UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 426

Simulation of Water Quality and Primary Productivity Control Strategies for Lake McCarrons

by

Deborah E. West-Mack and Heinz G. Stefan

Prepared for

METROPOLITAN COUNCIL ENVIRONMENTAL SERVICES (MCES)
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ABSTRACT

A one-dimensional lake water quality model, MINLAKE98, was calibrated to simulate water temperature, dissolved oxygen, total phosphorus and chlorophyll-a in Lake McCarrons, a lake with 0.33 km^2 surface area and 17.3 m maximum depth located in Roseville, MN. To improve the summer water quality of the lake, several management options have been considered. The potential effects of five of these management options were simulated using the model calibrated for 1995 and 1996 inflow and weather conditions. The model projected that total inflow diversion during the summer, phosphorus treatment of the inflow during the summer and reduction of phosphorus release from the anoxic sediments during the summer have all only a minor effect on phytoplankton standing crops in the lake. Phosphorus removal (precipitation) after ice-out (before the growing season) and artificial deepening of the surface mixed layer to 8 m or more were projected to give a significant (more than 50%) reduction in phytoplankton standing crop.

ACKNOWLEDGMENTS

The work reported herein was supported by the Metropolitan Council Environmental Services, St. Paul, Minnesota. Gary Oberts, Karen Jensen, and Randy Anhorn of the Metropolitan Council provided the water quality data for Lake McCarrons and its wetland. Omid Mohseni and Travis Bogan of the University of Minnesota provided technical assistance. David Ruschy of the Department of Soil, Water, and Climate, University of Minnesota, made meteorological data for St. Paul available.

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1. INTRODUCTION

Lake McCarrons is located in Roseville, Minnesota. It has a surface area of approximately 0.33 km^2 and a watershed area of approximately 3.3 km^2. There is only one primary inflow and that is from the adjoining wetland. The inflow from the wetland enters the lake from the northwest; outflow exits on the southeast side of the lake over a concrete weir. Approximately 90% of the runoff from the watershed goes through the wetland before entering the lake. The lake has a maximum depth of 17.3 m and is approximately oval in shape (Figure 1.1).

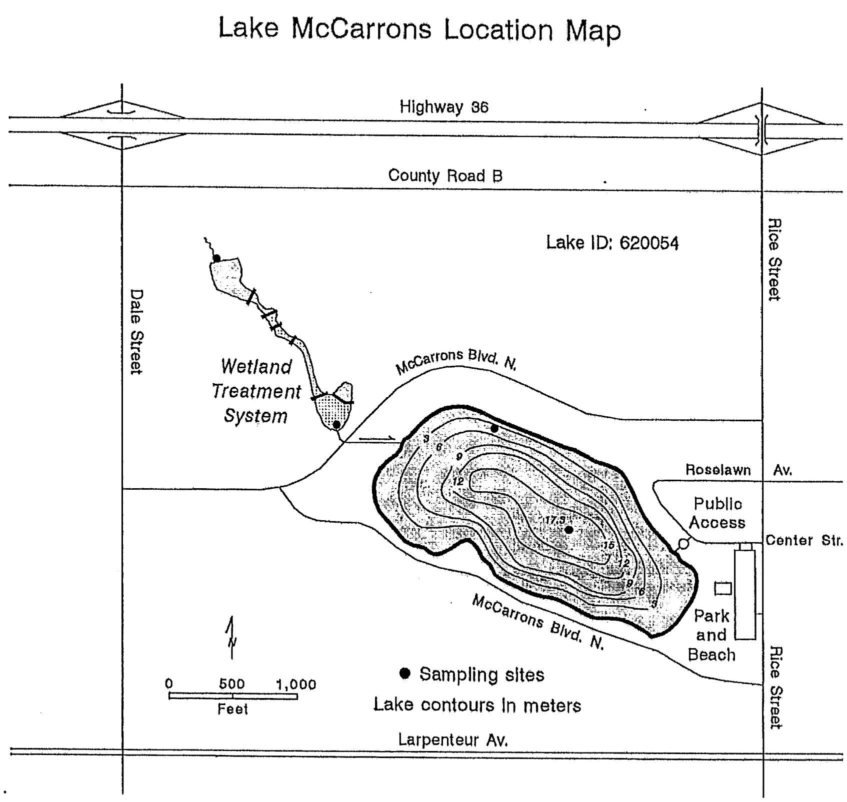

Figure 1.1. Lake McCarrons location and bathymetric map (after MCES, 1997).

2. MINLAKE98 MODEL

MINLAKE98 simulates a variety of materials and processes in a lake (Figure 2.1). A lake is represented as a series of stacked layers of varying thickness. The layers include snow, ice, water, and sediment. Each of the water layers is considered well mixed. All of the water layers are in contact with the sediment of the lake. Only the surface layer is in contact with the atmosphere during the open water season.

