correlates with variables such as chlorophyll, nitrogen, and anoxia (Nurnberg 1998).

Sunlight, temperature, nutrients, and wind all affect algae numbers and therefore chlorophyll *a* concentrations. A strong wind may mix the water in a lake, causing an immediate decrease in surface chlorophyll *a* concentrations, as the algae become mixed throughout the water column. An associate increase in surface nutrients may result from mixing with high nutrient bottom waters. The wind also may cause a release of nutrients into the water system by stirring up nutrient-laden bottom sediments. Then, after the wind dies down, the number of algae and the chlorophyll *a* concentrations may increase (Horne 1994).

Algae populations, and therefore chlorophyll *a* concentrations, also vary greatly with water depth. Algae must stay within the top portion where there is sunlight to be able to photosynthesize and grow. As they sink below the sunlit portion, they have a

negative energy balance and will start to die. The increase in nutrients caused by pollution usually results in more algae, assuming light is not limited (Horne 1994).

Guilford and Hecky (2000) found that the northern temperate lakes in their studies exhibited a direct correlation between TP and chlorophyll *a* (Chl *a*). Other studies by freshwater limnologists have determined a dependence of algal biomass on TP as determined by chlorophyll *a* (Dillion and Rigler 1974, Pridemore et al. 1974, Guilford et al. 1994).

A hypothesis concerning the relationship between chlorophyll *a* and phosphorus (Sakamoto 1996) suggests that chlorophyll is both a simple and accurate estimate of phytoplankton standing crops. This hypothesis is now used more widely than cell volume or cell count as an approximation of standing crops (Dillon and Rigler 1974).

Case Study

Rock Creek Lake is a recreational polymictic lake in Jasper, Iowa. Rock Creek Lake has a surface area of 199 ha, a mean depth of 2.3 m, and a mean Secchi disk depth of 0.50 m. A baseline study of Rock Creek Lake in Iowa was conducted from March 1998 to June 1999. This survey indicated that Rock Creek Lake was eutrophic, based on a combination of several parameters including: total phosphorus, dissolved ortho-phosphorus, inorganic nitrogen, Secchi disk measured water clarity, chlorophyll *a*, and dissolved oxygen. Data were collected at three depths, from two stations, one established in the deepest point in Rock Creek Lake, and another at a point of marsh influx into Rock Creek Lake. (Downing 2000).

During the 1998-1999 season, the lake was stratified through May and June, mixed at the end of June, stratified through July and August, mixed during September through November, stratified in early December, mixed in late December, stratified under ice in January, then circulated again in spring. The polymictic thermal regime led to rapidly changing oxygen conditions. During periods of stability, accumulation of silt and sediments led to lowered oxygen concentrations in bottom waters. Polymixis also caused pH to vary through the water column and across the season. During periods of water column stagnation, bottom waters declined to low values of DO due to decomposition in deeper waters (Downing 2000).

Conductivity patterns across the seasons showed a general trend of high conductivity in spring and declining conductivity in summer and autumn. This pattern may have been due to the high rate of import of dissolved substances washed from the watershed in spring, that progressively declined as they were removed throughout the season by chemical and biological processes (Downing 2000).

Seasonal patterns in nutrient concentrations were found to be driven principally by nutrient flux from the watershed in the spring, followed by nutrient regeneration from sediments during periods of summer stagnation. During this stagnant period nutrients accumulate in the hypolimnion, while oxygen accumulates in the epilimnion. Inorganic nitrogen in the water column was high during spring during run-off and was drastically reduced during the summer as nitrogen was absorbed by the biotic community.

Phosphorus concentrations in Rock Creek varied from a low of 43 $\mu\text{g/L}$ to a high of over

600 $\mu\text{g/L}$, making the lake hypereutrophic when viewed from a nutrient chemistry standpoint (Downing 2000).

Objectives

To examine the interaction between stratification, nutrients, and phytoplankton in a small suburban reservoir.

- ▶ To observe the sequence of stratification and mixing of the water column over the growing season
- ▶ To determine how long after stratification hypoxia and other chemical changes occurs
- ▶ To quantify nutrient concentrations as a function of depth and the development of stratification

Study Area

NASA Goddard Space Flight Center is located in Prince George's County, Maryland (Figure 1). The site is surrounded to the south and east by residential development, to the west by residential development and the Baltimore-Washington Parkway, and to the north by the Beltsville Agricultural Research Center of the U.S. Department of Agriculture. Surface runoff from the north and central portions of NASA Goddard flows northward to Beaverdam Creek, a tributary of the Anacostia and Potomac Rivers. The southern portion of the property drains southward to the Patuxent River (Jones, 2003).

Pond P (named for the purposes of this study) is a small impoundment located on the grounds of NASA Goddard Space Flight Center in Greenbelt, MD (Figure 2). It is roughly oval in shape, has an area of 2.37 ha, and a maximum depth of about 2.5 m. Pond P was constructed in 1966 and is currently used for recreation and stormwater management. The pond is located in the Beaverdam drainage basin and has a watershed area about of seventy-four ha which consists of buildings, fields, and roads. Data from monthly sampling in 2001 suggested that it may mix and restratify several times during the year (Jones 2003).

A site near the dam at the pond's maximum depth was chosen for sampling. This site was determined to be the deepest point, was not shaded by the surrounding forest canopy, was free of debris, and was canoe accessible. All samples in the current study were collected at this sampling site. Care was taken to ensure that the water column was not disturbed prior to sampling.

Goddard Space Flight Center and Vicinity

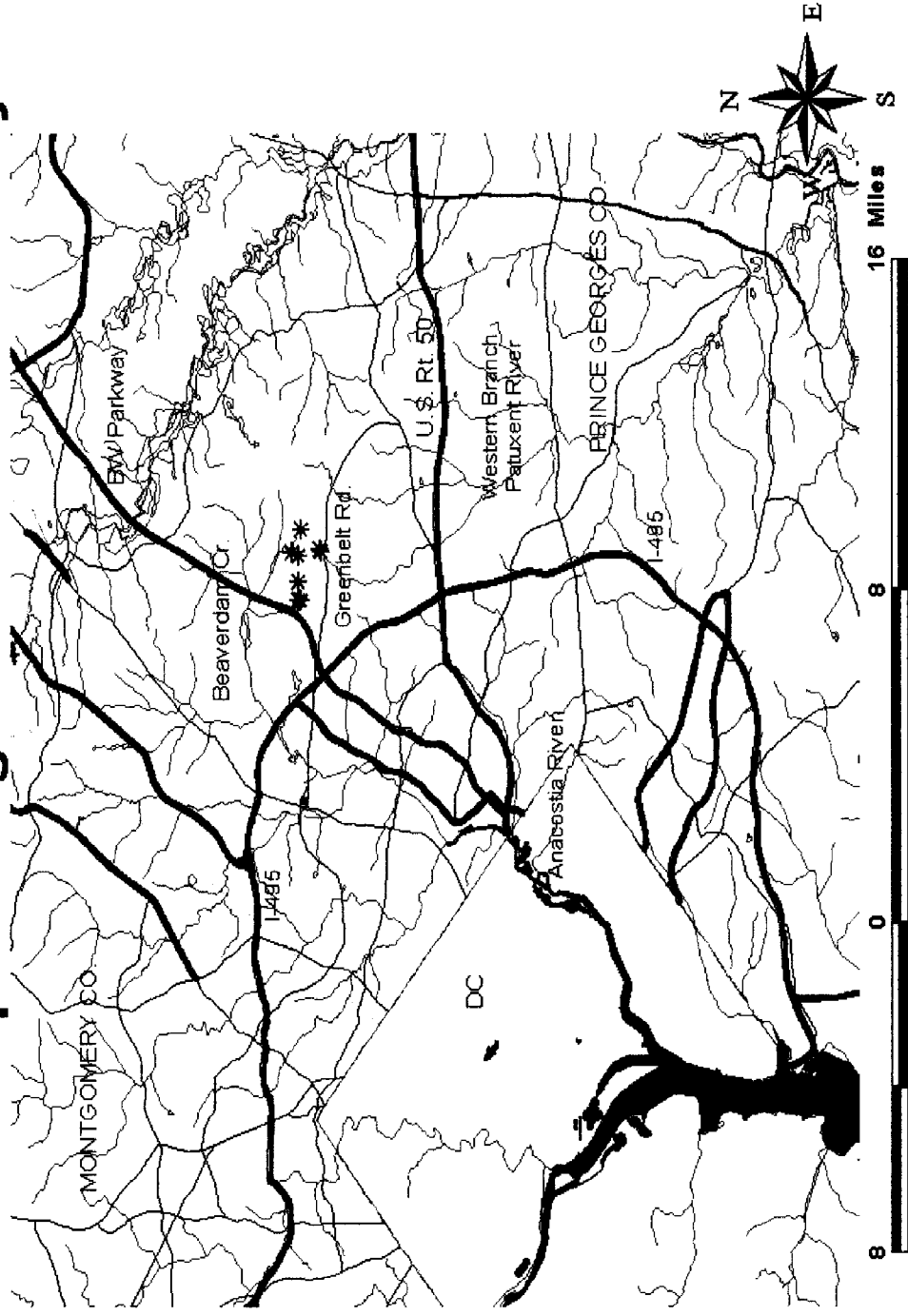


Figure 1. Goddard Space Flight Center (green stars) in relation to the District of Columbia and Maryland suburbs.

Goddard Space Flight Center with Aquatic Sampling Stations

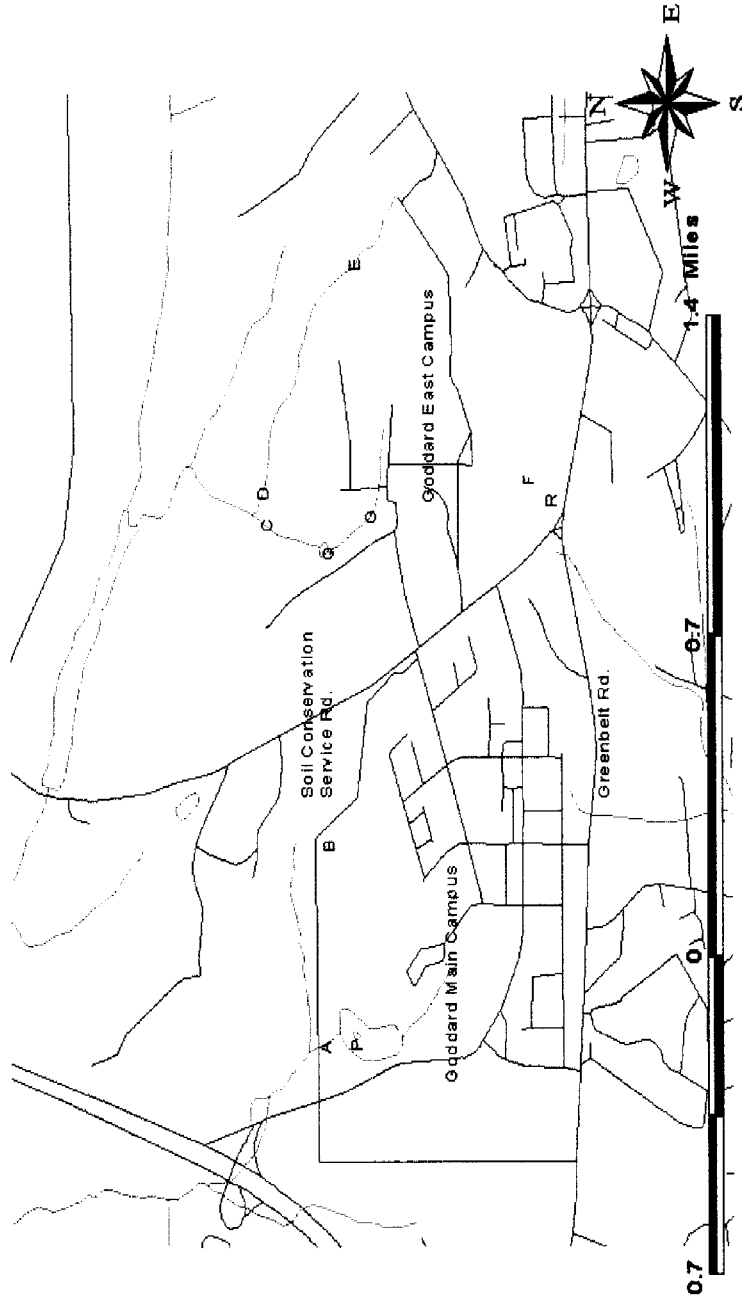


Figure 2. Sampling Sites at Goddard Space Flight Center. Letters A-G indicate Stream Sites. Red box indicates study sample site.

Methodology

A set of HOBO temperature loggers was deployed at 0.25m depth increments in mid-April and downloaded during sampling to obtain a continuous record of stratification status. The loggers collected temperature data at ten minute intervals throughout the water column. The temperature loggers were retrieved in mid-September after the last sample was collected. The loggers were intercalibrated at room temperature before deployment and were found to yield temperature values within 1°C of one another.

A DataSonde 4a Water Quality Multiprobe (Hydrolab) was used to measure pH, dissolved oxygen (DO), temperature, and conductivity at 0.25 m depth increments. The transparency of the water column was determined with a Secchi disk. The Secchi disk was lowered until it just disappeared and raised until it reappeared. The mean of those two depths was taken as the secchi depth. Light attenuation was measured with a LICOR underwater sensor. Surface readings were taken before and after the light profile to ensure that ambient light did not change during the reading.

Water samples were collected from pond P at approximately bi-weekly intervals between May and September 2003 at 0.5 m depth increments in the water column. Water was obtained by using a submersible bilge pump connected to a 2 cm ID plastic hose. The inlet-hose end was lowered to the specific depth and the pump actuated. The pump

was allowed to run long enough to ensure flushing of old water from the hose. It should be noted that on June 17 the pump was inoperable and water samples were not collected.

The samples were collected in pre-labeled 500 mL acid washed polyethylene bottles. Two full volumes of water were allowed to overflow the 500 ml polyethylene bottle before the sample was collected.

In the field 125 mL of the water collected from each depth were filtered through Whatman GF/F glass fiber filters. The filtrate was collected for laboratory analysis of ammonia-nitrogen, nitrate-nitrogen, and soluble reactive phosphorus. The remainder of the unfiltered water sample was left for analysis of total phosphorus, chlorophyll *a*, total suspended solids, and volatile suspended solids. All water samples were held on ice until reaching the lab and then were transferred to a refrigerator and held at 4°C until analysis.

Soluble reactive phosphorus, roughly equivalent to orthophosphate ion was determined by using the ascorbic acid method (Wetzel and Likens, 1999). The Solarzano method was used to determine the ammonia nitrogen concentrations (Wetzel and Likens 1999). The concentrations of nitrate-nitrogen were ascertained by cadmium reduction (Hach Nitra Ver 5 Method). Total suspended solids (particulates) was determined by filtering a known volume of water through a 0.45µm GF/F filter. The filter was placed into a drying oven at 80° C to obtain the dry weight and then ashed at 500° C to ascertain organic content (volatile suspended solids).

Chlorophyll *a* was determined using a fluorometric technique. Chlorophyll *a* was determined by the following equation which corrects for pheophytin interference: (Jones and Kelso, 2000).

$$\text{Chlorophyll a } (\mu\text{g/L}) = F_s R_s (R_b - R_a) / (R_s - 1)$$

where F_s = concentration per unit fluorescence for pure chlorophyll

R_s = fluorescence before acid / fluorescence after acid for pure chlorophyll

R_b = fluorescence of sample before acid

R_a = fluorescence of sample after acid

Data for each parameter were entered into Excel spreadsheets for graphing of temporal and spatial patterns.

After samples were processed in the lab the glassware and sample bottles were acid washed with 10% HCl before use. In the field the funnel and flask were rinsed with deionized water between samples to prevent cross-contamination.

Maryland state water quality standards are outlined in Table 1. These values are used as benchmarks for assessing data in the current study. State water quality standards generally specify a minimum of 5 mg/L of DO to maintain a balanced aquatic community. Additionally, DO values below 2 mg/L will eliminate most aquatic life and trigger chemical changes in nutrients and other bioactive chemicals. For the purposes of this study, values below 2 mg/L will be characterized as hypoxic. Values below the detection limit were set to zero.

Table 1. Maryland State Water Quality Standards.

Chemical Parameter	Detection Limit
Dissolved Oxygen (DO)	5 mg/L
Ammonia Nitrogen	0.02 mg/L
Nitrate Nitrogen	1 mg/L
Soluble Reactive Phosphorus	2 µg/L
Total Phosphorus	5 µg/L

Source: Maryland Biological Stream Survey: 2000-2004, Volume II).

Results

Climatic Parameters

Air temperature was generally below average for the period from January through July in 2003 (Table 2). April was less than 1°C above average. August and September yielded above normal temperatures, with August at +2.2°C. The remainder of the year was below average. The exception was in November which was + 3.2°C.

Precipitation was 57 cm above normal in 2003 (Table 2). Unusually large amounts of rainfall were observed in February (+11.6), May (+7.4), June (+17.9), and September (+12.1). January, March, and April yielded precipitation below normal averages. The May-June 2003 period was the fourth wettest on record and June was the eleventh coolest on record, according to the National Weather Service.

Hydrolab Profile Data

Data obtained from the DataSonde Hydrolab indicate that average temperatures exhibited a gradual seasonal pattern with a slow rise from about 13°C in April to just over 26°C in August (Figure 3). In September, average temperatures declined to 23 °C. The relatively small temperature differences within the 0.10 m to 0.50 m depth range indicate that this region is often mixed. Surface temperatures increased from roughly 19°C in

Table 2. Monthly Summary of Meteorological Data for 2003. Glenn Dale, Maryland.

Month	Avg Temp (°C)	Long-Term Temp. Avg (°C)	Precipitation (cm)	Long-Term Precip. Avg (°C)
January	-2.4	(-0.11)	6.9	(8.8)
February	-1.6	(1.3)	18.8	(7.2)
March	-0.9	(-0.4)	9.7	(10.0)
April	11.5	(11.1)	6.5	(8.7)
May	15.3	(16.5)	19.3	(11.9)
June	20.8	(21.3)	27.4	(9.5)
July	23.8	(24)	15.0	(10.6)
August	25.4	(23.2)	8.2	(10.4)
September	20.1	(19.3)	22.3	(10.2)
October	11.7	(12.8)	10.3	(9.2)
November	10.4	(7.2)	13.6	(8.7)
December	2.1	(2.5)	12.4	(8.3)

Note: 2003 monthly averages or totals are shown accompanied by long-term monthly averages (1971-2000).

Source: Maryland State Climatologist Office (2004)

Note: This station is 8 km west of the study site. It is the closest recording weather station.

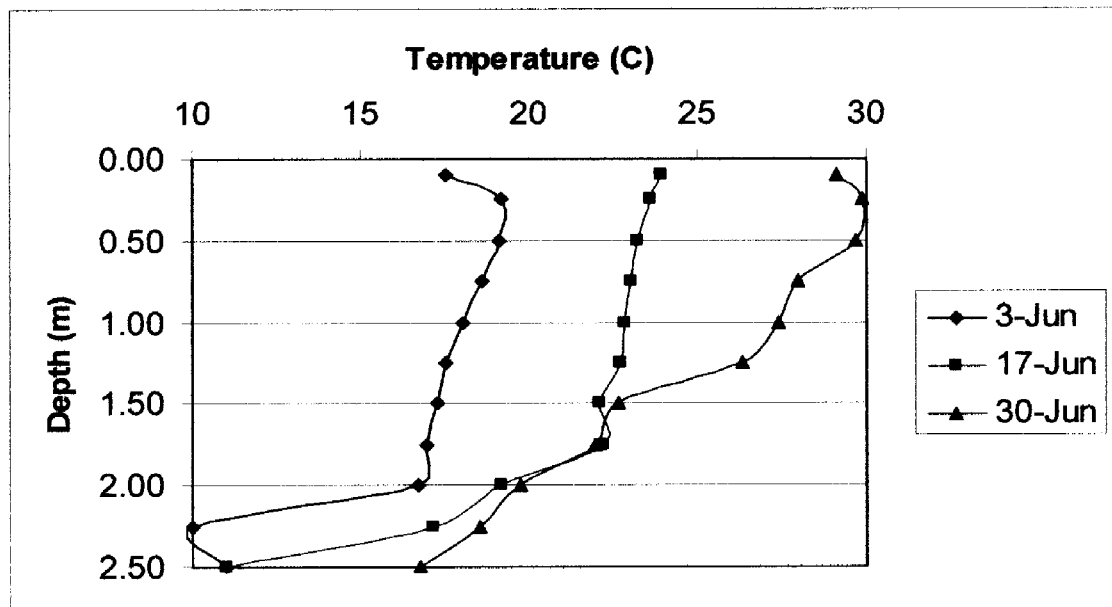
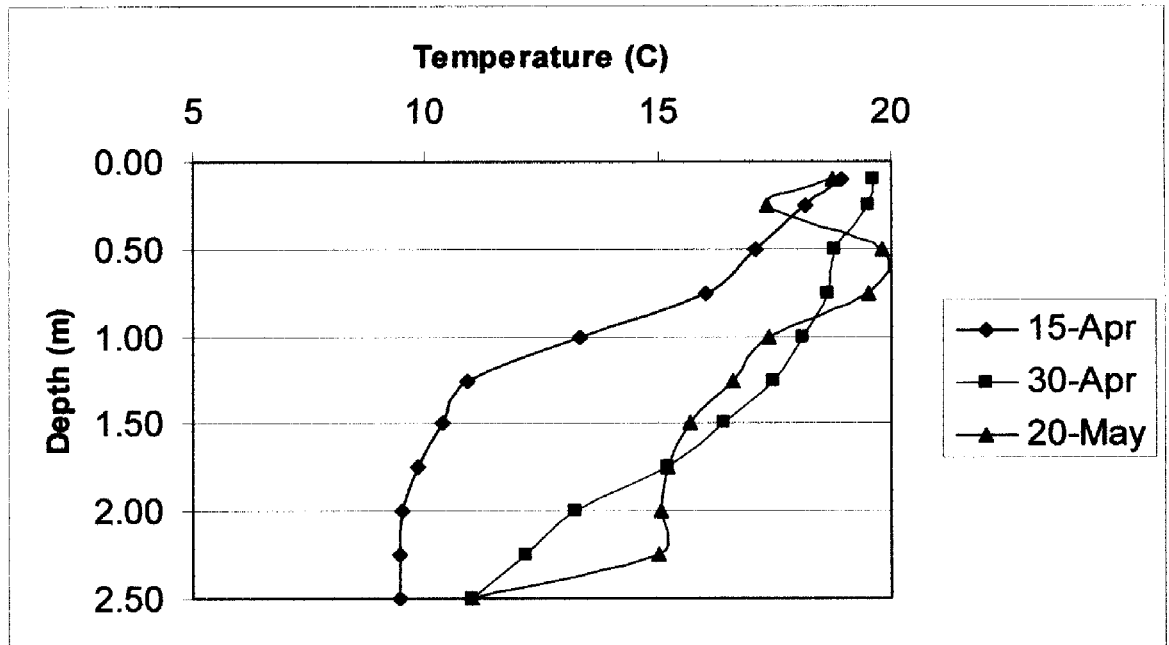


Figure 3. DataSonde temperature profiles. Note different scaling of axes.

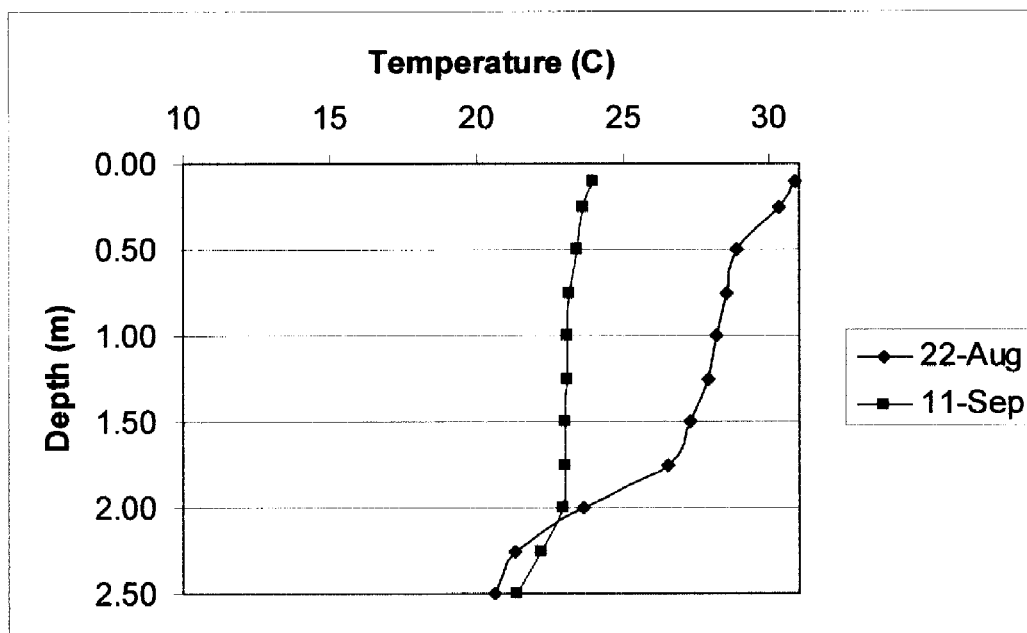
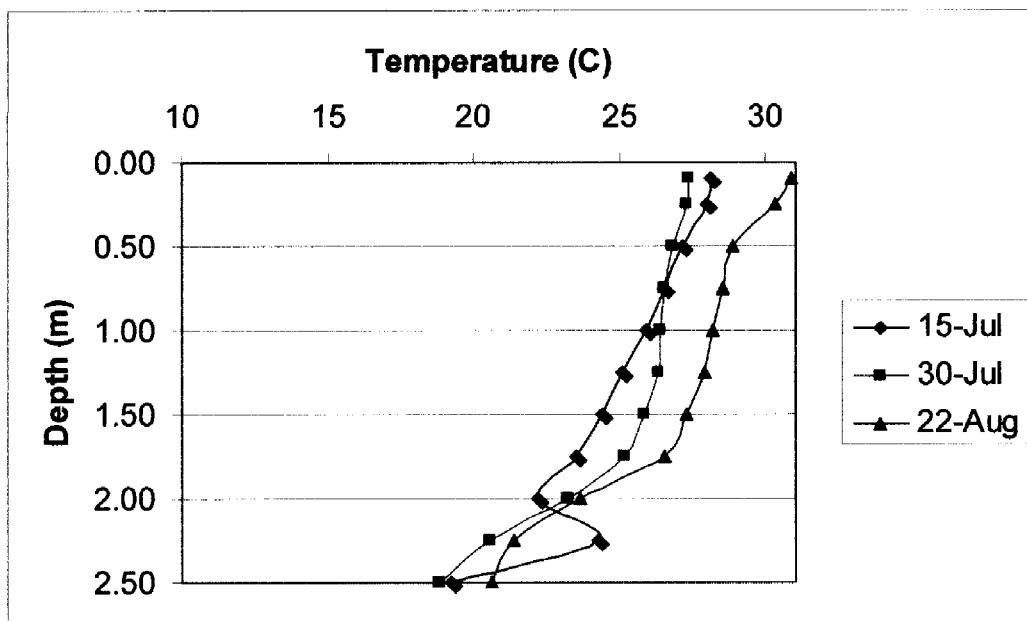


Figure 3. (Cont).

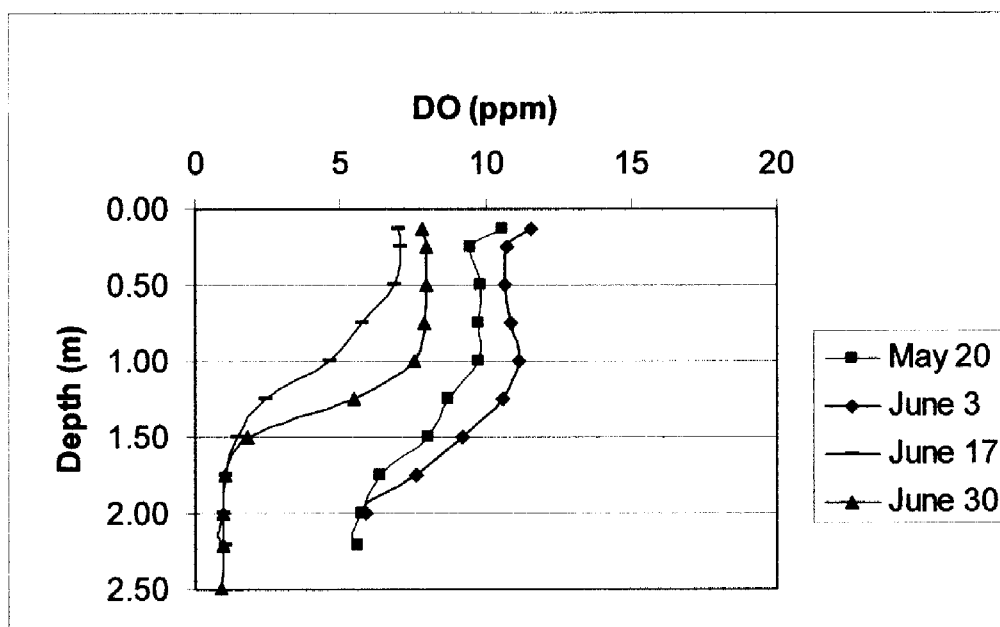
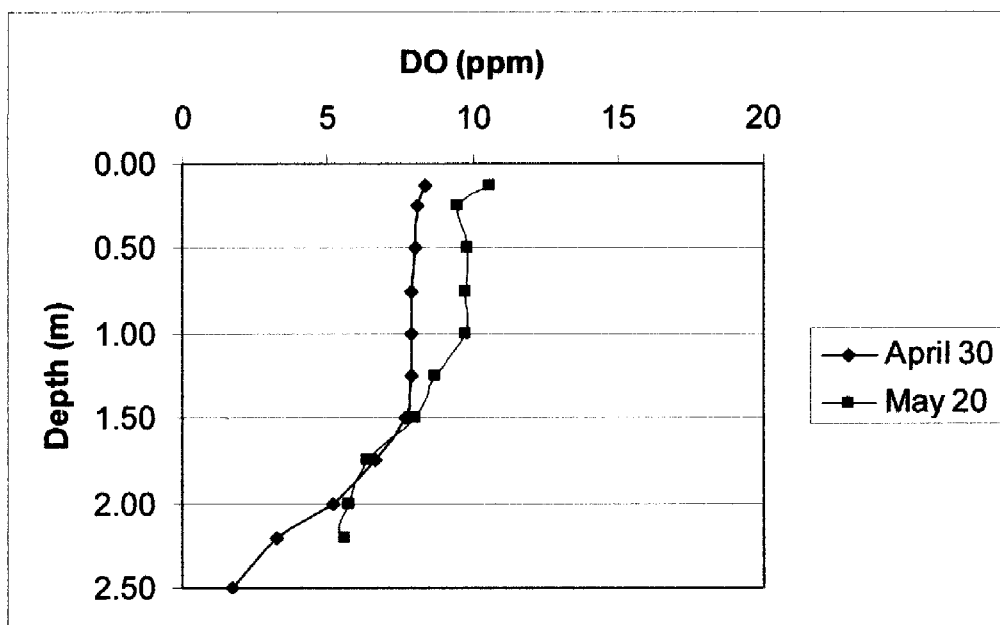


Figure 4. Dissolved Oxygen (DO) (ppm).

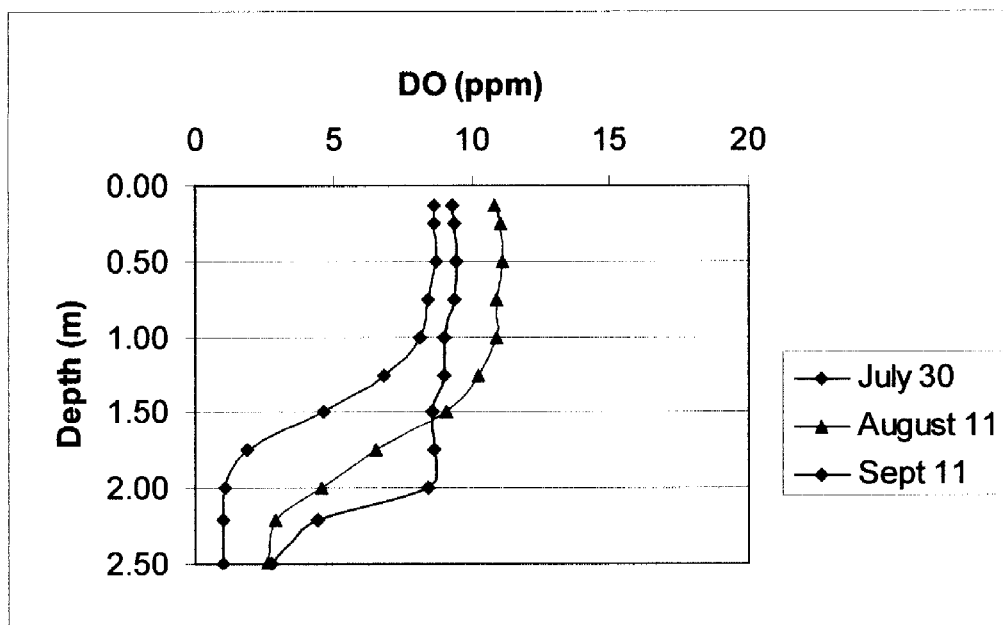
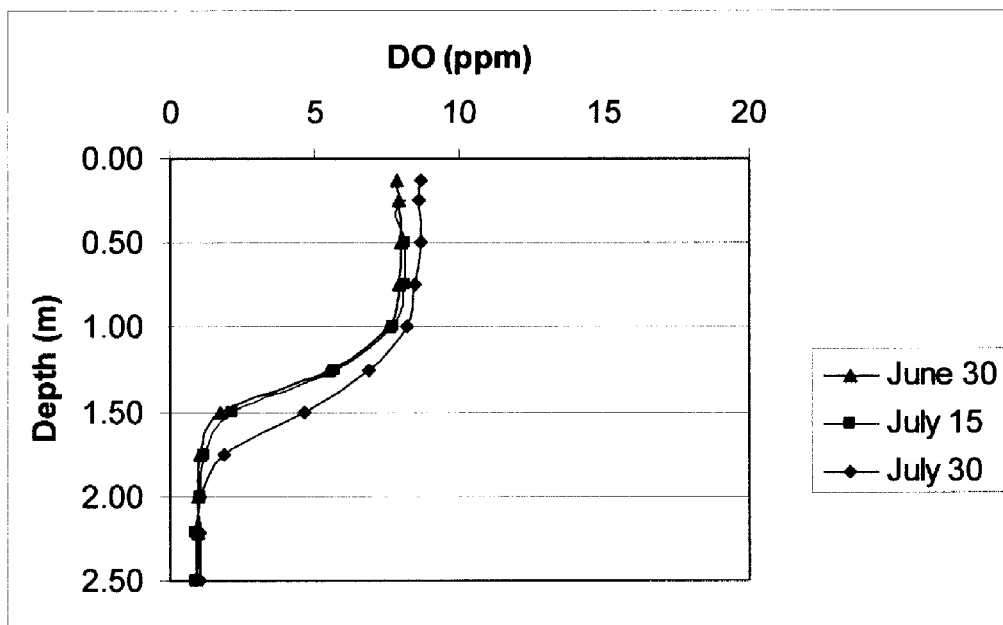


Figure 4. (Cont).

April to above 30°C in August and then declined to 24°C in September. Bottom temperatures increased from 9°C in April to 21°C in September.

Surface DO concentrations increased from 8.36 mg/L in late April to 11.58 mg/L in early June (Figure 4). By June 17, DO had decreased markedly at all depths to well below saturation suggesting a possible algae die-off. Resulting surface values remained below 10 mg/L and near saturation through late July. During July and August a strong seasonal pattern of stratification is apparent, with very limited DO near the bottom (Figure 4). In August another pronounced increase in DO was observed. Due to mixing of the water column in September DO concentrations remained >8 mg/L through 2.00 m.

Hypoxic conditions were rarely observed from April through early June. In mid-late June hypoxia occupied the water column from 1.5 m downward. In July the hypoxic zone began at a depth of 1.75 m. It disappeared in August and September, although DO remained low in bottom waters.

When DO concentrations are expressed as percent saturation, the temperature effect is removed and focus is primarily on photosynthesis and respiration. With the exception of April 30 and June 17, DO was above 100% in surface waters (Figure 5). On June 3 and August 22 maximum DO percent saturation values were 120% and 145% respectively. Supersaturation occurred to a depth of 1.25 m on June 3 and 1.5 m on August 22. These levels indicate supersaturation of water by photosynthetic activity.

pH is a measure of the hydrogen ion activity in the water and is affected by concentrations of specific ions, buffering processes, and metabolic activities.

Photosynthesis tends to raise pH and respiration tends to lower pH. A seasonal increase in pH was observed throughout the water column. Average pH values ranged between

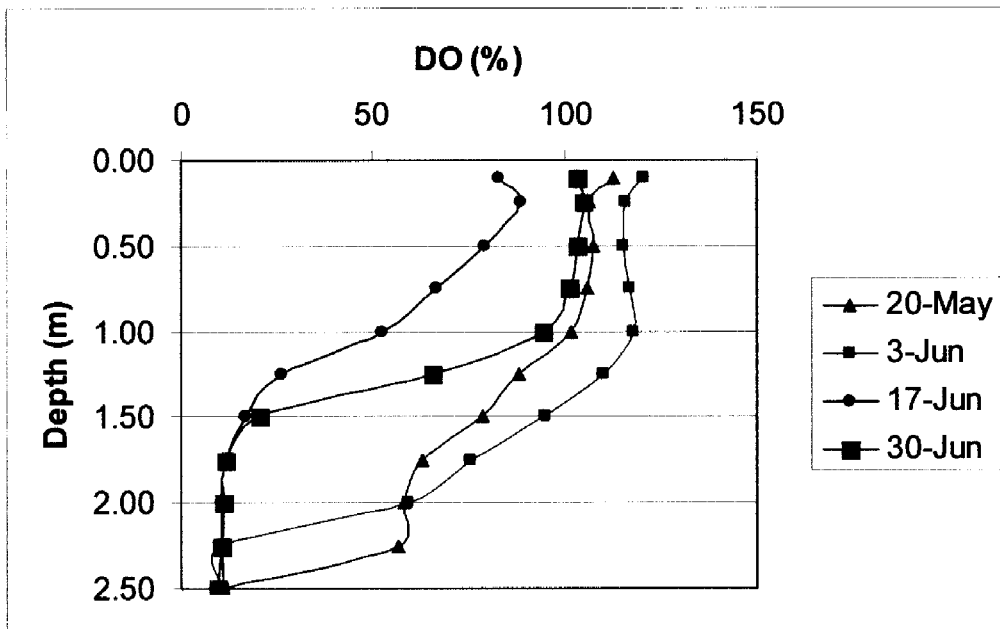
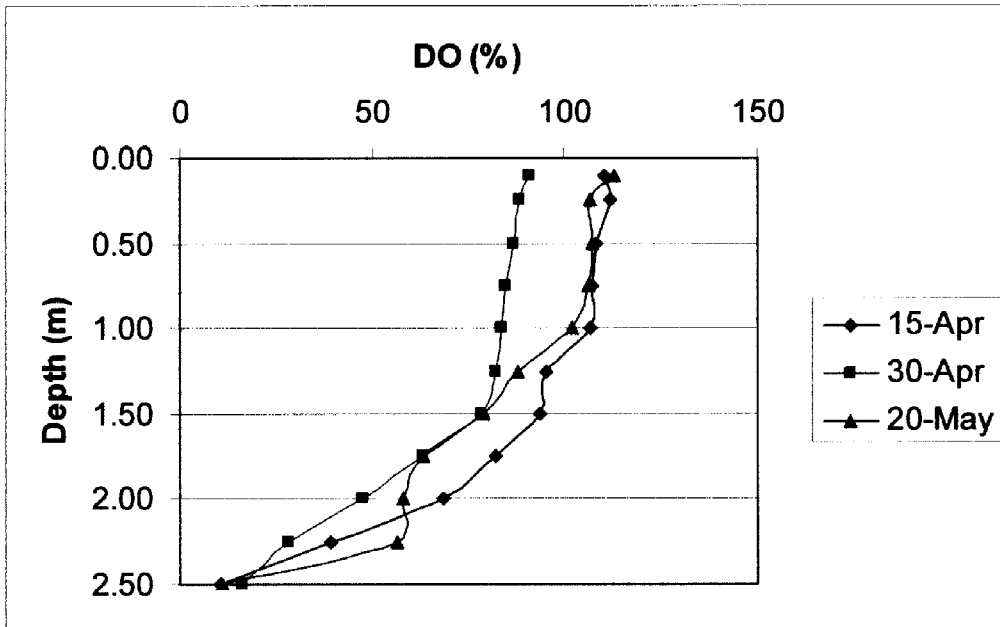


Figure 5. Dissolved Oxygen (DO) Percent Saturation.