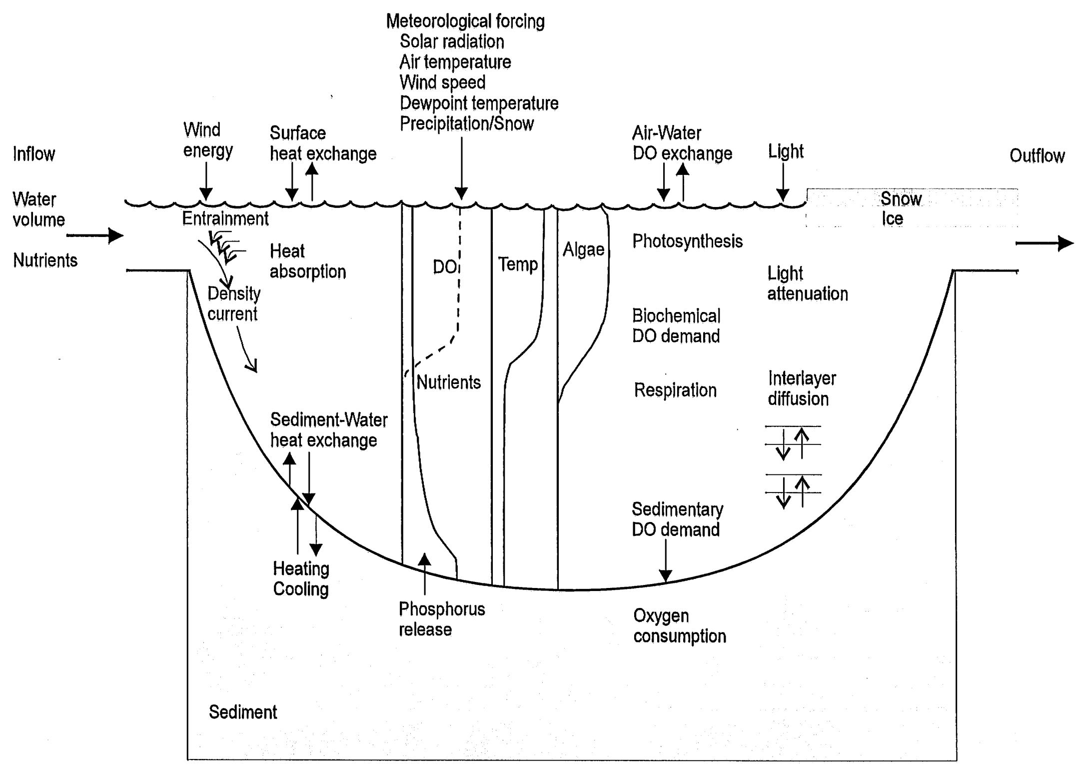

Figure 2.1. Schematic representation of processes in MINLAKE98.

The depth profile of **temperature** is computed from a balance between incoming heat from solar and long-wave radiation and the outflow of heat through convection, evaporation, and back radiation. The net increase in heat results in an increase in water temperature. A schematic diagram of the heat budget components is presented in Figure 2.2.

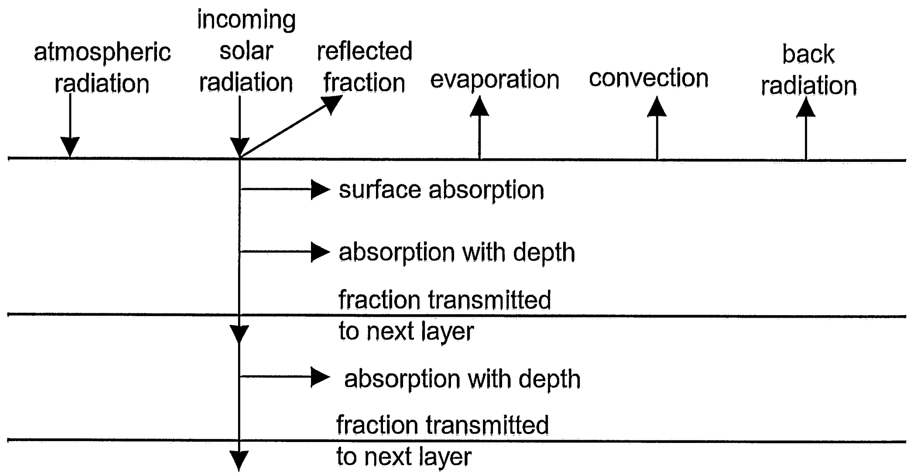

Figure 2.2. Schematic diagram of source and sink terms in the heat budget model.

Chlorophyll *a* is used in MINLAKE as an indicator of phytoplankton standing crop (primary productivity) in a lake. Up to three algal groups can be simulated by the MINLAKE model (Riley and Stefan, 1988). A schematic diagram of the phytoplankton interactions is presented in Figure 2.3. This general diagram is applicable to each algal group, but different coefficients and rates are used to represent a specific group. Phytoplankton (chlorophyll *a*) growth is simulated by external nutrient limitation using a Michaelis-Menten growth function. Light and phosphorus limitation are simulated. Respiration removes biomass (chlorophyll *a*) and releases a proportional amount of nutrients directly to the water column. Non-predatory mortality does not directly release nutrients to the water column but contributes to the detrital mass (BOD). Diffusion of chlorophyll occurs between layers at the same rate as heat (temperature). Loss of chlorophyll *a* due to grazing is treated separately as it is the result of the mobility of zooplankton. Settling removes chlorophyll from a layer and contributes it to the next layer (or the sediment).

Phosphorus is often the principal chemical affecting phytoplankton (chlorophyll *a*) concentration in lakes. The model simulates only the readily accessible phosphate composed of orthophosphate and polyphosphate ions referred to as soluble reactive phosphorus (SRP). A schematic diagram of the principal SRP flux components is presented in Figure 2.4. Mortality does not directly release phosphorus to the water column but contributes to the detrital mass (BOD); the phosphorus is released from the detrital mass through decay. The SRP is calculated for each layer. Diffusion of phosphorus occurs between layers but phosphorus is also transported indirectly between layers by phytoplankton and detritus settling. In MINLAKE98 there is no atmospheric deposition of phosphorus, as there is for models of Lake Superior (Chapra, 1977). Lake Superior has a considerable atmospheric input because of the large lake surface compared to the watershed area. For lakes modeled by MINLAKE98 the watershed area is usually much larger than the lake surface area.

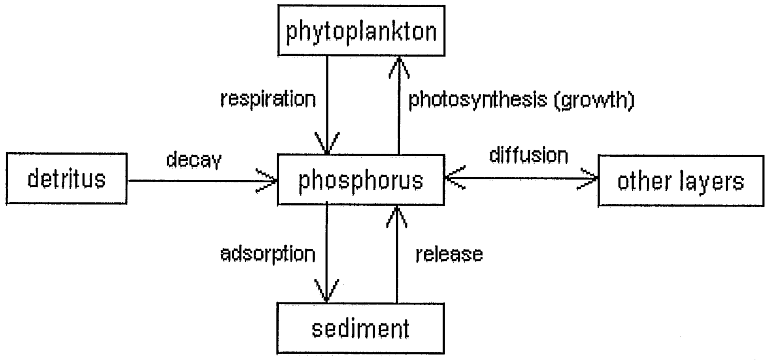

Figure 2.3. Illustration of the processes (arrows) and components (boxes) comprising the phytoplankton (chlorophyll *a*) submodel in MINLAKE98.