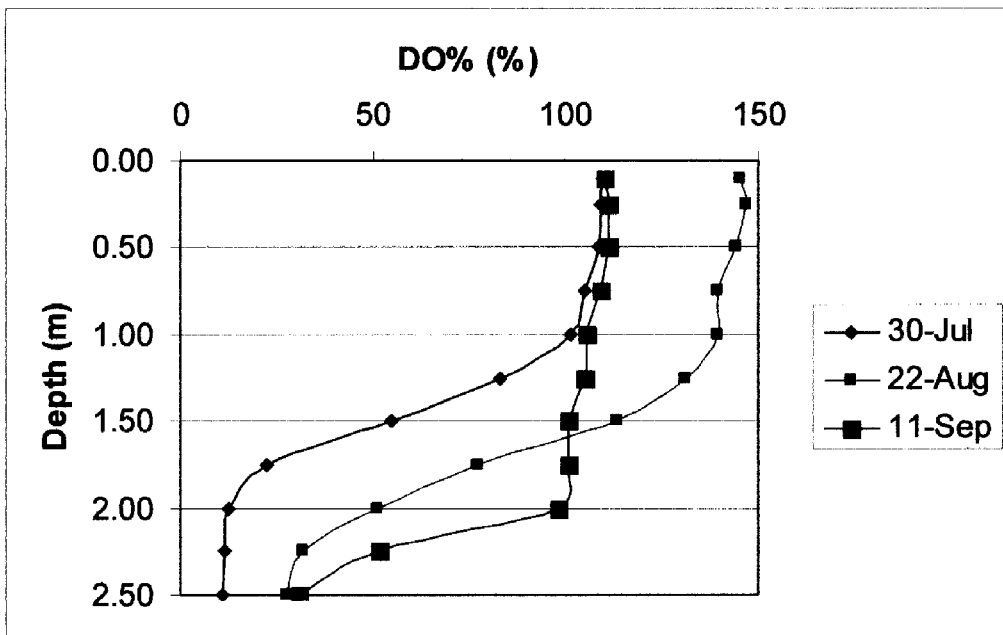
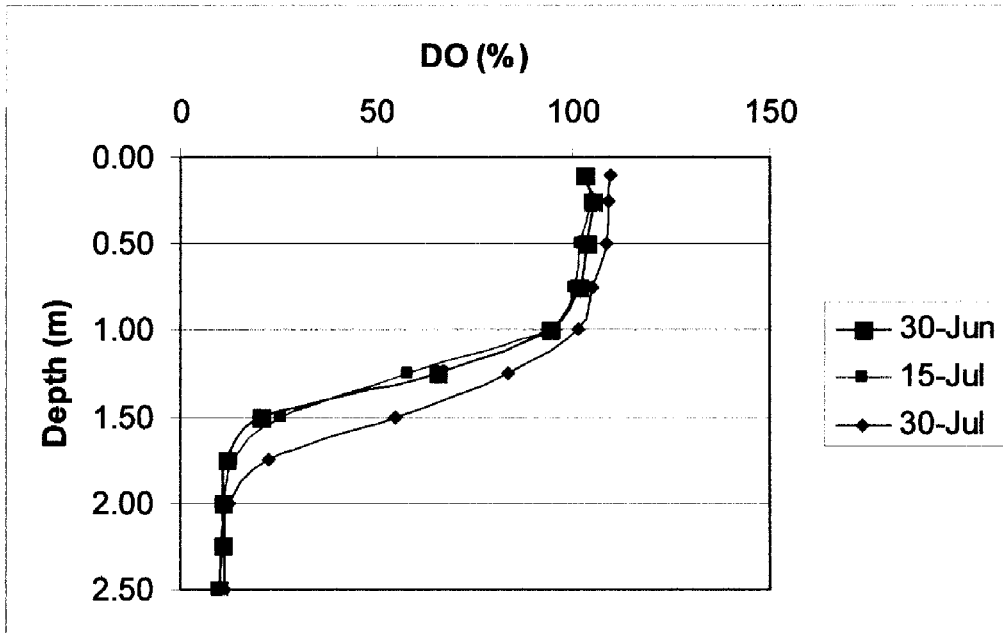


Figure 5. (Cont).

6.37 in April to 8.03 in August (Figure 6). Surface pH values increased from 6.47 in April to 8.60 in August. On most dates surface pH was 7-7.5. At the bottom pH values increased from 6.25 in April to 8.08 in September. pH was higher near the surface than near the bottom from April through August. However in September, surface levels had decreased substantially while pH remained elevated near the bottom. Similar pH values between 0.1 and 0.75m on several dates indicate that the top 0.75 m of the water column was often well-mixed.

Conductivity values reflect the total ionic concentration in fresh water. Conductance at the surface declined steadily from April at 810 uS/cm and reached a low of about 169 uS/cm in mid-July (Figure 7). For the remainder of the year there was a gradual increase in conductance, reaching 200 uS/cm by August and 250 uS/cm by September. The high values in spring are probably related to runoff of road deicing salts from roads and parking lots. The decrease through July is probably due to dilutions of this input during the summer and fall.

Conductance increased with depth particularly near the bottom on most dates. April conductance values were 810 uS/cm at the surface and 2870 uS/cm at the bottom. In late May and early June, conductance values were relatively constant throughout the water column. Hobo temperature data suggest that mixing events caused this change occurring throughout the pond. By mid-July conductance was about 200 uS/cm at the surface increasing to 610 uS/cm at the bottom. This near bottom increase was probably due to sediment release of ions.

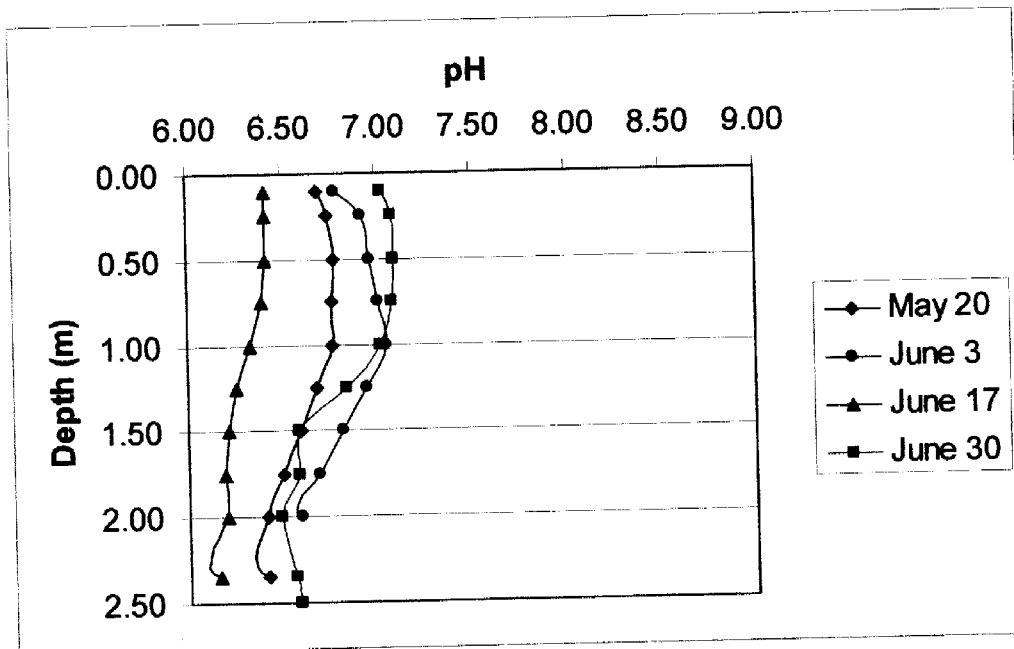
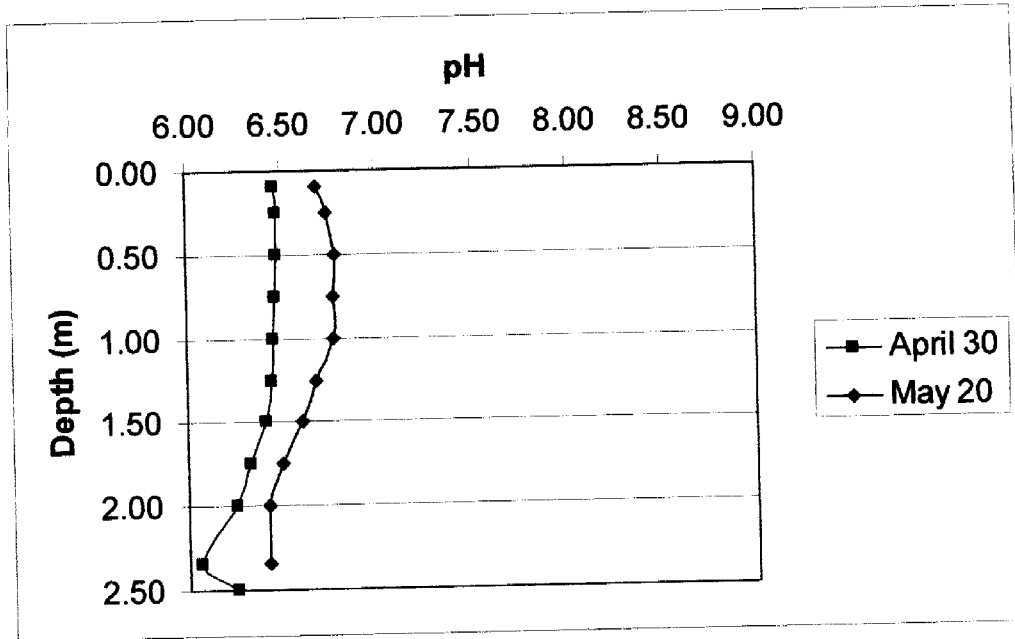


Figure 6. pH.

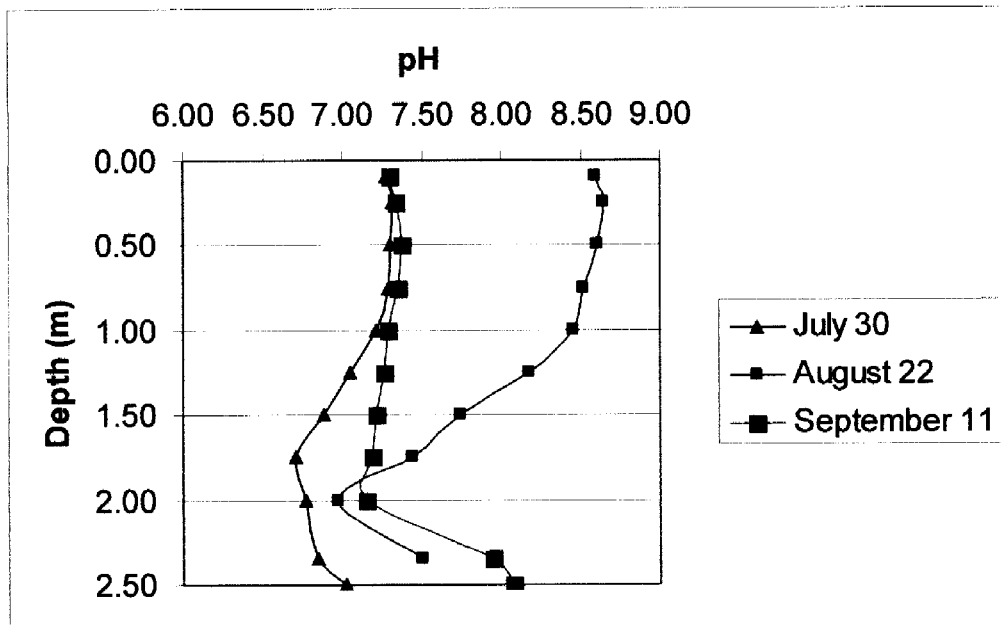
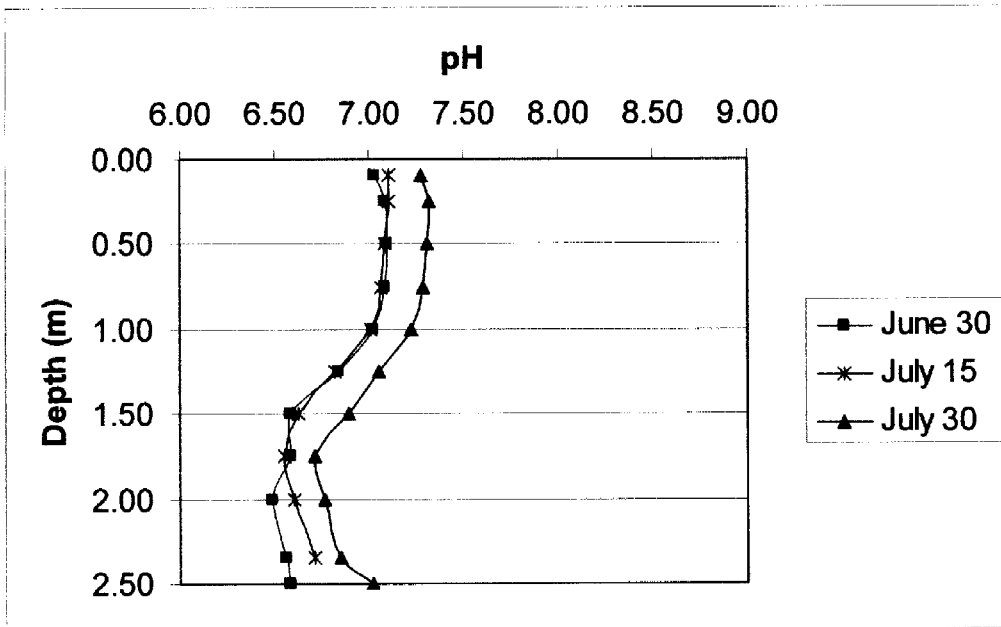


Figure 6. (Cont).

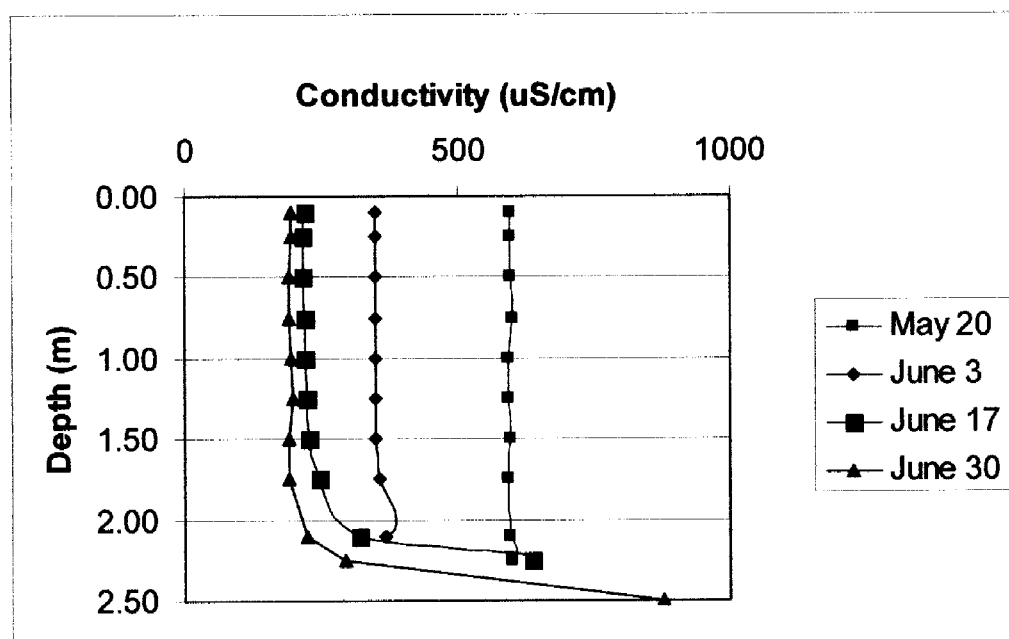
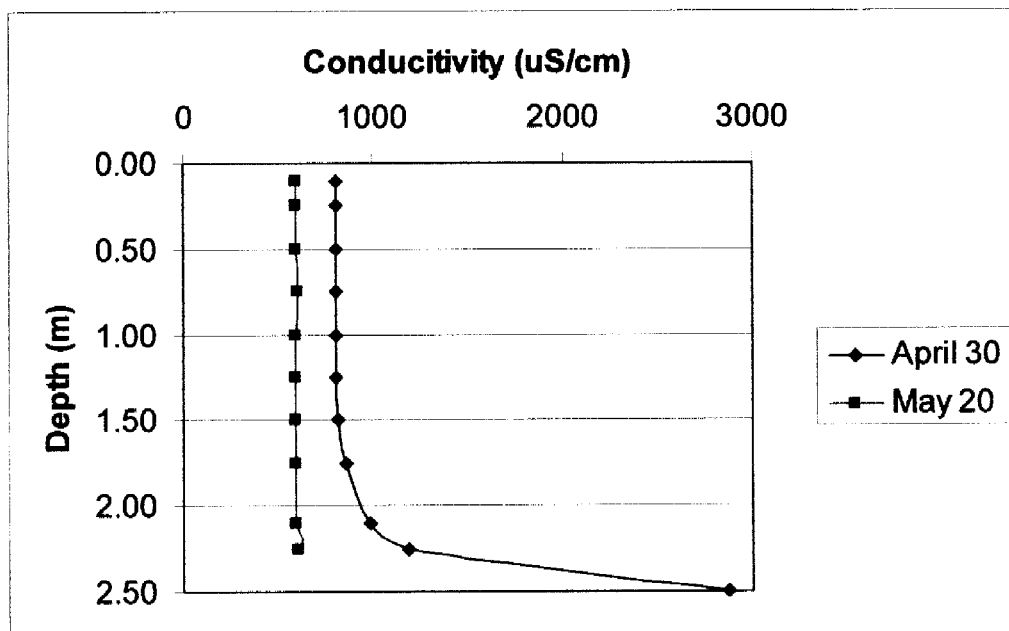


Figure 7. Conductivity (uS/cm). Note different scaling of axes.

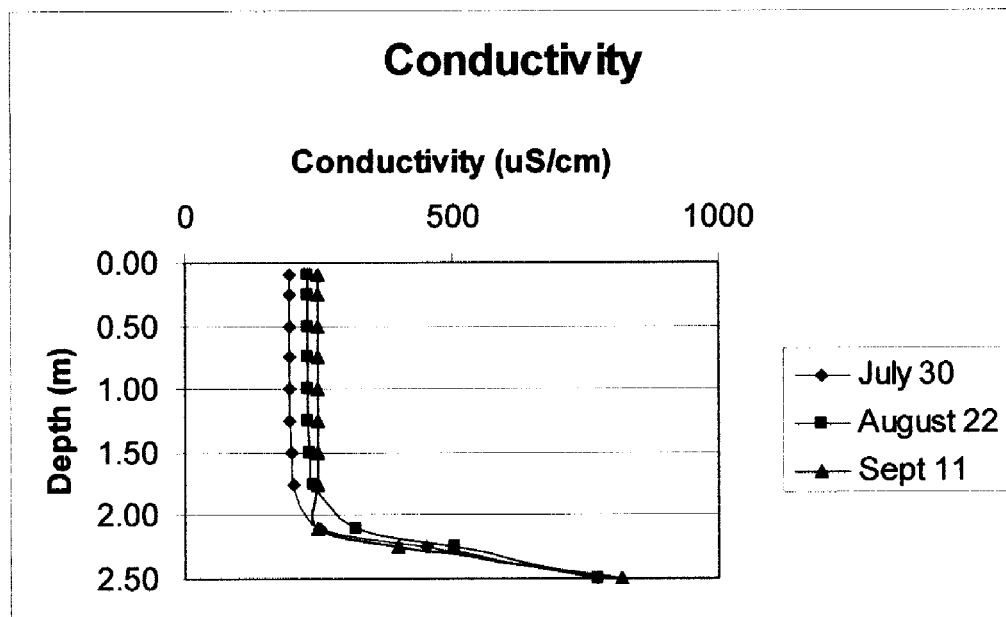
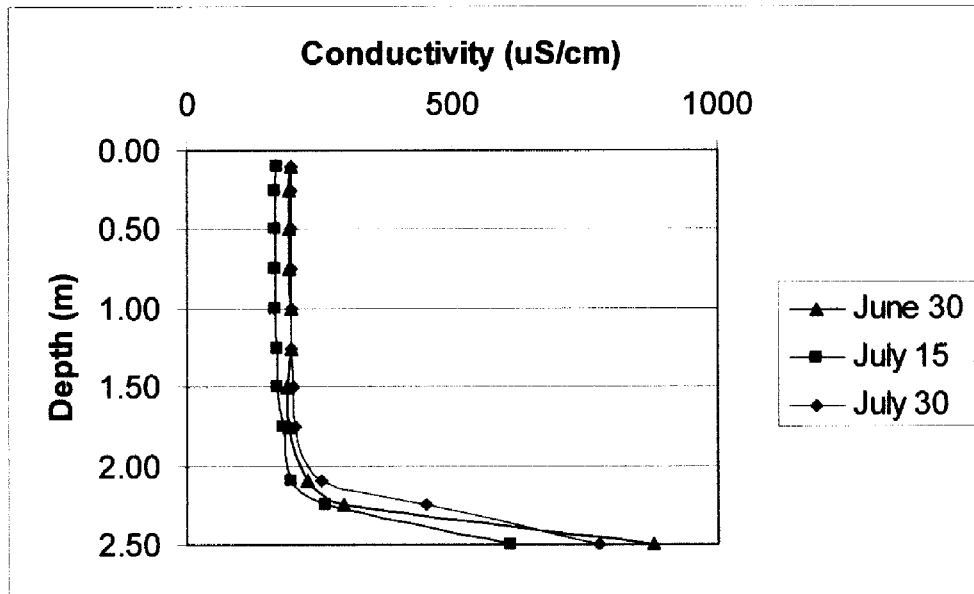


Figure 7 (Cont).

Light Parameters

The transparency of the water column was measured using Secchi depth. The water was very clear in April with a Secchi depth of 141 cm then decreased to 48 cm in May (Figure 8). In early June values were 45-60 cm. Then a major increase occurred on June 30 at 81 cm. Values decreased in July, then peaked again in August with an observed depth of 94 cm. Secchi depth decreased in September to 59 cm. Wetzel (1983) suggests that net photosynthesis occurs to a depth of approximately 1% of surface light, corresponding to 2.7 times the Secchi depth. According to these values net photosynthesis in Pond P occurs to a depth of about 1-2 m.

Turbidity is also an indication of water clarity, measuring the degree of light scattering properties in the water. April turbidity was very low at all depths, consistent with high Secchi depth. Average turbidity levels rose from 7.8 in April to 26.2 in May as Secchi depth decreased markedly (Figure 9). Values decreased in June then peaked on July 15 at 36.4. Turbidity continued to decrease throughout late July and August. September exhibited increased average turbidity values at 33.4. Peaks in turbidity observed at 1.0 m on June 3 and July 15 corresponded with maxima in Chl *a* values on those dates. Elevated values at 2.5 m may reflect suspension of sediments during sampling or accumulation of flocculent sediments.

Light attenuation coefficient is another method for measuring the transparency of water. Lower (more negative) values indicate more light extinction and higher (less negative) values indicate more transparent water. These readings were successfully recalculated on six of the nine sampling dates (Figure 10). The values obtained were consistent with the range of Secchi depths observed.

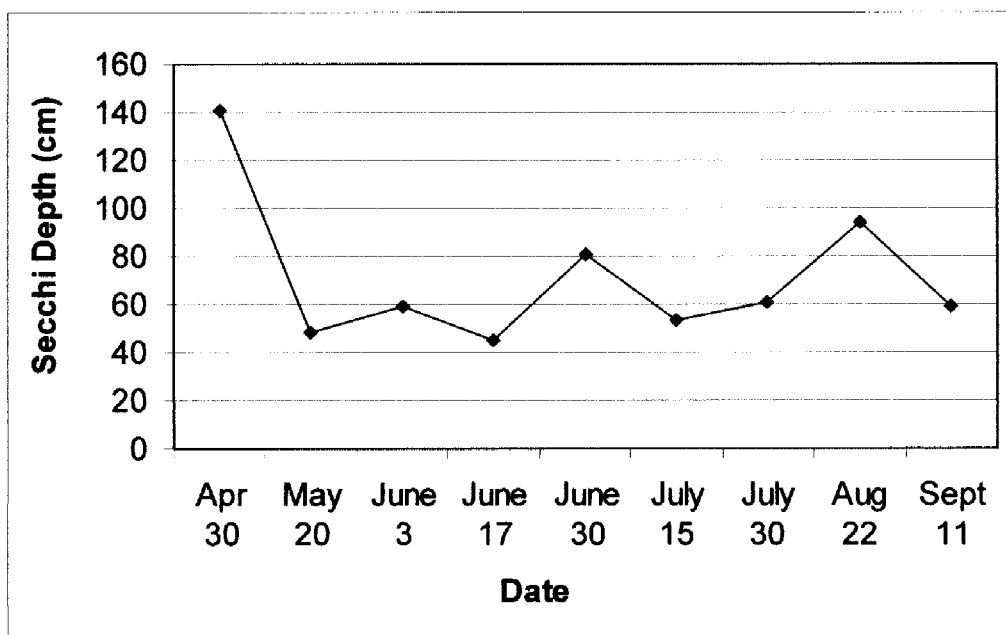


Figure 8. Secchi Disk Depth (cm)

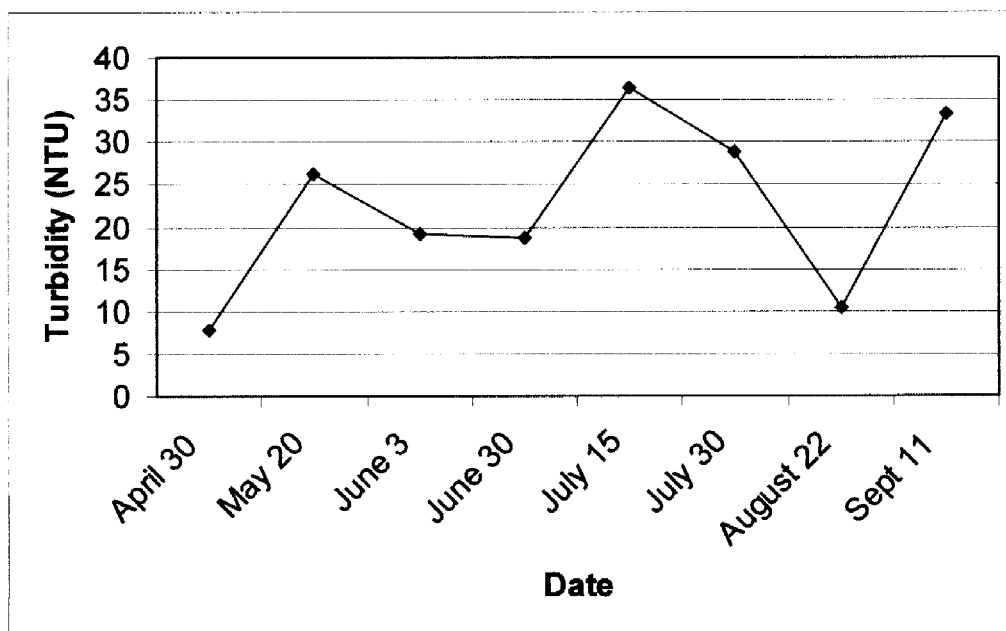


Figure 9. Turbidity (NTU)

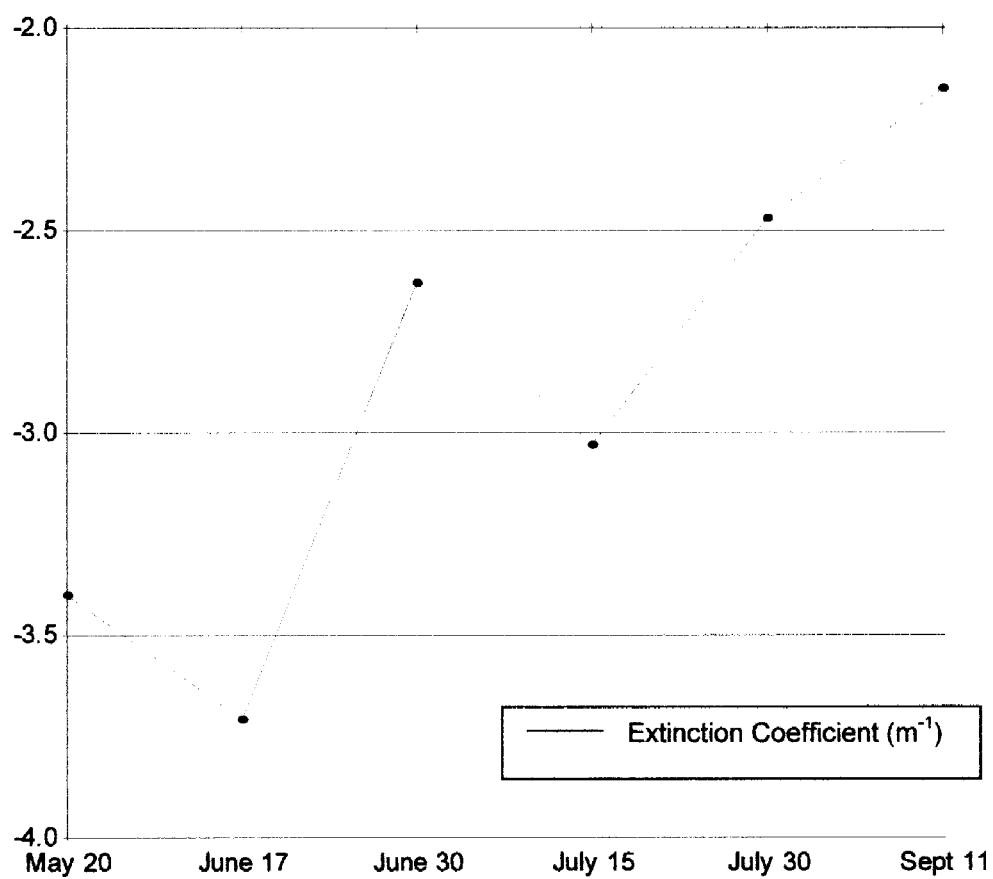


Figure 10. Light Extinction Coefficient (m^{-1})

Suspended Solids

Total suspended solids (TSS) is a measure of the particulate material in the water column. The particulate matter may include suspended sediments, phytoplankton cells, detritus, or inorganics. Average TSS values increased from 10 mg/L to 24 mg/L in mid July . Values began to decrease in late July and continued through September (Figure 11). Total suspended solids values were not consistent with depth, fluctuating throughout the water column. On most dates values peaked around 1.0 m and 2.5 m. These peaks are likely due to phytoplankton suspended in the water column and settling near the bottom.

Volatile Suspended Solids (VSS) is a measure of the amount of particulate organic matter in the water. A similar seasonal pattern exhibited in TSS values was also seen in VSS values. Average VSS values increased from 4 mg/L to 23 mg/L in July (Figure 12). Values began to decrease in late July and continued through September. Uniformity throughout the water column was also absent in VSS.

Nutrients

Ammonia nitrogen was evenly distributed with depth at 0.1-0.2 mg/L in April and May (Figure 13). In June and July, values were generally negligible in surface waters, but increased over the period near the bottom. A change was observed by August with values below the detection limit throughout the water column. In September ammonia nitrogen was again detected in bottom waters.

Nitrate values tended to decrease at all depths as the year progressed. In April they were 1-1.5 mg/L at surface and bottom, and by September they were below the detection limit at all depths except the bottom (Figure 14). This decline can partially be

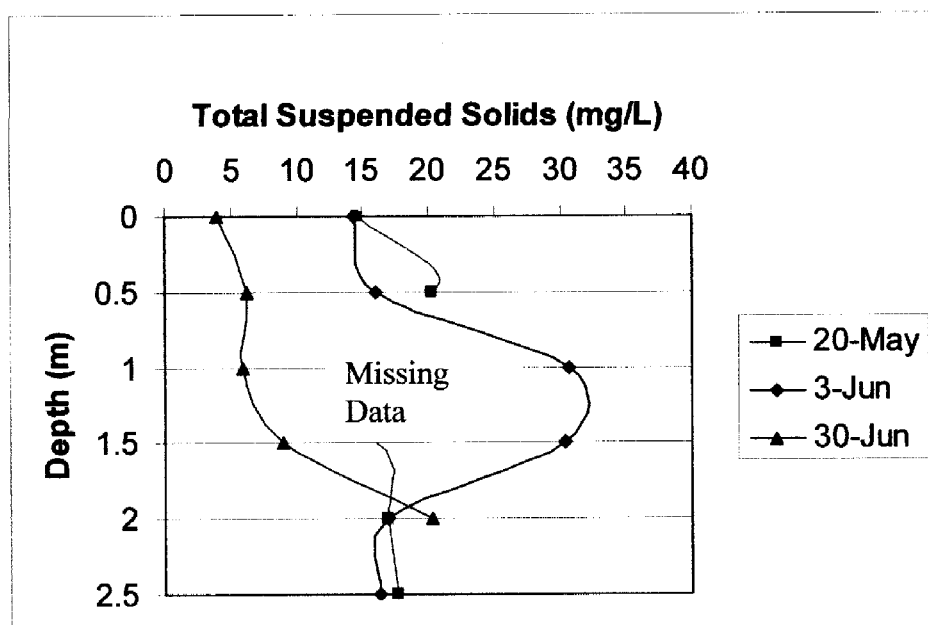
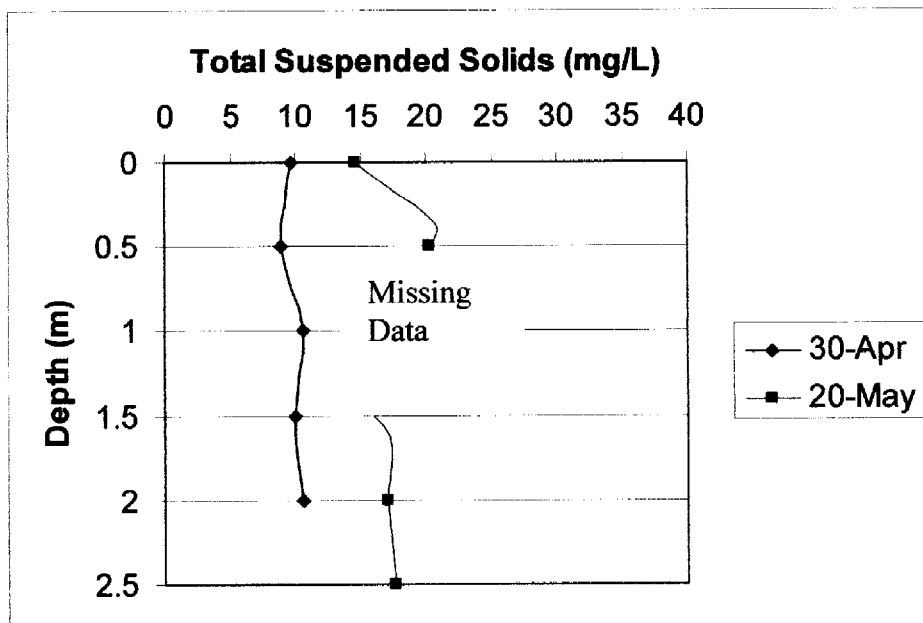


Figure 11. Total Suspended Solids (mg/L)

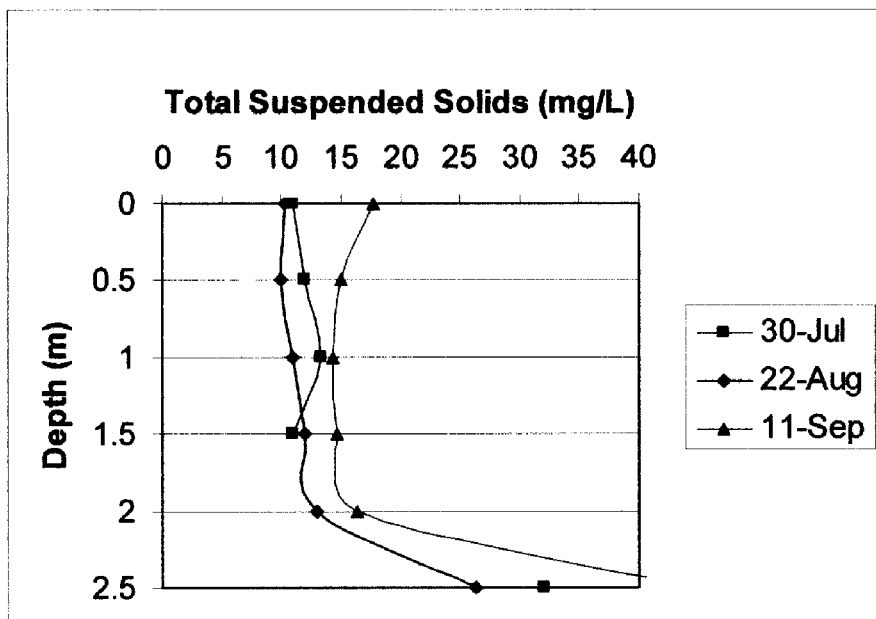
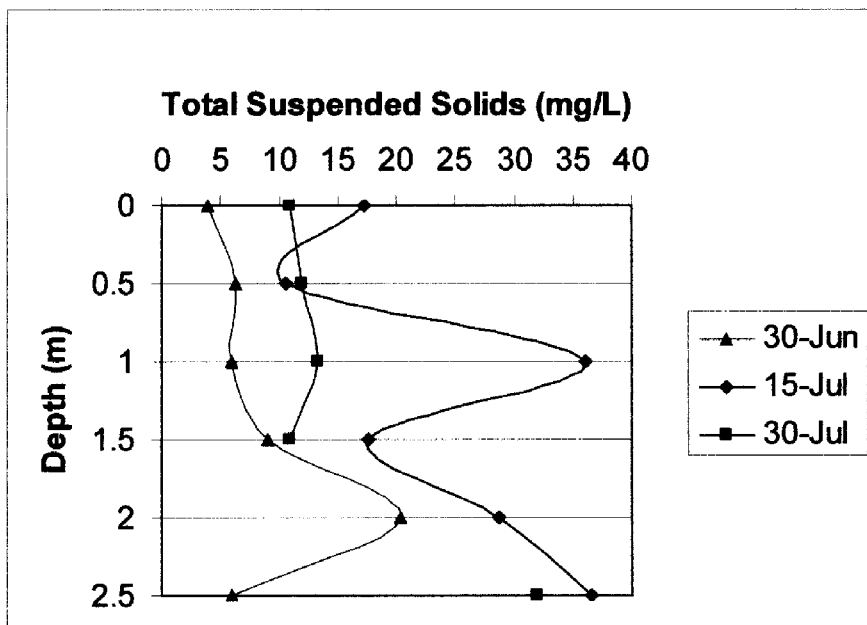


Figure 11. (Cont).

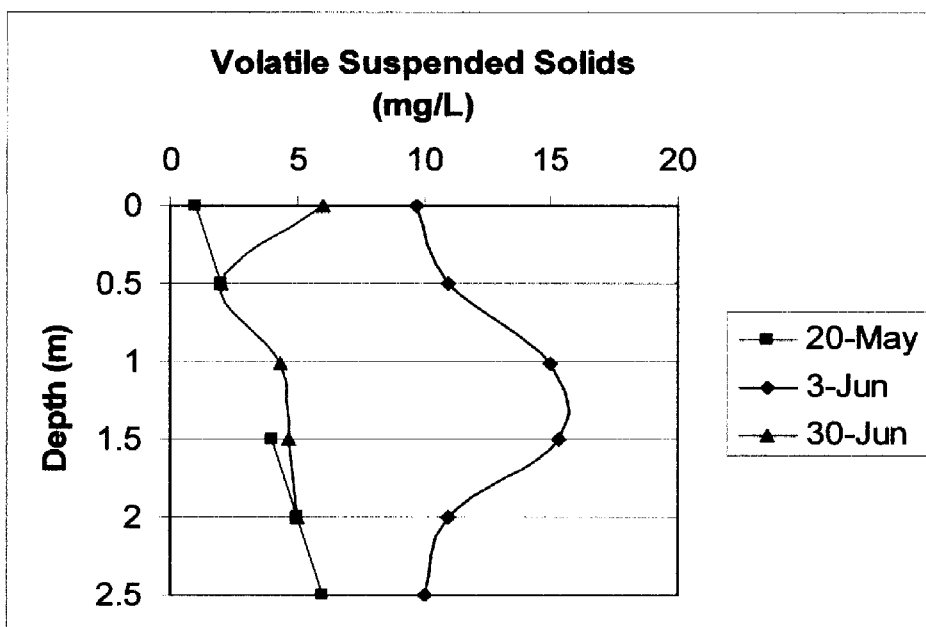
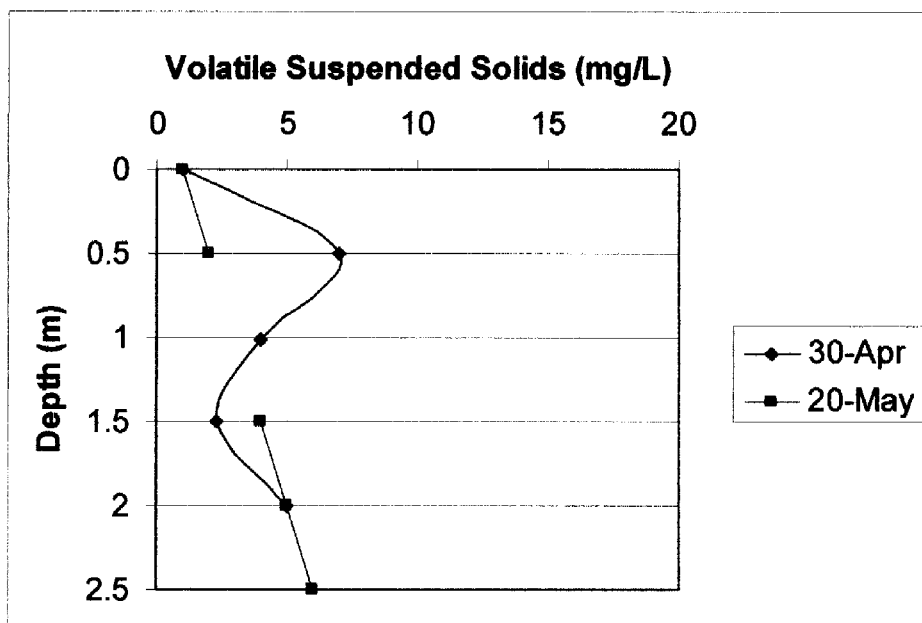


Figure 12. Volatile Suspended Solids (mg/L).