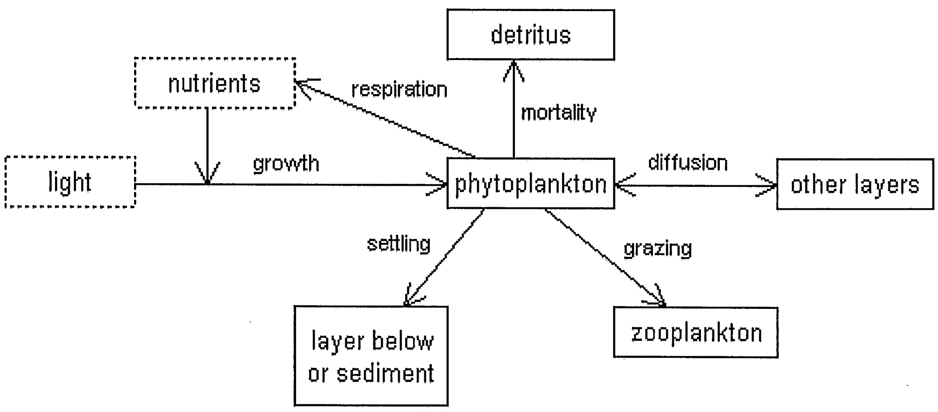

Figure 2.4. Illustration of the processes (arrows) and components (boxes) comprising the soluble reactive phosphorus submodel in MINLAKE98.

A schematic diagram of **dissolved oxygen** (DO) fluxes in a lake is presented in Figure 2.5. During the open water season reaeration is a significant source of dissolved oxygen. It is possible for the phytoplankton (chlorophyll *a*) to add dissolved oxygen to the water layer through photosynthesis to the point where water is supersaturated with dissolved oxygen. In this case the dissolved oxygen is released into the atmosphere. These dynamic processes can have time scales of less than one day - the timestep of the simulation. Therefore the simulated dissolved oxygen profiles are an average over the day and not "snapshots" like observed profiles. Dissolved oxygen removal from the water layer through respiration is simulated to occur at a constant rate throughout the day while photosynthesis occurs only during day light hours. The sediment oxygen demand is applied to all layers in proportion to the sediment surface area in contact with the water layer. Biochemical oxygen demand (BOD) removes oxygen from the water layer through the decay of detrital material.

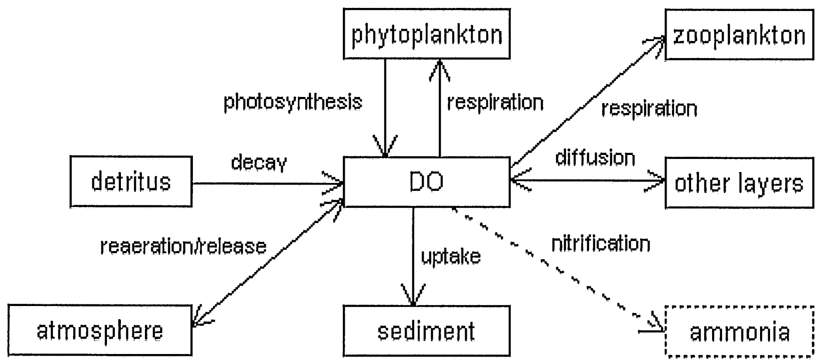

Figure 2.5. Illustration of the processes (arrows) and components (boxes) comprising the dissolved oxygen submodel in MINLAKE98. Nitrification is simulated only if nitrogen is simulated.

Outflow from a lake is simulated as surface outflow. Only the layers in direct contact with the outflow channel contribute to the outflow. The volume of water removed from a layer by outflow is proportional to the thickness of the layer. Outflow calculations assume a rectangular cross-section for the outflow channel.

3. MODELING OF EXISTING CONDITIONS

MINLAKE98 was used to model Lake McCarrons for the open-water season, April through October for 1995 and 1996. The model was calibrated using 1995 field data from Lake McCarrons. To validate the model, MINLAKE98 was applied for 1996 using the calibration coefficients for 1995. The simulated results were then compared with the observed data for those years. This provides a predictor of the accuracy of the model for simulating Lake McCarrons. Then the model was calibrated using the 1996 field data to determine the best fit coefficients. The best fit coefficients for each year were then used for modeling the productivity control strategies.

The temperature and primary productivity (as chlorophyll *a*) as well as dissolved oxygen and total phosphorus were simulated using MINLAKE98. Two types of phytoplankton were simulated: green and blue-green algae. Phosphorus is the only nutrient simulated because a comparison of the nitrogen to phosphorus ratios showed that Lake McCarrons is currently a phosphorus limited lake (Appendix A). An additional parameter simulated was detritus (as BOD). The following parameters were not simulated: silica, nitrogen, suspended solids, and dissolved solids. Coefficients for simulating Lake McCarrons using MINLAKE98 are listed in Appendix B.

The lake has been monitored since 1984 by the Metropolitan Council. In addition to lake water quality the water quality of the McCarrons wetland outlet was monitored in 1995 and 1996 (MCES, 1997). The field data were retrieved from the EPA database, STORET and through personal communication with Gary Oberts, Karen Jensen, and Randy Anhorn of the Metropolitan Council Environmental Services.

The meteorological data needed for the simulation of Lake McCarrons were obtained from Dave Ruschy from the Department of Soils, Water and Climate of the University of Minnesota (St. Paul) and from the National Oceanic and Atmospheric Administration (NOAA) website (http://www.ncdc.noaa.gov/). The St. Paul weather station provided daily maximum and minimum air temperature, precipitation, and solar radiation. Daily air temperature was calculated using the mean of the maximum and minimum air temperature for the day. Dew point temperature, cloud cover, windspeed, and snowfall were obtained from the NOAA weather station located at the Minneapolis/St. Paul airport. After June 1996 cloud cover was no longer reported. Cloud cover for dates after June 1, 1996 was calculated from the ratio of observed radiation and maximum possible solar radiation (Maidment, 1993). Dew point temperature from the airport was adjusted for air temperature in St. Paul.

The temperature of the wetland outflow into Lake McCarrons was measured directly most of the time although some values for 1995 and 1996 were not reported. Missing outflow temperatures were estimated from the measured air temperatures. (See Appendix C.) The dissolved oxygen (DO) in the wetland outflow was not measured. The wetlands are shallow and full of plants so that it is possible that during the day the DO will become higher than saturation and in the morning lower. The model requires average daily values. Without further information, daily DO values were estimated using dissolved oxygen saturation values for the daily water temperature. Values were calculated from an empirical relationship given by Thomann and Mueller (1987).