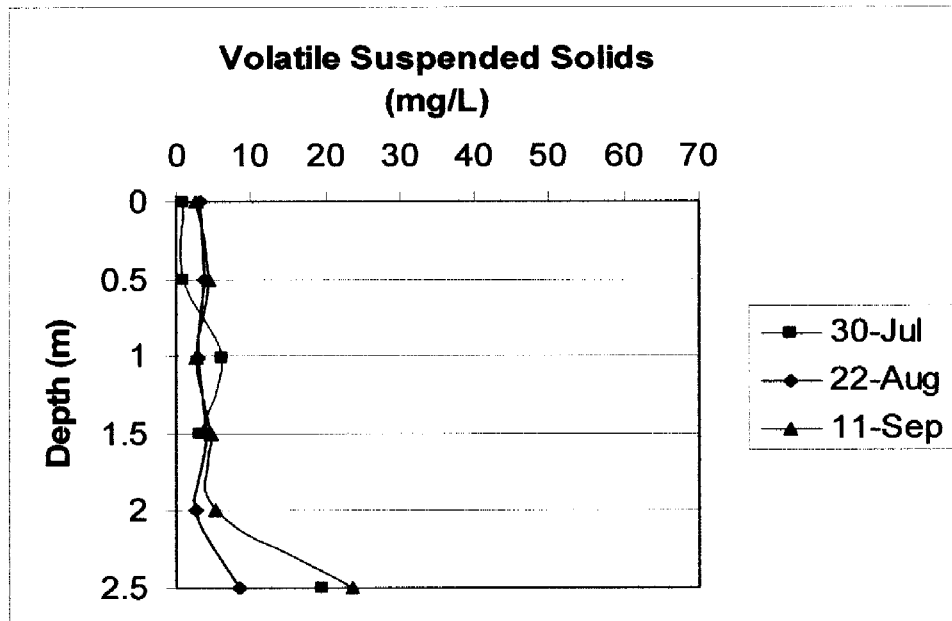
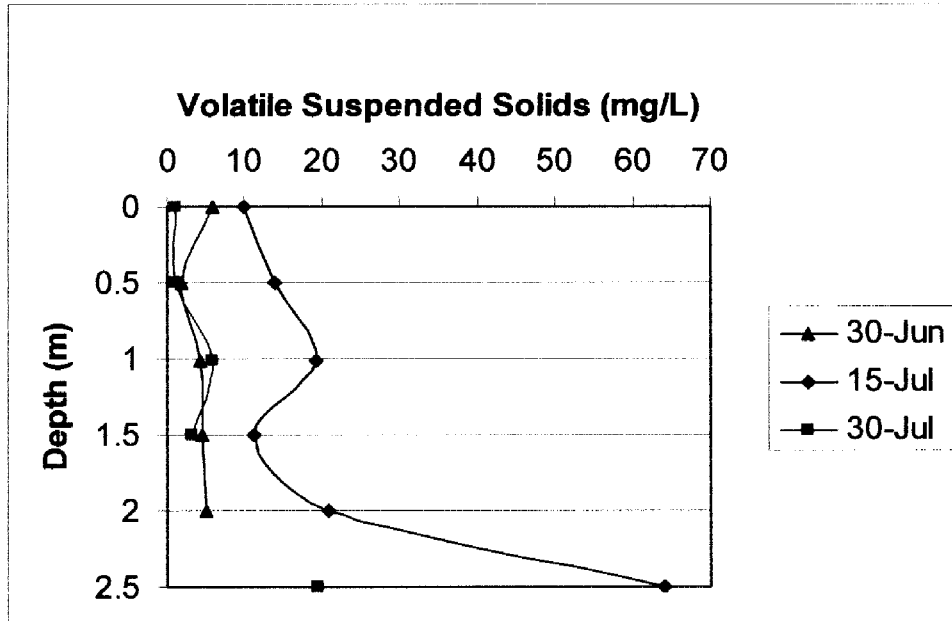


Figure 12. (Cont). Note different scaling of axes.

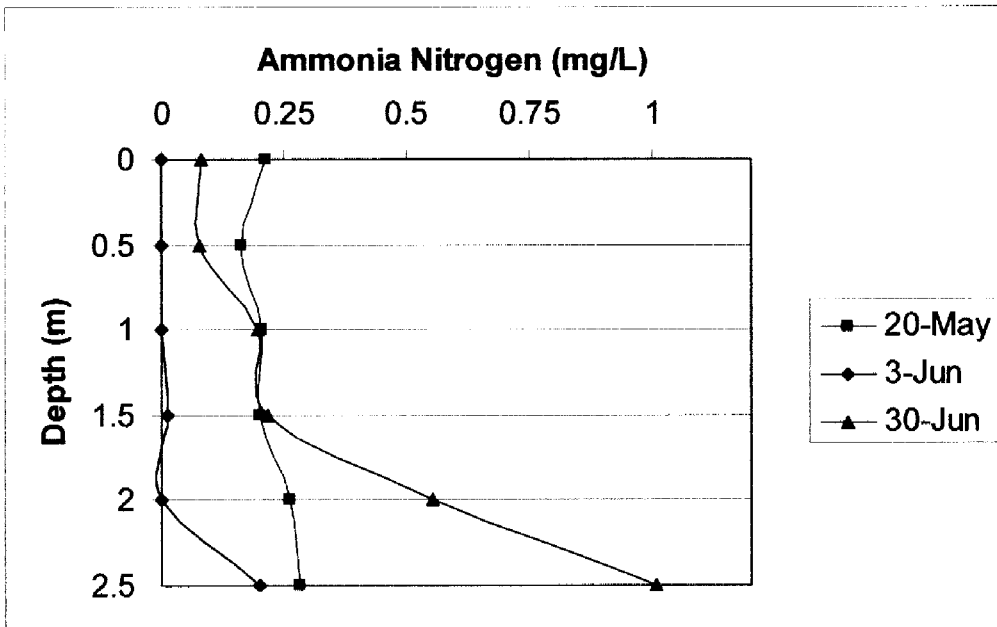
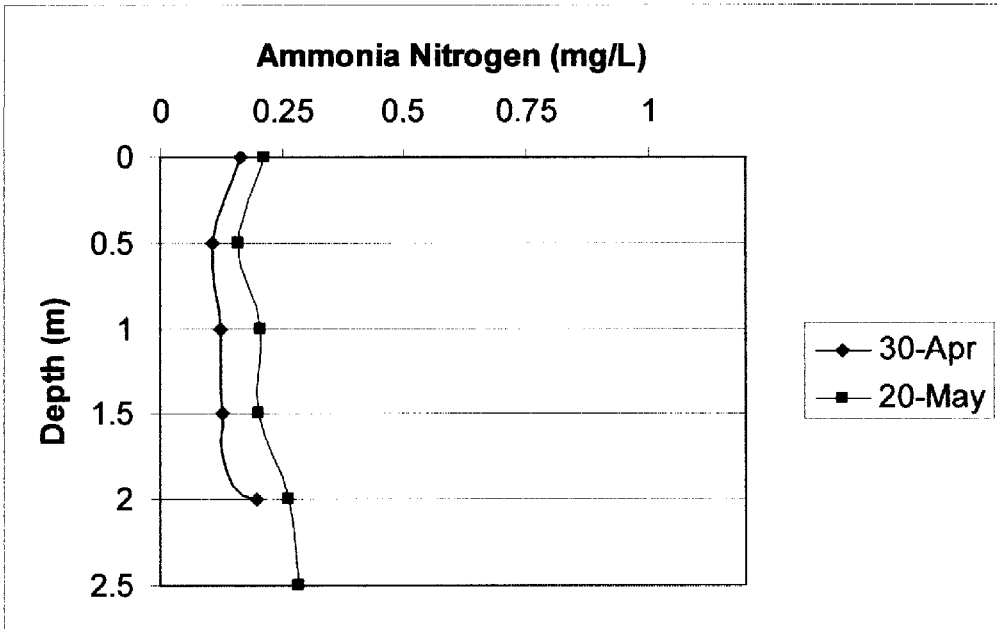


Figure 13. Ammonia Nitrogen (mg/L)

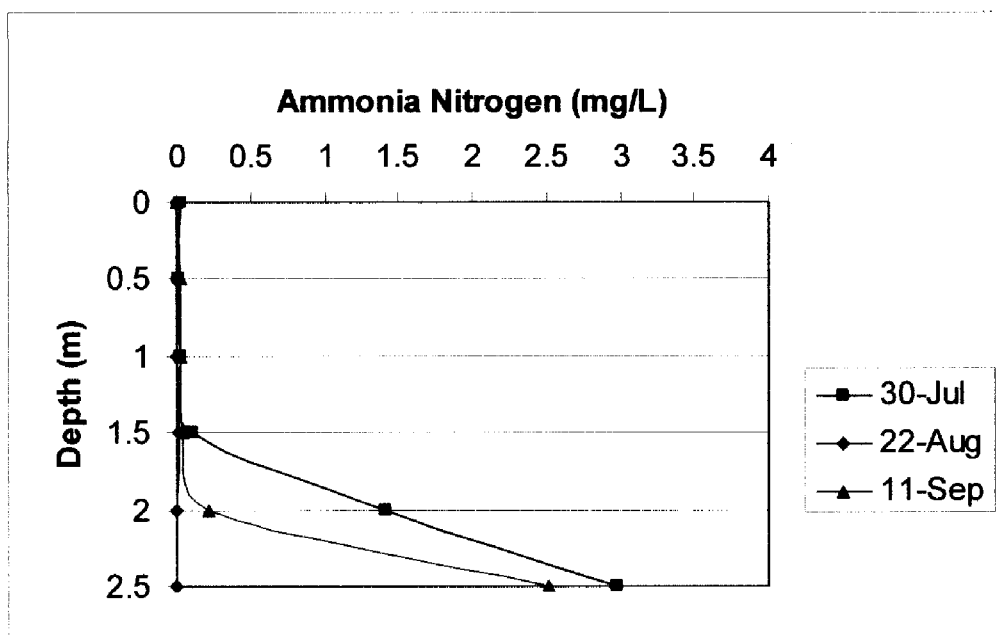
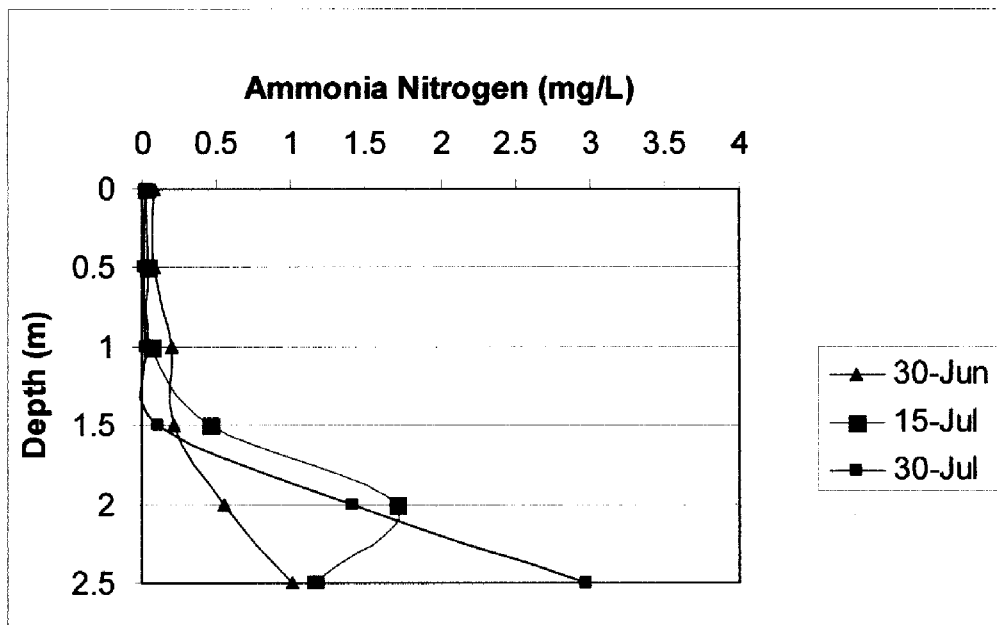


Figure 13 (Cont). Note different scaling of axes.

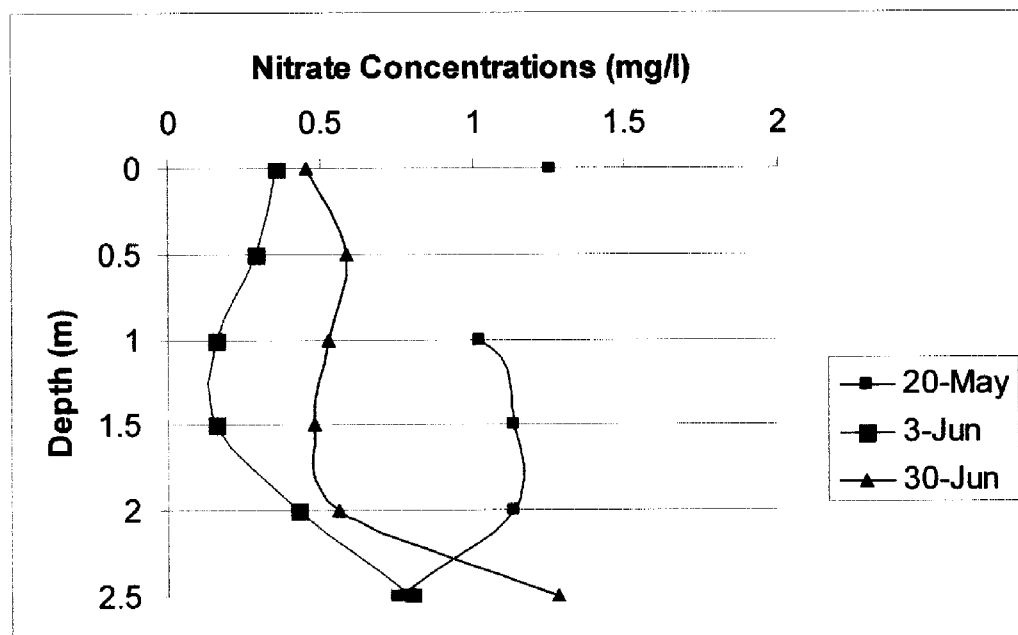
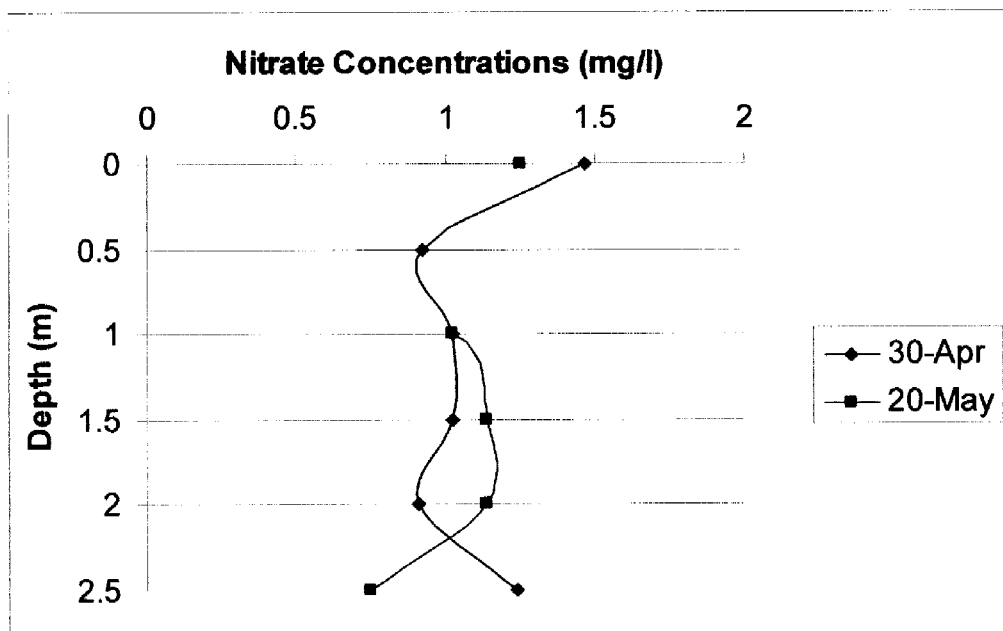


Figure 14. Nitrate Nitrogen (mg/L)

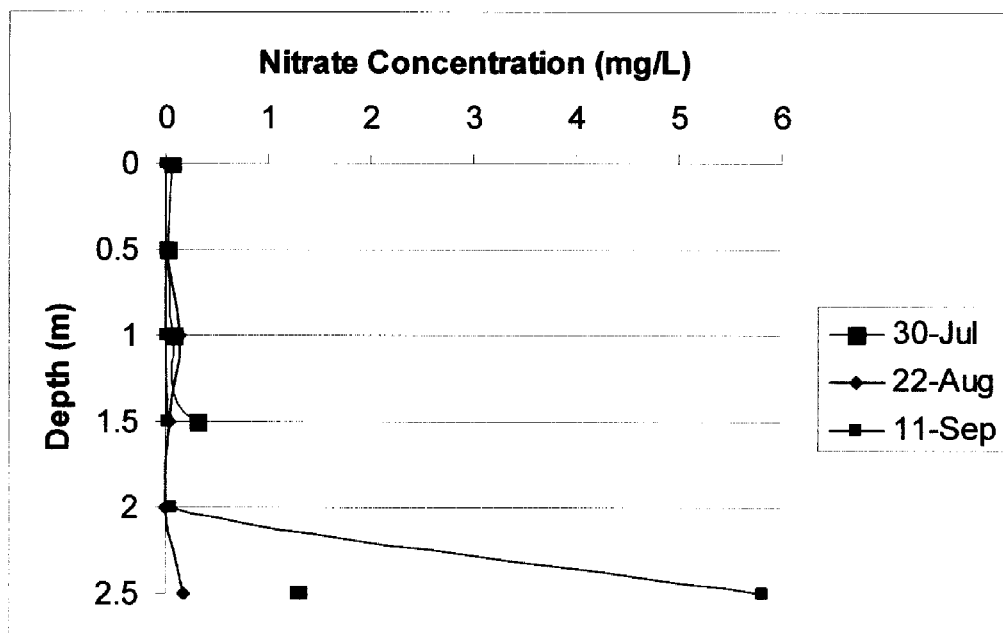
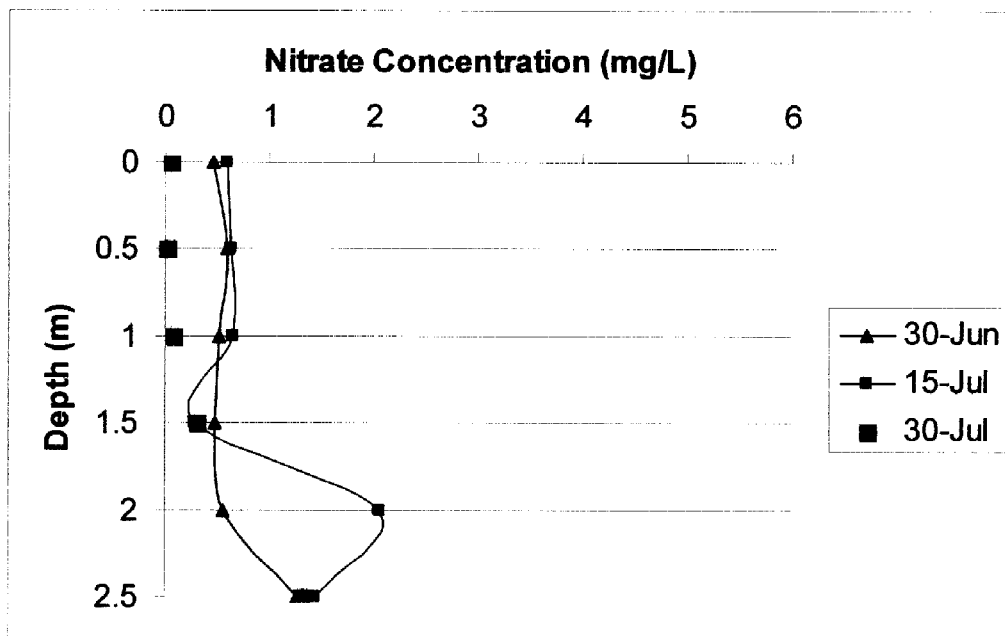


Figure 14 (Cont). Note different scaling of axes.

explained by the uptake of nitrogen by phytoplankton during the growing season. Higher values seen at the bottom in July may be attributed to decomposition of organic matter or bacterial nitrification.

Soluble reactive phosphorus concentrations in April which read 67.3 ug/L at 1.0 m were depleted to 4.5ug/L at 1.0 m in May. Soluble reactive phosphorus levels at the surface continued to decline, resulting in undetectable levels on July 30 at 1.0 m (Figure 15). This is most likely due to the uptake of phosphorus by algae. During late June and July elevated SRP near the bottom suggested sediment release. In August and September values were undetectable at all depths.

Total phosphorus throughout the water column generally increased from May through July and decreased slightly in August and September (Figure 16). Surface values ranged from 23 µg/L to 89 µg/L in September. Bottom levels increased from 42 µg/L to over 500 µg/L in July. Elevated bottom levels may be attributed to sediment release.