The daily inflow data for the 1995-96 Lake McCarrons simulations were extracted from the MCES (1997) report. The 1995-96 Lake McCarrons data were also available in electronic files. The missing daily values were interpolated using snowmelt and rainfall event loads in the report. In order to find the daily flow rate and daily nutrient concentrations, the duration of an event (number of days) was determined using the hydrograph in the report. The total nutrient loads or total flow rates given in the report were divided by the duration of each event. To determine the accuracy of this method, calculations for daily flow and daily nutrient concentrations were compared to values that were already known. The comparison was satisfactory. Plots of the daily input data for 1995 and 1996 are given in Appendix H.

Lake outflow rates for 1995 and 1996 were estimated using the approximate seasonal hydrologic budget for Lake McCarrons presented in the MCES (1997) report. Seasonal outflow values were reported; daily outflow values were estimated by using the average number of days in the season.

The model was calibrated using 1995 and 1996 field data from Lake McCarrons. MINLAKE98 contains some rate coefficients that need to be adjusted to simulate a specific lake. Calibration was based on both statistical and visual comparison with the field data.

The goodness of fit of the simulated water quality parameters to the field data was evaluated using a linear regression constrained through the origin. The linear regression provides a slope of the regression line, a regression coefficient (r^2), and a standard error of the estimate. A perfect fit would give a slope of 1.0, a regression coefficient of 1.0, and a standard error of 0.0. A slope greater than 1.0 indicates that the model is overpredicting and a slope less than 1.0 indicates that the model is underpredicting.

The regression coefficient and the standard error are related parameters, but provide different information. The regression coefficient in a constrained regression has a range of $-\infty$ to 1.0. Negative values indicate that the standard error of the model prediction (estimate) is greater than the standard deviation of the field data. When the standard deviation of the field data is small, an acceptable simulation may still yield a negative regression coefficient. For this reason, the standard error of the estimate is also calculated. In the case where the regression coefficient is less than zero, the standard error of the estimate is used to evaluate the magnitude of error. The statistical results were calculated for water temperature, dissolved oxygen, total phosphorus, and chlorophyll *a*.

3.1 Temperature

3.1.1 Calibration

The statistical results of the water temperature calibrations are presented in Table 3.1 (statistical results for dissolved oxygen, total phosphorus, and chlorophyll *a* are presented in later sections). The statistical results show that water temperature is simulated well, i.e. with standard errors < 0.9 °C, maximum errors < 3.5°C, slopes of 0.98 ± 0.01 and regression coefficients of 0.99 ± 0.01. The model is able to simulate the location of the thermocline. Temperature profiles of the 1995 calibration are presented in Figure 3.1. Temperature profiles of the 1996 and 1999 calibration are presented in Appendix E. The model also simulates the daily dynamics of the water temperature as can be seen in the time series plot for the surface water. Simulated and observed temperature values at 5 water depths (surface, 3 m, 5 m, 9 m, and 16 m) for 1995 are presented in Figure 3.2. Simulated and observed water temperature values at the 5 water depths for 1996 are presented in Appendix E.

Table 3.1. Statistical results from the temperature calibration of the MINLAKE98 model to the 1995 and 1996 field data for Lake McCarrons.

	Temperature (°C)	
	1995	**1996**
Standard error	0.88	0.85
Maximum error	-3.43	3.04
Slope of regr. line	0.99	0.97
Regr. coefficient	0.98	0.99
No. of data points	405	400

3.1.2 Validation

The statistical results of the water temperature validations of the calibration coefficients determined from the 1995 data, are presented in Table 3.2. The statistical results show that temperature is simulated well, i.e. with standard errors < 1°C, maximum errors < 4 °C, slopes of 0.97 and regression coefficients of 0.98. The model simulates the location of the thermocline well. Temperature profiles of the 1996 validation are presented in Figure 3.3 and in Appendix F. The model simulates the daily dynamics of the water temperature well, as can be seen in the time series plot of the surface water. Simulated and observed temperature values at 5 water depths (surface, 3 m, 5 m, 9 m, and 16 m) for 1996 are presented in Figure 3.4.

Table 3.2. Statistical results from the temperature validation of the MINLAKE98 model to the 1996 field data for Lake McCarrons.

	Temperature (°C)
	1996
Standard error	0.94
Maximum error	-3.89
Slope of regr. line	0.97
Regr. coefficient	0.98
No. of data points	400

3.2 Productivity

Primary productivity is measured by chlorophyll *a* concentration changes. Both green and blue-green algae were simulated. Many factors determine the chlorophyll concentration in each class of algae simulated: available phosphorus, growth rate, mortality rate, and respiration rate of the algae, and zooplankton grazing rate. The coefficients used for the simulations are presented in Appendix B.

3.2.1 Calibration

The statistical results of the chlorophyll *a* calibrations are presented in Table 3.3. The statistical results show that chlorophyll is simulated with standard errors of ≤ 0.015 mg/L and maximum errors < 0.045 mg/L. Surface chlorophyll profiles of the 1995 and 1996 calibrations are presented in Figures 3.5, 3.6, and 3.7, respectively. The simulation of the chlorophyll *a* in the surface water for 1995 (Figure 3.5) represents the overall level of chlorophyll concentration in the lake, but does not capture the population dynamics (i.e. the ups and downs in chlorophyll over time). It should be cautioned that the variability in the measured concentrations may not only be due to the growth dynamics of the algal population, but may also reflect the patchiness of the algae in the lake. It appears that each reported chlorophyll concentration is from one point sample. The simulation of the chlorophyll in the surface water for 1996 (Figure 3.6) also represents the overall level of chlorophyll concentration in the lake. The 1996 mean observed chlorophyll concentration, 0.013 mg/L, is less than half of the mean observed chlorophyll concentration 1995. It is not clear why the chlorophyll concentration in 1996 was so much less than in the previous years. The observed total phosphorus concentration in the upper 5 m was around 0.062 mg/L for both years. The mixed layer depth is only around 10% deeper for 1996 than 1995 and the wind speed appears to be the same for both years.