Chlorophyll

Chlorophyll *a* (Chl *a*) is a measure of the concentration of phytoplankton algae in the water column. Chl *a* values were low in April and May, increased dramatically through July, and then declined in August (Figure 17). Chl *a* concentrations showed a distinct seasonal pattern, with values less than 5 ug/L during April increasing to greater than 100 µg/L in early June and mid July. Chl *a* values on May 20th were very consistent with depth, showing the effects of a mixing event of the complete water column which occurred just prior to sampling. During the growing season Chl. *a* often exhibited a mid-depth peak between 1-1.5 m and then decreased below the photic zone. Beginning in late

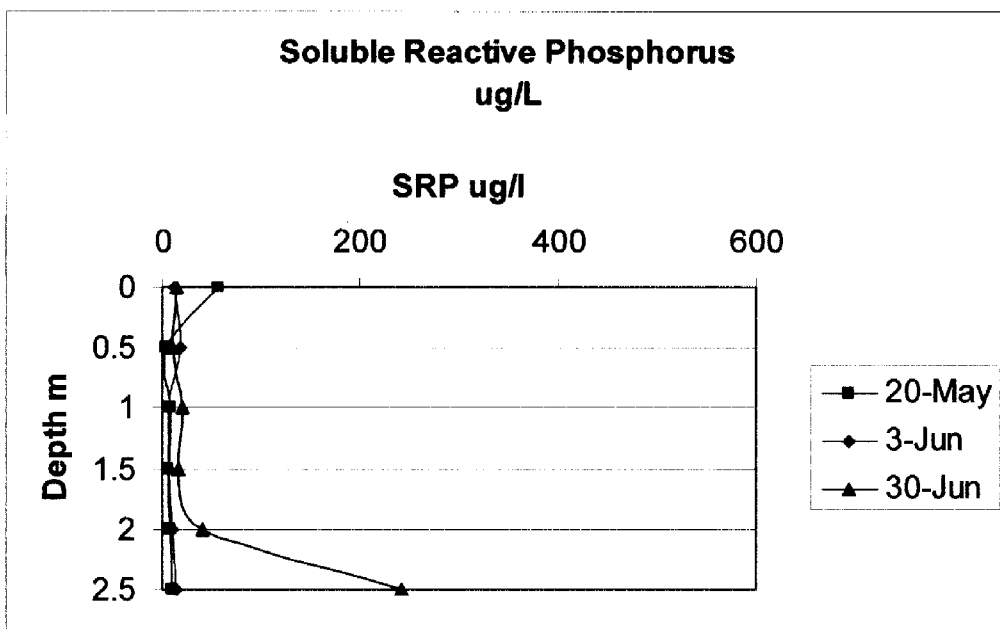
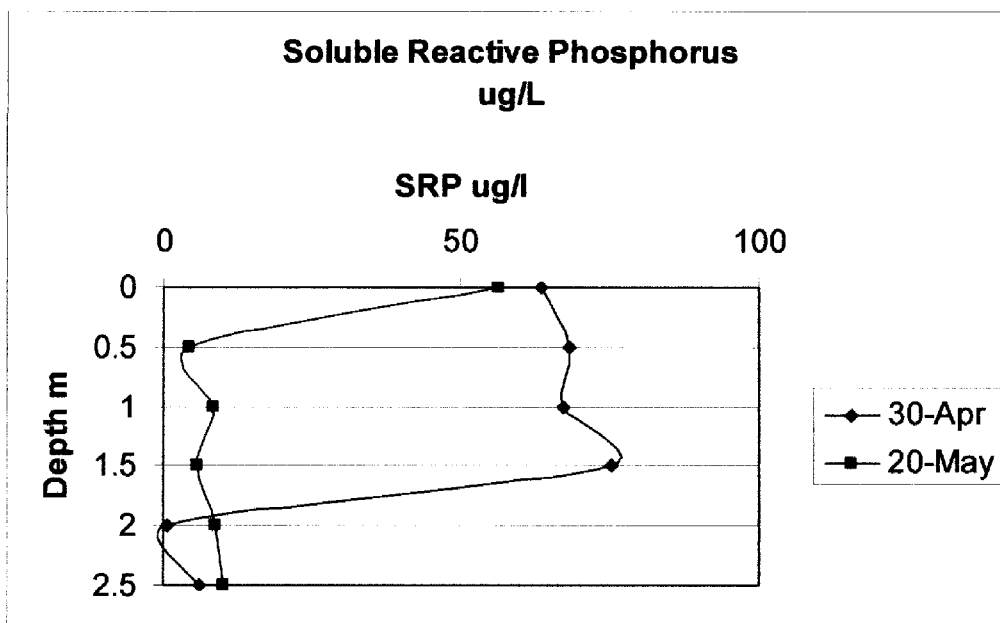


Figure 15. Soluble Reactive Phosphorus (mg/L)

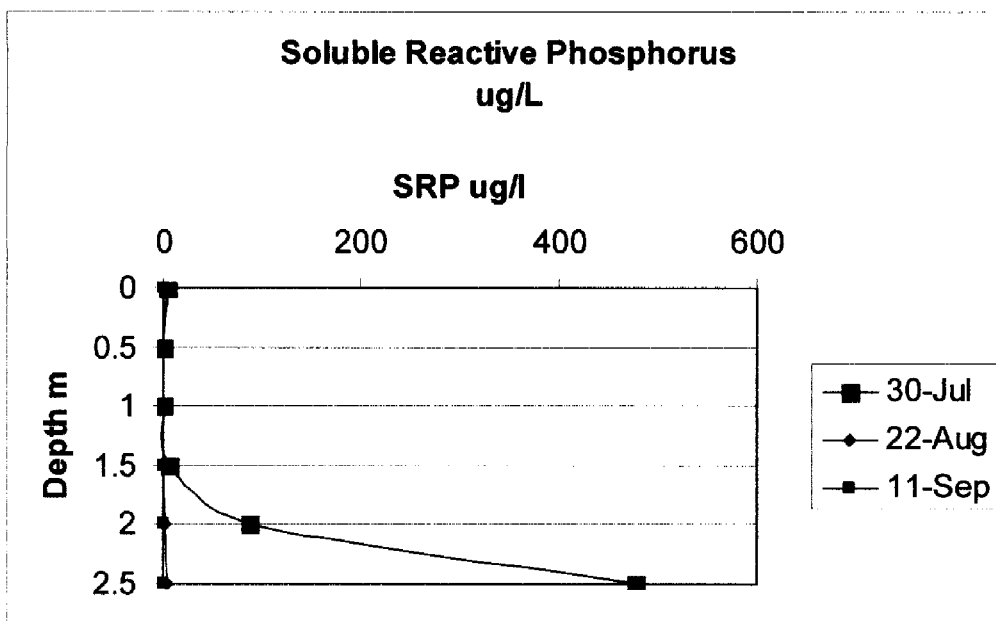
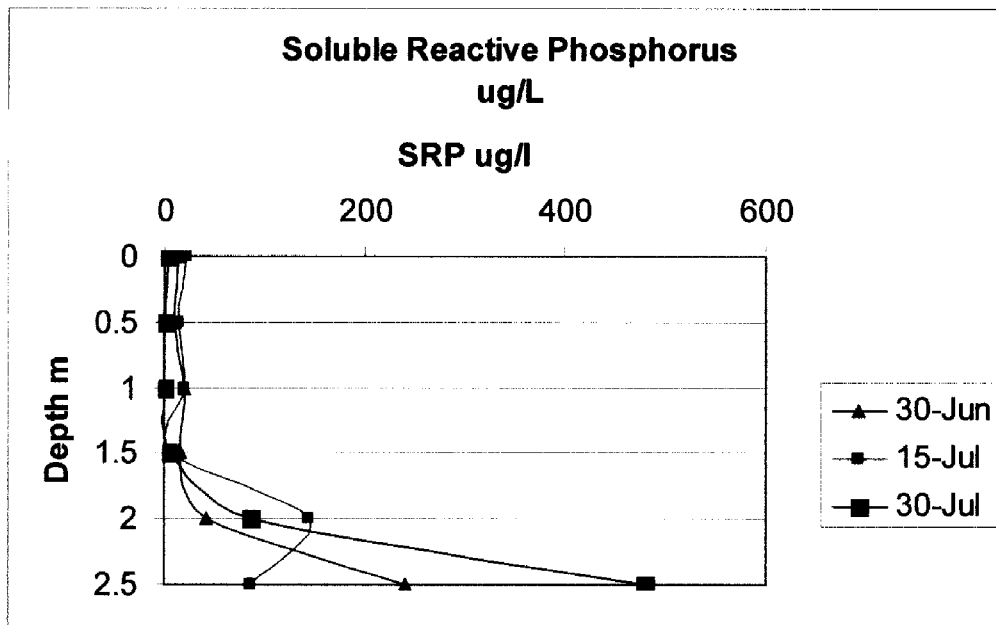


Figure 15 (Cont).

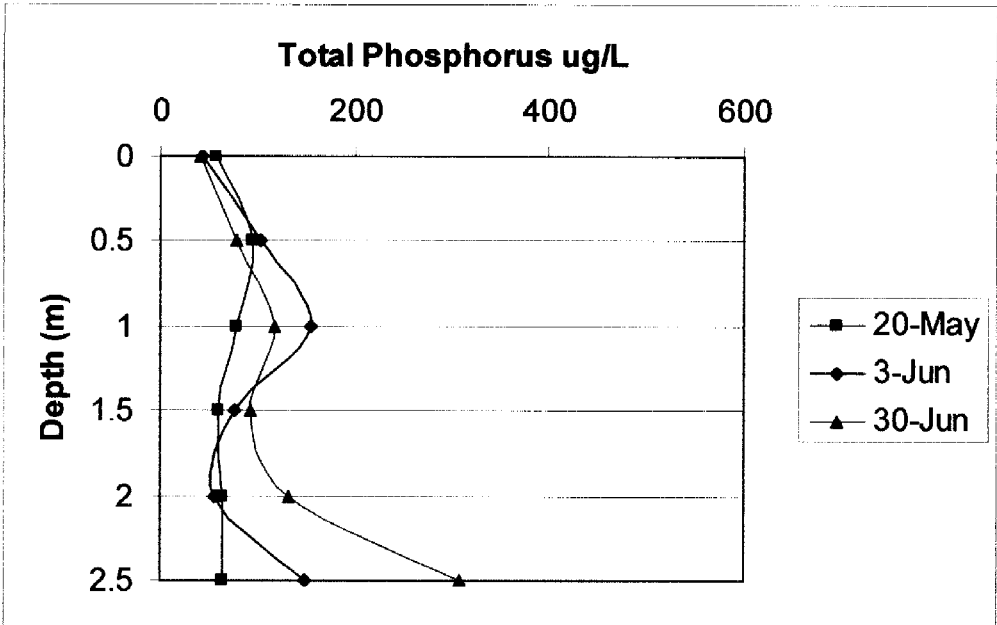
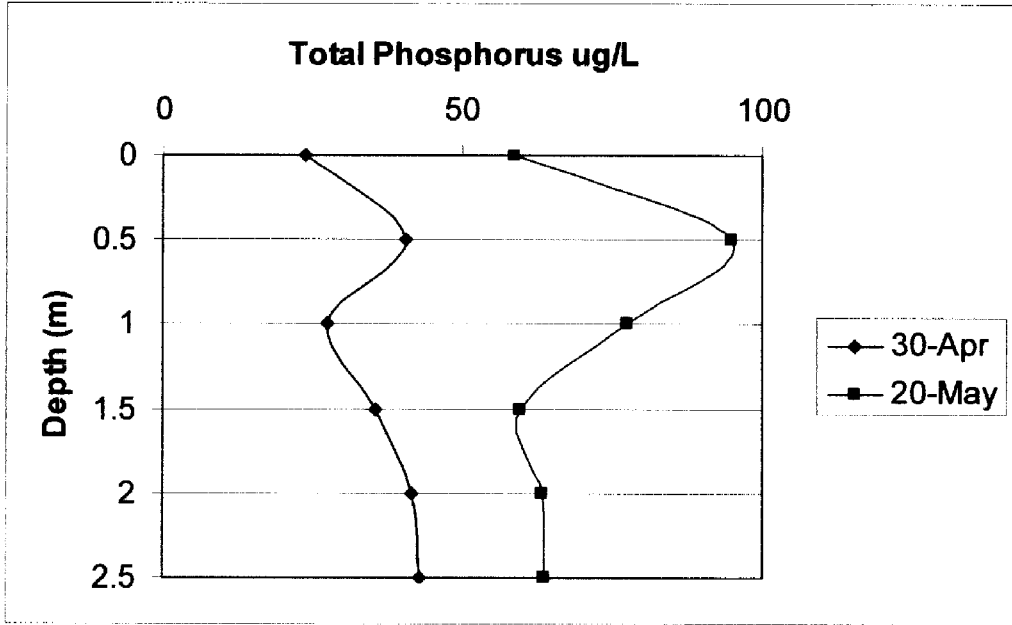


Figure 16. Total Phosphorus (ug/L). Note different scaling of axes.

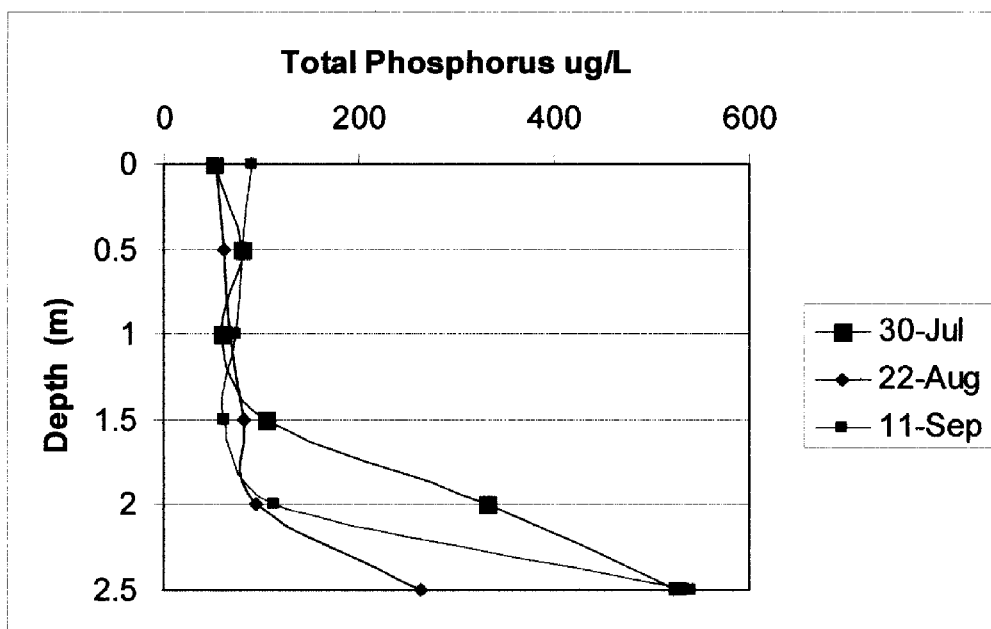
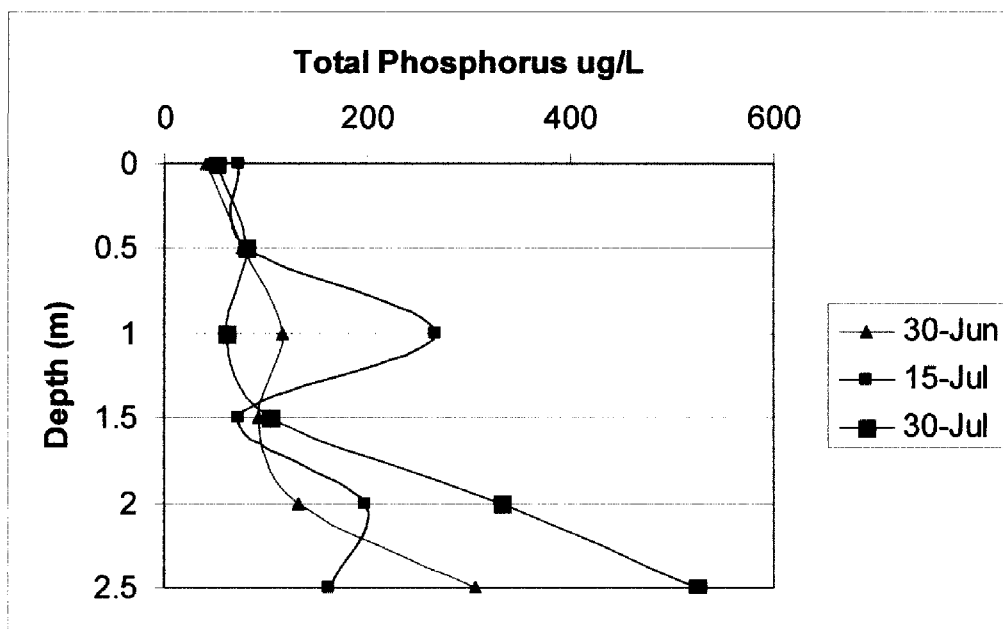


Figure 16. (Cont)

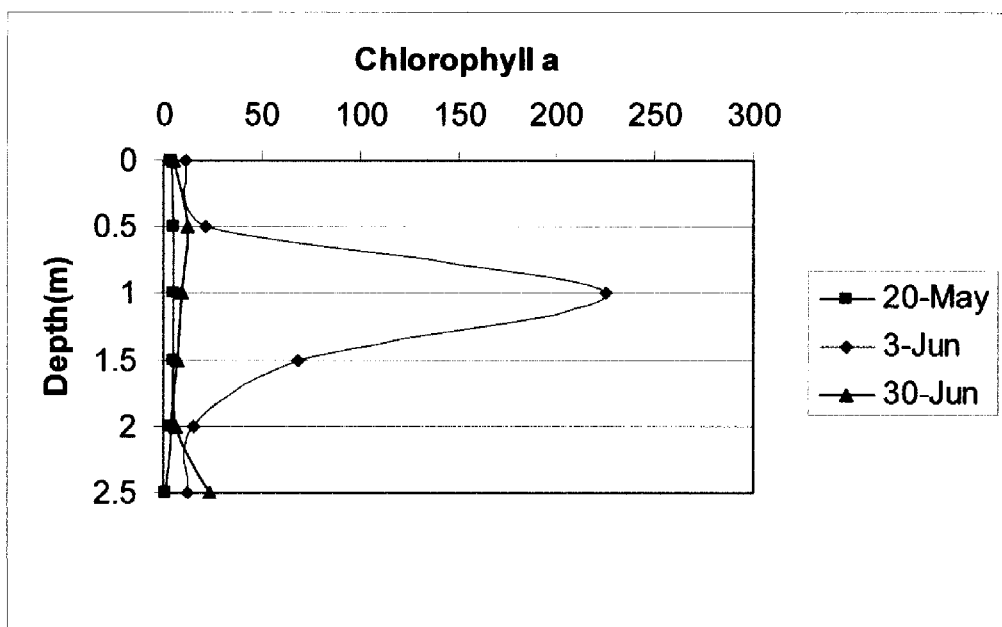
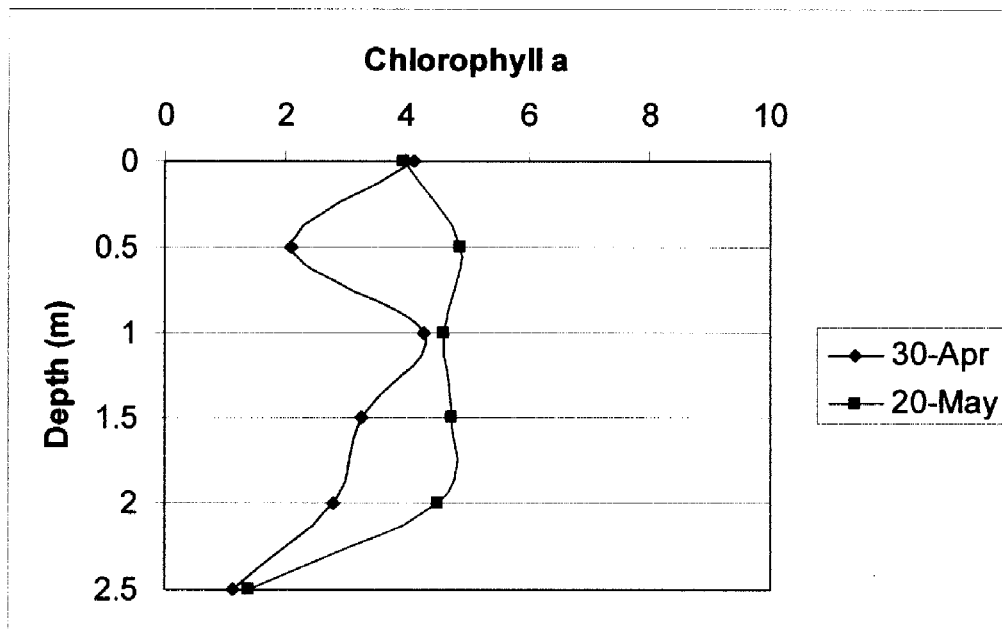


Figure 17. Chlorophyll *a* (ug/L). Note different scaling axes.