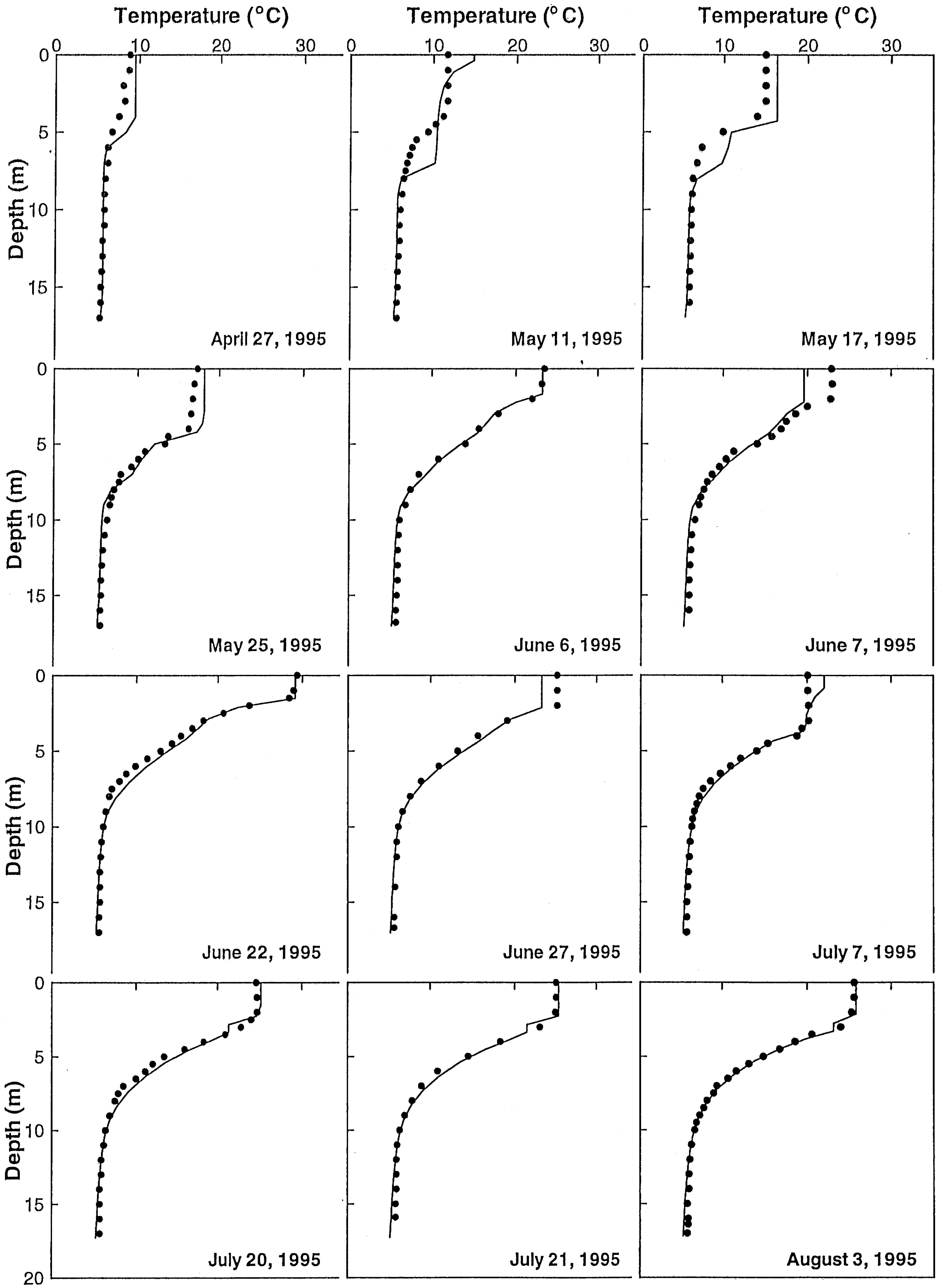

Figure 3.1 Simulated (line) and observed (dot) water temperature profiles for Lake McCarrons calibrated for 1995.