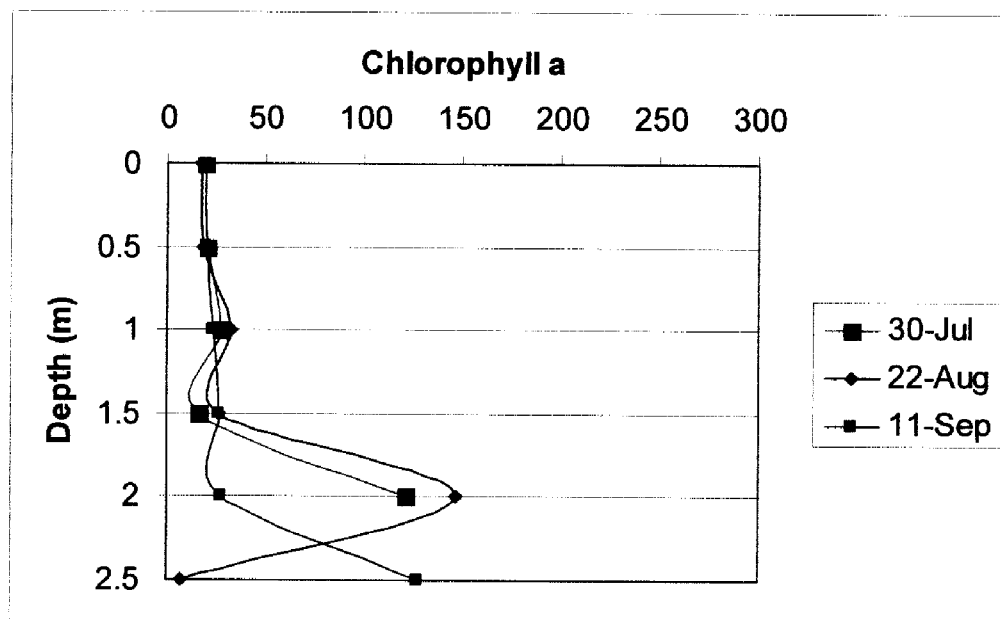
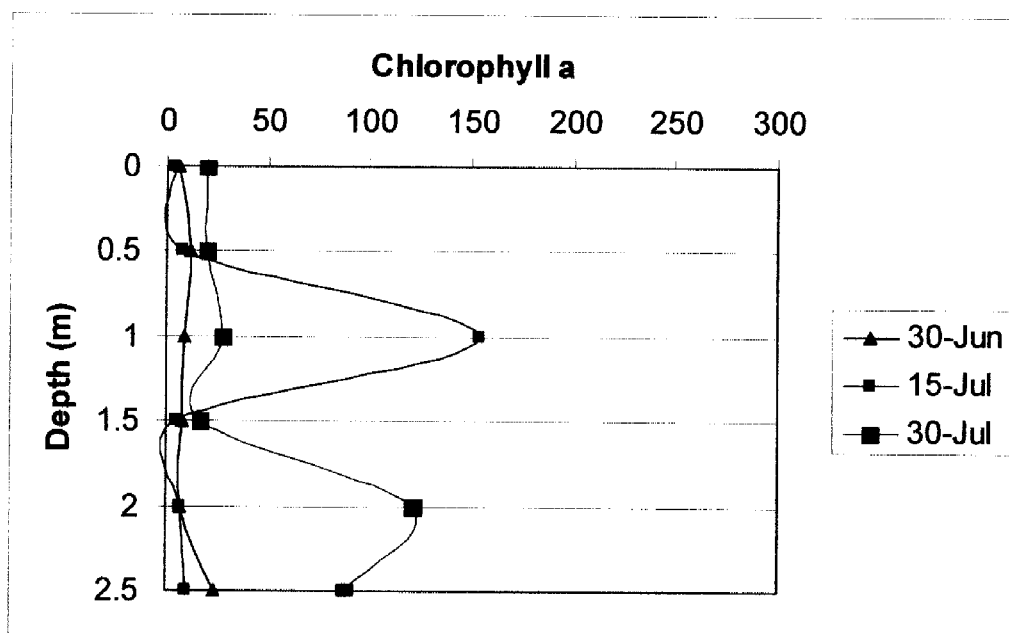


Figure 17. (Cont)

July, Chl. *a* levels remained relatively constant near the surface and began to increase in the bottom waters perhaps due to settling.

Continuous Temperature Profiles

Temperature data was also collected by HOBO temperature loggers. The complete Hobo data set is plotted in Appendix A. The Hobo data allow us to determine the detailed temperature regime at each depth. Temperature is used here as a surrogate for density and the assumption is that two layers that are the same temperature are mixing. By comparing the regime between depths we can ascertain the extent of mixing within the water column. To illustrate this, the temperature record for each of several depths is compared to the surface record for the months of May and June.

A comparison of the records for 0.1 m and 0.25 m shows that the temperature data are almost identical, that is the lines track each other almost continuously (Figure 18). This type of relationship indicates continuous and complete mixing between the two layers.

A second type of relationship can be observed in a comparison of 0.1 m readings with those from 0.75 m (Figure 19). In this case the deeper waters seem to reflect buffered and lagged response relative to the surface conditions. The surface waters exhibit rather large diurnal fluctuations which are generally not observed at depth. However, the 0.75 m temperature does track multiday changes in surface temperature.

This response can be explained in two ways. First, on some dates (eg. 5/25-5/30, 6/8-6/9) the surface curve dropped to the point of intersecting the 0.75 curve indicating a brief period of mixing. Secondly, on some occasions (ex. 6/11-6/12) temperature rose in the lower layer, even though the curves do not meet completely (Figure 20). In this case

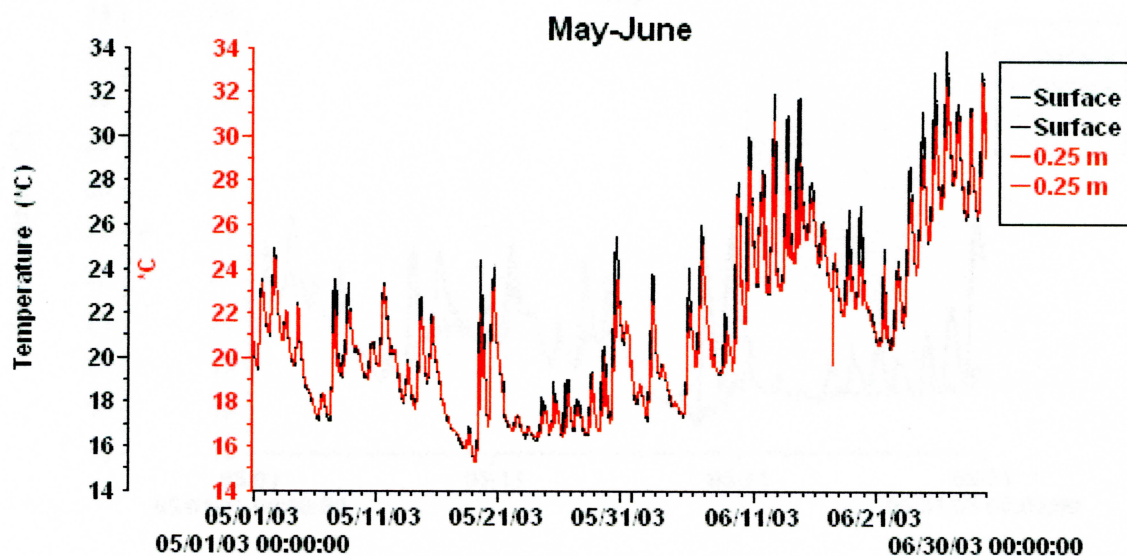


Figure 18. May –June Hobo Data at 0.25 m

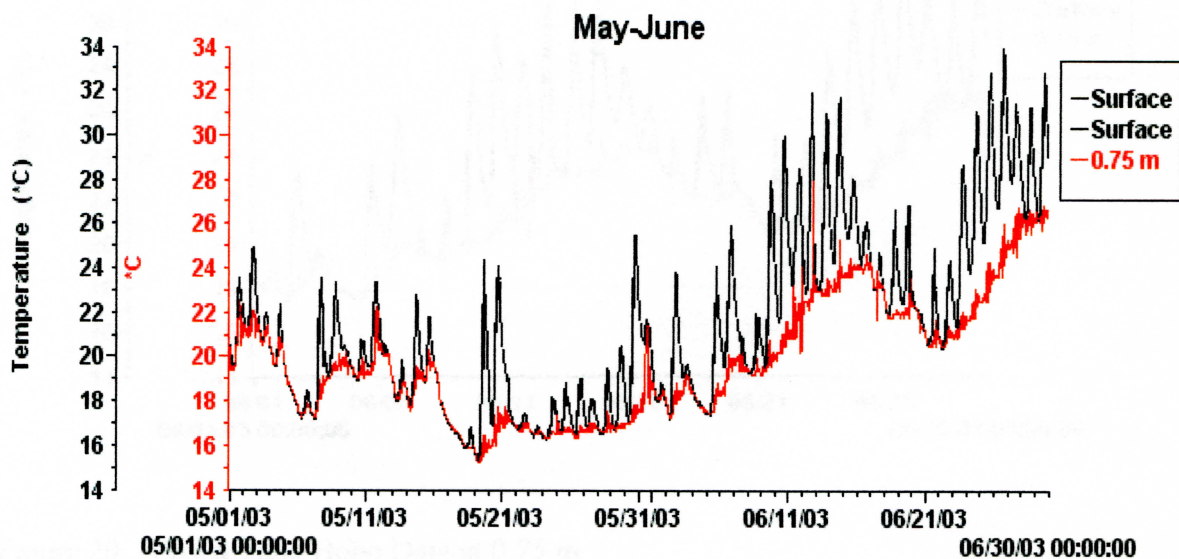


Figure 19. May –June Hobo Data at 0.75 m

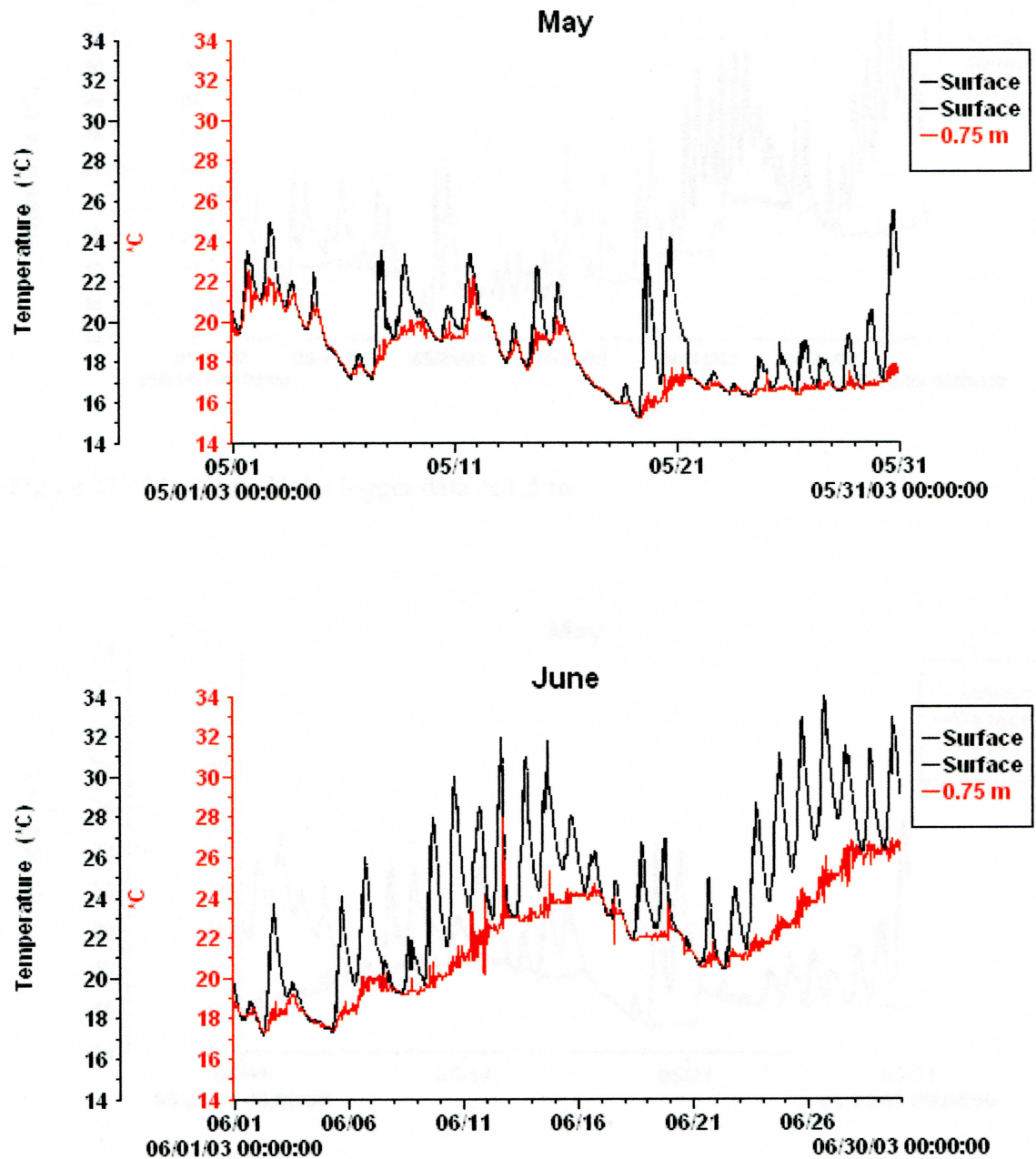


Figure 20. May & June Hobo Data at 0.75 m

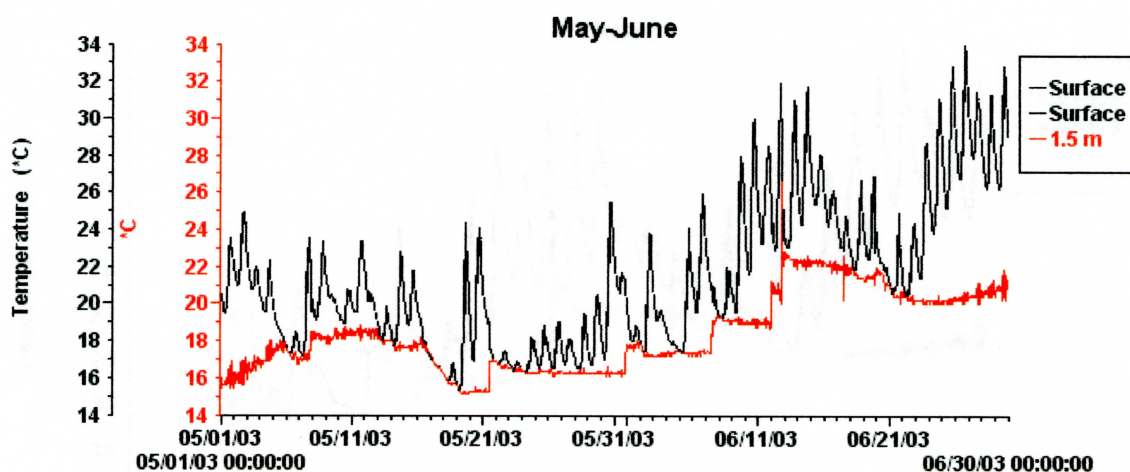


Figure 21. May-June Hobo logger data at 1.5 m

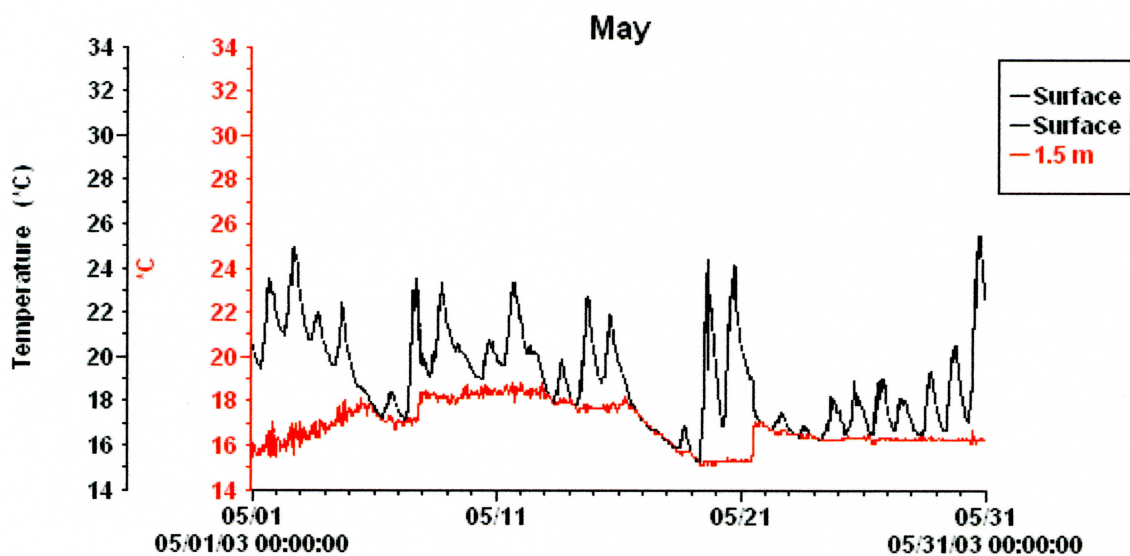


Figure 22. May Hobo logger data at 1.5m

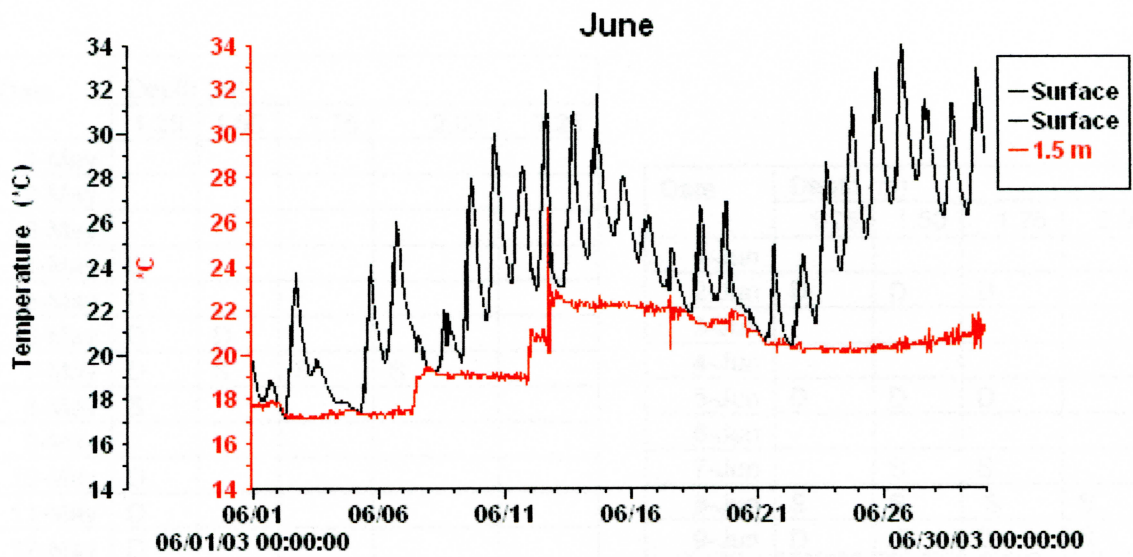


Figure 23. June Hobo logger data at 1.5m

Table 3. Mixing events by date and depth.

Date	Depth (m)				
	1.25	1.50	1.75	2.00	2.25
1-May					
2-May					
3-May					
4-May	D				
5-May	D				
6-May	D	D			
7-May	D	S	S	S	
8-May	S				
9-May					
10-May	D				
11-May	D				
12-May	D				
13-May	D	S			
14-May	D	S	D		
15-May					
16-May	D	D	D	S	S
17-May	D	D	D	S	
18-May	D	D	D	D	
19-May	D	D	D	D	D
20-May					
21-May	S	S	S	S	
22-May	D	D	D	S	
23-May	D	D	D		
24-May	D	D	D		
25-May	D	D			
26-May	D	D			
27-May	D				
28-May	D				
29-May	D	D			
30-May	D				
31-May	S				

Date	Depth (m)				
	1.25	1.50	1.75	2.00	2.25
1-Jun					
2-Jun	D	D	D		
3-Jun					
4-Jun					
5-Jun	D	D	D		
6-Jun					
7-Jun		S	S		
8-Jun	S	S	S	S	S
9-Jun	D	S	D	S	
10-Jun					
11-Jun					
12-Jun	S	S	S		
13-Jun	S	S	S	S	
14-Jun					
15-Jun					
16-Jun					
17-Jun	D				
18-Jun	D				
19-Jun					
20-Jun	D	D	D		
21-Jun	D	D	D		
22-Jun	D	D	D		
23-Jun					
24-Jun					
25-Jun					
26-Jun					
27-Jun					
28-Jun					
29-Jun					
30-Jun					

D = Decline Pattern
S = Step Pattern

Table 3. (Cont)

Date	Depth (m)				
	1.25	1.50	1.75	2.00	2.25
1-Jul					
2-Jul	D	D	D	D	
3-Jul	D	D	D	D	
4-Jul	D				
5-Jul					
6-Jul					
7-Jul	S	S			
8-Jul	S	S			
9-Jul					
10-Jul	D	D	D	D	D
11-Jul	D	D		D	D
12-Jul					
13-Jul					
14-Jul					
15-Jul					
16-Jul					
17-Jul					
18-Jul					
19-Jul					
20-Jul					
21-Jul	S				
22-Jul					
23-Jul		S	S		
24-Jul	D				
25-Jul					
26-Jul					
27-Jul					
28-Jul	D				
29-Jul	D	D	D		
30-Jul					
31-Jul					

Date	Depth (m)				
	1.25	1.50	1.75	2.00	2.25
1-Aug	D	D			
2-Aug	D	D			
3-Aug					
4-Aug					
5-Aug					
6-Aug					
7-Aug					
8-Aug	D				
9-Aug					
10-Aug					
11-Aug					
12-Aug					
13-Aug					
14-Aug					
15-Aug					
16-Aug					
17-Aug					
18-Aug					
19-Aug	D				
20-Aug	D				
21-Aug					
22-Aug					
23-Aug					
24-Aug					
25-Aug					
26-Aug					
27-Aug					
28-Aug					
29-Aug					
30-Aug					
31-Aug					

D = Decline Pattern
S = Step Pattern

Discussion

Thermal stratification had a major impact on the depth distribution of several parameters. Dissolved oxygen was distinctly depth-stratified for much of the season. The oxygen profile formed a clinograde curve, in which the epilimnion became supersaturated, while the hypolimnion became hypoxic. Chlorophyll data reinforces the likelihood that photosynthesis was the factor responsible for high DO concentrations. The onset of hypoxia was seen in mid-June and continued through July. Although the DataSonde Hydrolab data indicated that there was a limited amount of oxygen in the bottom waters (~1 mg/L), the real value may have been 0 (anoxic), because the oxygen sensors are frequently inaccurate in this range.