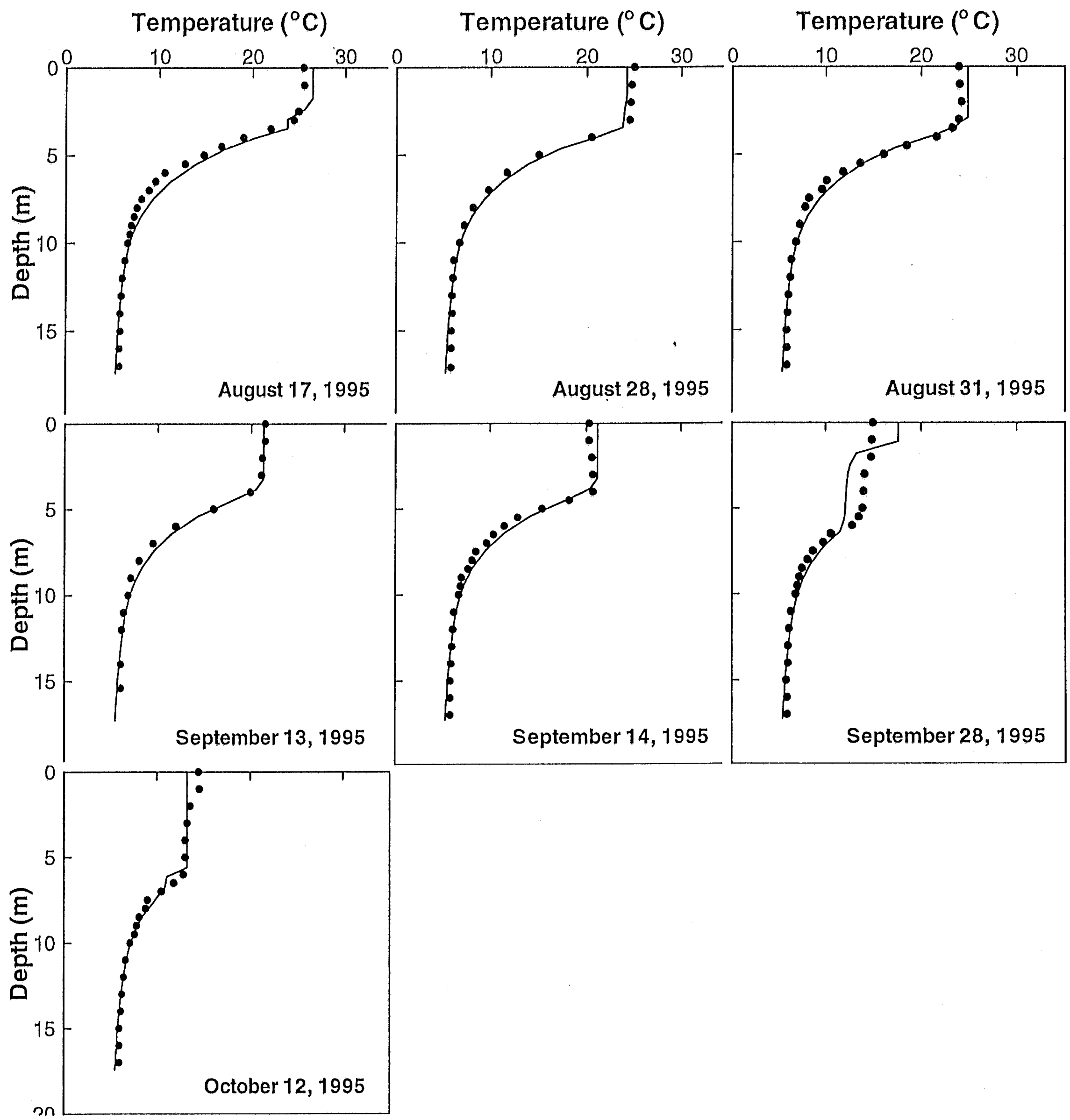

Figure 3.1 (Cont'd) Simulated (line) and observed (dots) water temperatures profiles for Lake McCarrons calibrated for 1995.

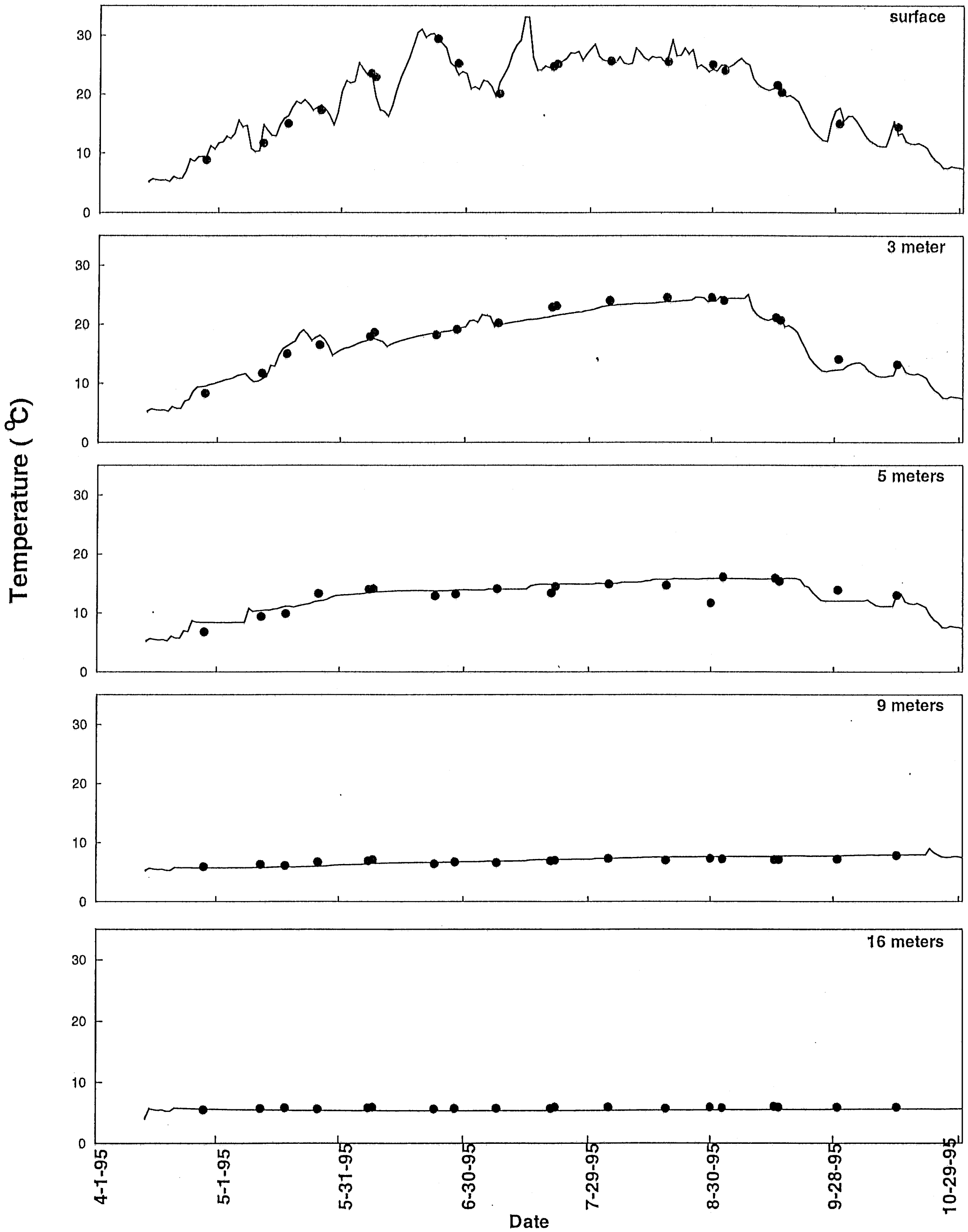

Figure 3.2 Simulated (line) and observed (dots) water temperatures at a) surface, b) 3m, c) 5m, d) 9m, and e) 16 m below the surface for Lake McCarrons, April to October 1995.