By September oxygen concentrations had become relatively constant with depth, attributable to a complete mixing of the pond. Studies conducted in 2002 indicated that a clear water column allowed lush growth of an algal mat on the bottom of the pond (Jones, 2002). Active photosynthesis of this mat pumped DO into the bottom waters of the pond in 2002. Low DO concentrations in the bottom waters indicate the absence of such benthic algae during the course of this study.

pH, like dissolved oxygen, is also regulated by the interaction of photosynthesis and respiration. On most sampling dates pH values mirror those of DO, reflecting the balance between photosynthesis and respiration. Surface pH was more variable during the

growing season due to the greater variability in the photosynthetic processes than in the hypolimnion where respiration was more constant.

Nutrient concentrations in the pond reflect inputs and outputs from the pond as well as internal processes resulting from stratification, mixing, algal uptake, and microbial transformations. For the purposes of this discussion inputs and outputs are assumed to be roughly balanced both annually and seasonally. Inputs to the pond occur episodically during periods of stormwater runoff since much of the watershed is paved and served by storm sewers. It is possible that nutrient loading may be higher at certain times such as immediately following fertilizer applications or when geese were active on the lawn areas in the watershed. Base personnel indicated that fertilizer applications were not made to lawn areas in 2003. Also, no information was available on possible groundwater inputs, although these sources were likely minimal for ammonia and phosphorus.

Ammonia nitrogen followed a seasonal pattern with a maximum in May and a decline throughout the remainder of the season. Ammonia nitrogen values in the epilimnion were generally low, at or below the detection limit of 0.02 mg/L. However, in the hypolimnion many readings surpassed the detection limit. Frequently, ammonia levels increased as depth increased. The low values in the surface waters are attributable to uptake by algae. Higher ammonia in bottom waters may relate to active decomposition, release from the sediments, or ammonia creation by reducing bacteria which stripped oxygen from nitrate to use as a terminal electron acceptor in the absence of oxygen.

Nitrate nitrogen values also followed a seasonal pattern with a maximum in May and a decline through the rest of the year. One potential source of nitrate to the pond is atmospheric wet and dry deposition. Although the high values observed during May could be attributable to higher than average precipitation, rainfall was higher during the month of June, when lower values were observed. The seasonal decline in the epilimnion could result from algal uptake. As with ammonia nitrogen, nitrate typically demonstrated an increase with depth. The increase in hypolimnetic values may be caused by sediment release or bacterial nitrification.

Soluble reactive phosphorus values which reached a maximum in April steadily declined resulting in undetectable levels in upper waters during August. Higher values in the upper levels during April and May were consumed rapidly by plankton during June and July, some of which then settled, giving rise to higher accumulations in bottom waters. The increase of SRP accumulation in the lower layers is attributable to active decomposition which released SRP into the water column.

Total phosphorus generally increased with depth throughout the sampling season. Peaks in total phosphorus in the upper waters are due to algal blooms. Algae take up most of the soluble phosphorus and incorporate it into tissue mass. Increased values in bottom waters may be caused by the settling of algae or sediment release.

Total suspended solids, which includes both the inorganic and organic components of suspended solids, was higher than volatile suspended solids, the organic component of suspended solids. This indicates that the suspended solids in the pond are a mixture of inorganic solids such as sediment and clay particles as well as organic solids such as phytoplankton and detritus.

TSS peaks observed in early June and mid July can be attributed to greater than average amounts of rainfall during this time which may have increased inorganic solids input from the watershed.

Chl *a* showed a distinct seasonal pattern in the upper waters with values below 5 ug/L in April and May increasing to approximately 200 ug/L in early June. A depth pattern could also be seen as the algae began to settle. A peak of 225 ug/L at 1.0 m in early-June declined in late June possibly due to a mixing event and low light levels during mid-June. Another peak is seen in mid-July at 1.0 m, and then seen at 2.0 m in late-July, and at 2.5 m in August. The downward progression of this peak could be due to settling of the algae throughout the growing season.

Continuous temperature profiles indicate that the surface and 0.25 layers are constantly mixing. The surface waters also demonstrated large diurnal fluctuations which are not observed in deeper waters. The deeper waters to generated two patterns of mixing with surface waters.

One pattern of mixing observed in deeper water was cooling of surface waters until they reached the temperature of a given lower layer. Once the temperatures of the two layers were relatively equal, the densities are also equal and it is assumed that the two layers are mixing. This pattern was most apparent at the middle depths.

Another pattern of mixing occurred when the bottom water temperature increased abruptly to the level of mid-depth or surface water. This was often preceded by some degree of cooling of mid-depth and surface water. The abrupt change in water temperature at depth was interpreted as a forced mixing event by wind shear. This was observed more commonly in bottom water.

During the course of the study the frequency of mixing events decreased with depth. During the month of May, twenty-five mixing events occurred at 1.25 m. At 1.75 m mixing took place on ten occasions and at 2.25 m mixing was only observed on two occasions.

For the purposes of this study, water quality sampling occurred approximately every two weeks. One goal of the study was to relate mixing events to change in water quality profiles. Results indicate that within the two week period stratification and associated water quality conditions often had returned to pre-mixing levels. However, some sampling dates occurred just after a mixing event and can be related to pre-mix conditions. The mixing event recorded on May 16-19 which was followed by sampling on May 20 appears to present an opportunity to examine such relationships. DO, pH, and conductivity exhibited marked stratification on April 30 especially in the lower layers. The degree of stratification was much less on May 20 following the mixing event a few days earlier. For example, conductivity was almost 50% higher at 2.25 m compared to the surface on April 30 whereas on May 20 conductivity at these two depths was virtually identical. Some parameters such as nutrients were not stratified on either date, so effects of mixing could not be determined.

Conclusions

The nutrient data reveal that the pond is generally eutrophic. The pond was stratified in April when the study began. By mid-September seasonal stratification had ended. Seasonal stratification coupled with significant nutrient concentrations resulted in eutrophic conditions including severe oxygen depletion in the lower layers of the pond. Hypoxia set up in mid-June and remained throughout the summer ending in the fall.

The pond was found to be polymictic, mixed completely on approximately five occasions during the course of the study. While this was not the typical diurnal mixing observed in some tropical lakes, it did qualify the pond as polymictic. Partial mixing was found more often and for longer periods. Two patterns of mixing were observed in the bottom waters. In the first pattern the surface water cooled to the temperature of a mid-depth or bottom layer resulting in mixing. In the second pattern mixing was induced by wind action, often following a limited degree of surface cooling.

Continuous temperature logging indicated that most mixing events occurred between the bi-weekly sampling dates and were not detected in the bi-weekly data. The complexity of the mixing events also was not apparent when simply considering the bi-weekly data. Thus continuous temperature logging is very important, in this type of system and is strongly recommended in future studies

Water chemistry parameters exhibited uniform values with depth immediately following mixing events, but stratified patterns were reasserted within a matter of days following mixing.

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Appendix B Physical water quality data

Sample Date	Date ID	Depth m	Temp. °C	DO ppm	DO % Sat.	pH	Cond. uS/cm
April 30	1	0.10	19.62	8.36	91.10	6.47	809.50
April 30	1	0.25	19.51	8.11	88.30	6.48	808.40
April 30	1	0.50	18.81	8.06	86.80	6.48	800.60
April 30	1	0.75	18.63	7.89	84.50	6.47	801.40
April 30	1	1.00	18.13	7.86	83.60	6.46	803.00
April 30	1	1.25	17.47	7.89	81.90	6.44	810.00
April 30	1	1.50	16.43	7.67	78.50	6.41	815.90
April 30	1	1.75	15.23	6.62	63.40	6.33	861.70
April 30	1	2.00	13.24	5.19	47.60	6.25	985.30
April 30	1	2.25	12.18	3.22	28.30	6.06	1192.00
April 30	1	2.50	10.99	1.76	16.10	6.25	2870.00
May 20	2	0.10	18.74	10.62	113.00	6.69	598.40
May 20	2	0.25	17.35	9.51	106.60	6.74	598.70
May 20	2	0.50	19.83	9.84	107.30	6.78	597.40
May 20	2	0.75	19.52	9.74	105.90	6.77	599.80
May 20	2	1.00	17.39	9.74	101.80	6.77	595.60
May 20	2	1.25	16.60	8.70	88.00	6.68	594.40
May 20	2	1.50	15.68	8.03	78.90	6.60	596.50
May 20	2	1.75	15.22	6.36	63.00	6.50	595.70
May 20	2	2.00	15.06	5.85	58.20	6.42	597.70
May 20	2	2.25	15.02	5.72	56.50	6.38	601.40
May 20	3	2.50	n.a	n.a	n.a	n.a	n.a
June 3	3	0.10	17.55	11.58	120.60	6.79	351.90
June 3	3	0.25	19.17	10.71	115.90	6.93	351.80
June 3	3	0.50	19.10	10.66	115.30	6.97	351.50
June 3	3	0.75	18.60	10.89	117.00	7.01	350.20
June 3	3	1.00	18.06	11.16	117.90	7.05	349.90
June 3	3	1.25	17.51	10.56	110.00	6.95	349.50
June 3	3	1.50	17.25	9.20	94.90	6.82	350.20
June 3	3	1.75	16.99	7.60	75.40	6.69	356.60
June 3	3	2.00	16.72	5.90	59.20	6.60	370.60
June 3	4	2.25	n.a	n.a	n.a	n.a	n.a
June 3	5	2.50	n.a	n.a	n.a	n.a	n.a

Appendix B Physical water quality data continued

Sample Date	Date ID	Depth m	Temp. °C	DO ppm	DO % Sat.	pH	Cond. uS/cm
June 17	4	0.10	23.94	7.00	83.10	6.42	220.10
June 17	4	0.25	23.62	7.07	88.40	6.42	219.30
June 17	4	0.50	23.21	6.83	79.10	6.42	218.90
June 17	4	0.75	23.01	5.71	66.60	6.39	220.30
June 17	4	1.00	22.85	4.67	52.50	6.33	220.80
June 17	4	1.25	22.74	2.43	26.00	6.25	223.50
June 17	4	1.50	22.12	1.45	16.60	6.21	227.40
June 17	4	1.75	22.20	1.07	11.60	6.19	248.80
June 17	4	2.00	19.19	1.00	10.70	6.20	320.70
June 17	4	2.25	17.17	1.01	10.60	6.16	639.50
June 17	4	2.50	n.a.	n.a.	n.a.	n.a.	n.a.
June 30	5	0.10	29.10	7.83	103.10	7.03	196.40
June 30	5	0.25	29.86	7.93	104.90	7.09	195.00
June 30	5	0.50	29.66	7.98	103.40	7.10	193.50
June 30	5	0.75	28.00	7.92	101.30	7.09	193.10
June 30	5	1.00	27.40	7.55	94.40	7.02	196.30
June 30	5	1.25	26.31	5.49	65.40	6.84	198.80
June 30	5	1.50	22.68	1.77	20.50	6.59	191.10
June 30	5	1.75	21.94	1.03	11.60	6.58	192.30
June 30	5	2.00	19.75	0.99	10.80	6.49	225.70
June 30	5	2.25	18.55	0.99	10.50	6.56	296.60
June 30	5	2.50	16.80	0.93	9.70	6.58	878.30
July 15	6	0.10	28.12	18.08	103.10	7.11	169.00
July 15	6	0.25	28.00	8.12	104.50	7.11	167.20
July 15	6	0.50	27.12	8.14	101.80	7.08	166.20
July 15	6	0.75	26.51	8.10	100.40	7.06	165.60
July 15	6	1.00	25.93	7.73	93.60	7.01	166.40
July 15	6	1.25	25.09	5.66	58.00	6.82	168.60
July 15	6	1.50	24.42	2.16	25.80	6.63	171.80
July 15	6	1.75	23.51	1.20	13.50	6.55	180.10
July 15	6	2.00	22.22	1.01	11.40	6.61	196.70
July 15	6	2.25	24.24	0.92	10.40	6.71	260.00
July 15	6	2.50	19.25	0.93	10.10	6.72	609.50

Appendix B Physical water quality data continued

Sample Date	Date ID	Depth m	Temp. °C	DO ppm	DO % Sat.	pH	Cond. uS/cm	
July 30		7	0.10	27.37	8.68	109.70	7.28	197.80
July 30		7	0.25	27.28	8.64	109.10	7.32	197.10
July 30		7	0.50	26.81	8.71	108.70	7.31	197.10
July 30		7	0.75	26.55	8.47	105.20	7.29	196.60
July 30		7	1.00	26.42	8.17	101.60	7.22	197.10
July 30		7	1.25	26.30	6.87	83.30	7.05	197.70
July 30		7	1.50	25.87	4.66	54.70	6.89	200.70
July 30		7	1.75	25.13	1.87	22.70	6.71	204.70
July 30		7	2.00	23.23	1.07	12.50	6.77	254.10
July 30		7	2.25	20.56	1.04	11.50	6.85	452.60
July 30		7	2.50	18.80	1.04	11.20	7.02	774.90
August 22		8	0.10	30.83	10.83	145.40	8.60	231.50
August 22		8	0.25	30.29	11.08	147.10	8.65	231.60
August 22		8	0.50	28.89	11.12	144.00	8.61	231.00
August 22		8	0.75	28.50	10.90	139.40	8.52	230.70
August 22		8	1.00	28.21	10.89	139.60	8.45	230.60
August 22		8	1.25	27.88	10.27	131.00	8.18	231.20
August 22		8	1.50	27.31	9.11	113.20	7.75	234.80
August 22		8	1.75	26.53	6.58	77.40	7.44	242.50
August 22		8	2.00	23.66	4.56	51.40	6.97	319.80
August 22		8	2.25	21.33	2.93	32.10	7.51	503.80
August 22		8	2.50	20.61	2.64	27.80	7.66	773.40
September 11		9	0.10	23.99	9.29	110.40	7.31	250.00
September 11		9	0.25	23.69	9.38	111.40	7.34	248.60
September 11		9	0.50	23.42	9.47	111.50	7.38	248.30
September 11		9	0.75	23.21	9.35	109.40	7.36	248.40
September 11		9	1.00	23.14	9.05	105.40	7.29	250.00
September 11		9	1.25	23.08	9.00	105.20	7.27	248.70
September 11		9	1.50	23.04	8.60	101.10	7.22	249.80
September 11		9	1.75	23.02	8.64	100.80	7.19	249.50
September 11		9	2.00	23.00	8.41	98.10	7.15	250.50
September 11		9	2.25	22.23	4.40	51.90	7.95	400.00
September 11		9	2.50	21.42	2.73	30.80	8.08	818.10

Abbreviations

Temp-Temperature
 Cond-Conductivity
 DO-Dissolved Oxygen
 n.a -data not available

Appendix C Chemical water quality data

Sample Date	Date ID	Depth m	Ammonia mg/L	Nitrate mg/L	SRP ug/L	TP ug/L	Chl a ug/L
April 30	1	0.10	0.165145	1.467339	63.5916	23.81	4.118044
April 30	1	0.50	0.10885	0.92487	68.13584	40.66608	2.084908
April 30	1	1.00	0.124814	1.026008	67.36563	27.3964	4.281758
April 30	1	1.50	0.127335	1.026008	75.37582	35.4658	3.253297
April 30	1	2.00	0.197074	0.906481	0.665445	41.742	2.784542
April 30	1	2.50	n.a	1.237479	na	42.99724	1.116615
May 20	2	0.10	0.213038	1.255868	56.42865	58.7774	3.95433
May 20	2	0.50	0.162624	0	4.516495	94.82072	4.89044
May 20	2	1.00	0.205476	1.026008	8.367545	77.606	4.610586
May 20	2	1.50	0.200435	1.136341	5.748831	59.674	4.743516
May 20	2	2.00	0.262612	1.136341	8.829671	63.2604	4.503402
May 20	2	2.50	0.283617	0.750176	10.21605	63.79836	1.409132
June 3	3	0.10	0.00046	0.357123	11.38951	42.81792	10.99125
June 3	3	0.50	0	0.287426	17.36571	102.7108	21.78659
June 3	3	1.00	0	0.155774	6.90736	154.1756	225.7018
June 3	3	1.50	0.011383	0.155774	6.90736	76.35076	68.5641
June 3	3	2.00	0	0.426821	11.0907	56.44624	14.99595
June 3	3	2.50	0.201275	0.798543	14.0788	149.6926	12.63678
June 17	4		n.a.	n.a.	n.a.	n.a.	n.a.
June 30	5	0.10	0.083083	0.457798	14.67642	41.8126	5.433355
June 30	5	0.50	0.076964	0.589449	10.79189	78.1118	11.85179
June 30	5	1.00	0.198583	0.527496	20.35381	117.0038	8.966505
June 30	5	1.50	0.21694	0.481031	15.87166	92.3722	7.674282
June 30	5	2.00	0.553496	0.558473	41.27051	132.3013	6.598945
June 30	5	2.50	1.006317	1.278683	241.772	307.5746	23.36777

Appendix C Chemical water quality data continued

Sample Date	Date ID	Depth m	Ammonia mg/L	Nitrate mg/L	SRP ug/L	TP ug/L	Chl a ug/L
July 15	6	0.10	0.021126	0.604938	23.0431	72.66692	4.136934
July 15	6	0.50	0.042543	0.635915	14.0788	81.74172	7.713462
July 15	6	1.00	0.06855	0.659147	20.95143	267.3862	153.5346
July 15	6	1.50	0.457119	0.287426	6.30974	74.2226	4.589597
July 15	6	2.00	1.713085	2.060847	144.0612	198.1584	7.157253
July 15	6	2.50	1.157002	1.441311	87.28725	162.3778	9.885824
July 30	7	0.10	0.033364	0.057869	3.32164	50.85084	19.30884
July 30	7	0.50	0.017301	0.021094	0	80.22972	20.09313
July 30	7	1.00	0.022656	0.076256	0.93116	60.74076	27.42564
July 30	7	1.50	0.108324	0.31529	6.01093	105.5363	16.79925
July 30	7	2.00	1.416303	3.946762	87.28725	332.1318	121.7922
July 30	7	2.50	2.974405	1.299005	478.7284	525.567	87.39824
August 22	8	0.10	0	0	5.41331	53.75964	17.05987
August 22	8	0.50	0.000905	0	0	62.77692	17.29495
August 22	8	1.00	0.001586	0.140611	0	68.8854	18.80056
August 22	8	1.50	0.011122	0.030288	0	83.13852	32.88278
August 22	8	2.00	0.000223	0	1.82759	95.0646	26.13832
August 22	8	2.50	0.003629	0.177386	4.21807	264.0659	146.6187
September 22	9	0.10	0	0	0	89.82876	18.96007
September 22	9	0.50	0.030193	0	0	80.22972	20.16694
September 22	9	1.00	0.020657	0	0	73.2486	23.08791
September 22	9	1.50	0.047221	0.021094	0	61.03164	26.44615
September 22	9	2.00	0.216823	0.057869	0	113.39	27.51659
September 22	9	2.50	2.51768	5.83145	0.22916	540.6928	127.7811

Abbreviations:

Chl-Chlorophyll

SRP-Soluble Reactive
Phosphorus

TP-Total Phosphorus

n.a.-data not available

Curriculum Vitae

Shannan D. Wheat was born on June 10, 1980, in Hopewell, Virginia. She graduated from Dinwiddie County High School, Dinwiddie, Virginia, 1998. She received a Bachelor of Science in Marine and Environmental Science from Hampton University in 2002. She was employed as a graduate research assistant and as a graduate teaching assistant at George Mason University and received her Master of Science in Environmental Science and Policy in 2004.