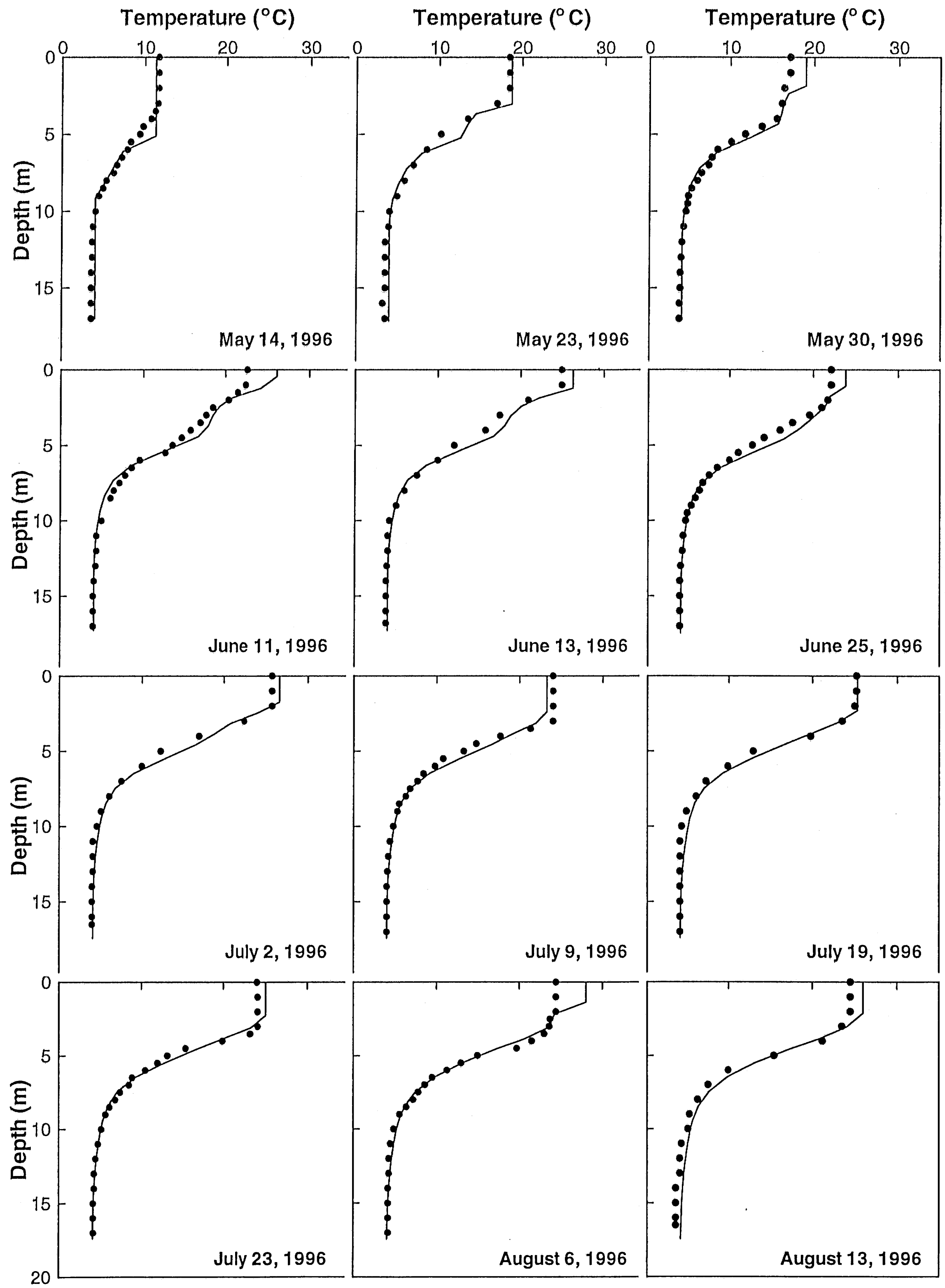

Figure 3.3 Simulated (line) and observed (dot) water temperature profiles for Lake McCarrons for 1996 using coefficients calibrated for 1995.

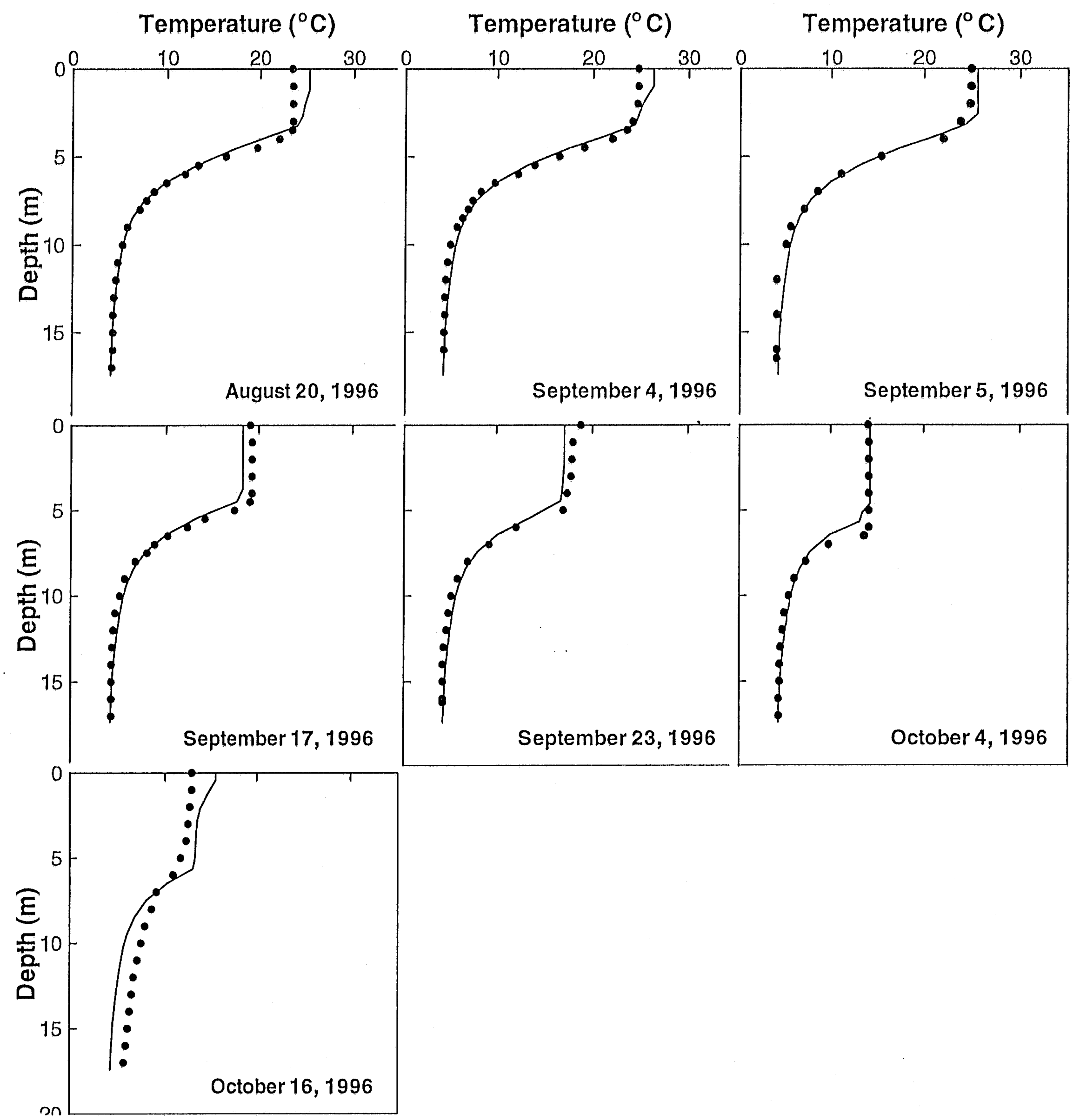

Figure 3.3 (cont'd) Simulated (line) and observed (dot) water temperature profiles for Lake McCarrons for 1996 using coefficients calibrated for 1995

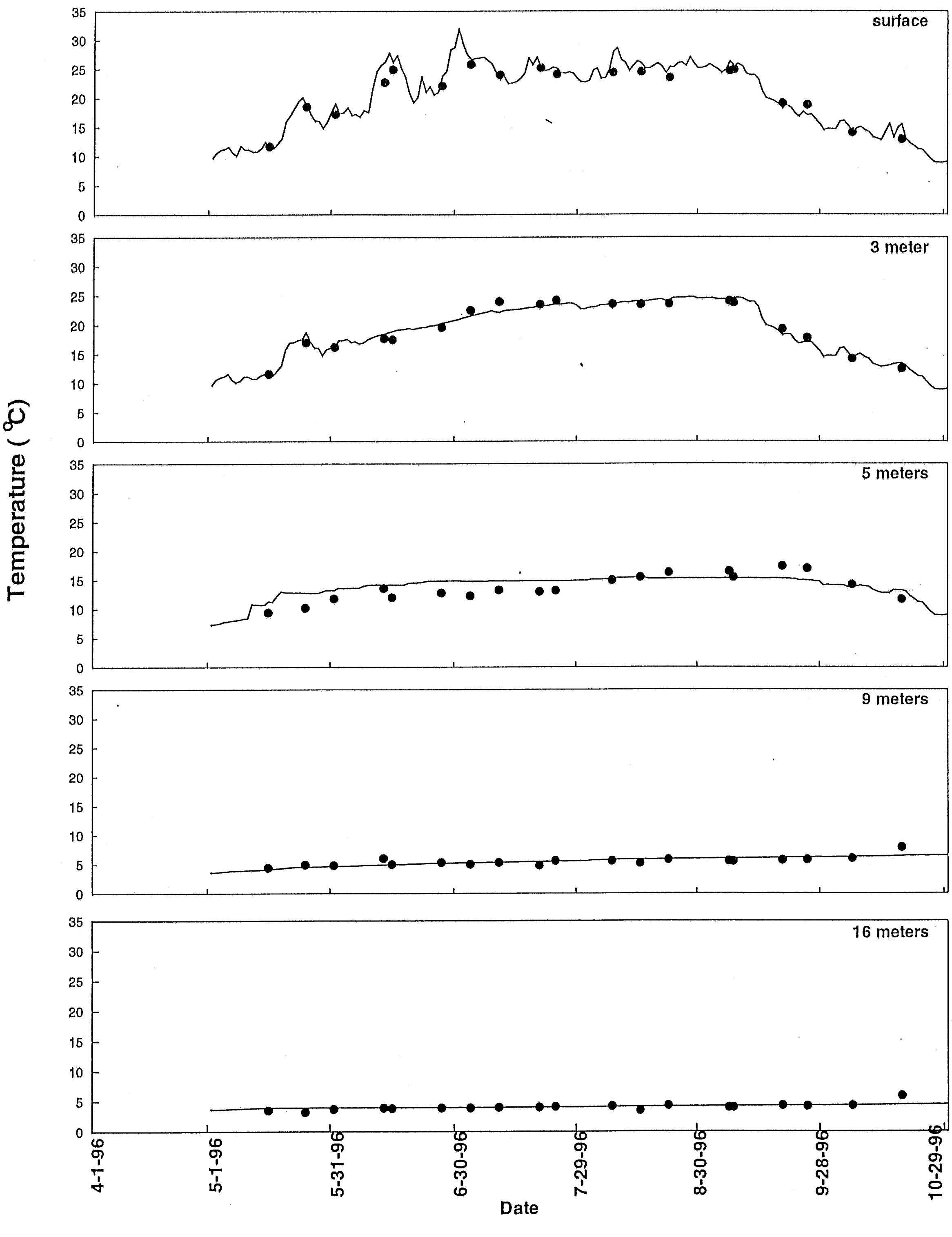

Figure 3.4 Simulated (line) and observed (dots) water temperatures at a) surface, b) 3m, c) 5m, d) 9m, and e) 16m below the surface for Lake McCarrons, April to October 1996 using coefficients calibrated for 1995.

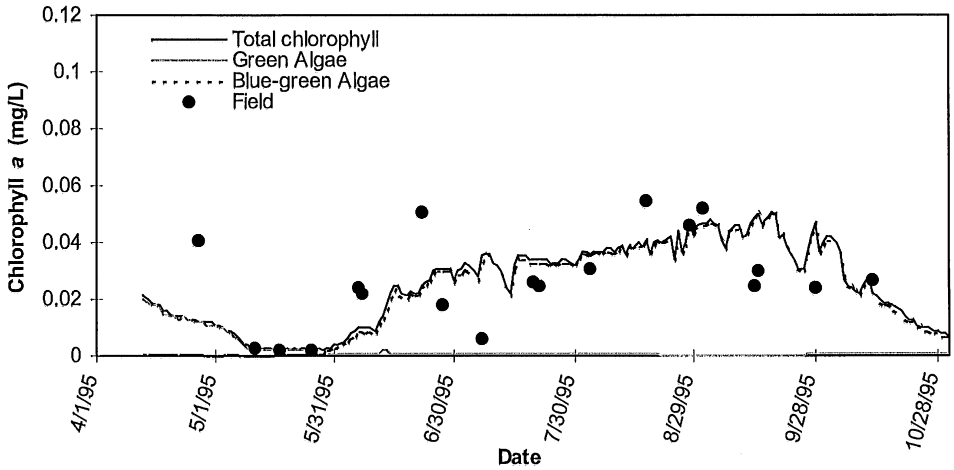

Figure 3.5. Simulated surface chlorophyll *a* (lines) after the calibration of the MINLAKE98 model to the 1995 field data (dots) for Lake McCarrons.

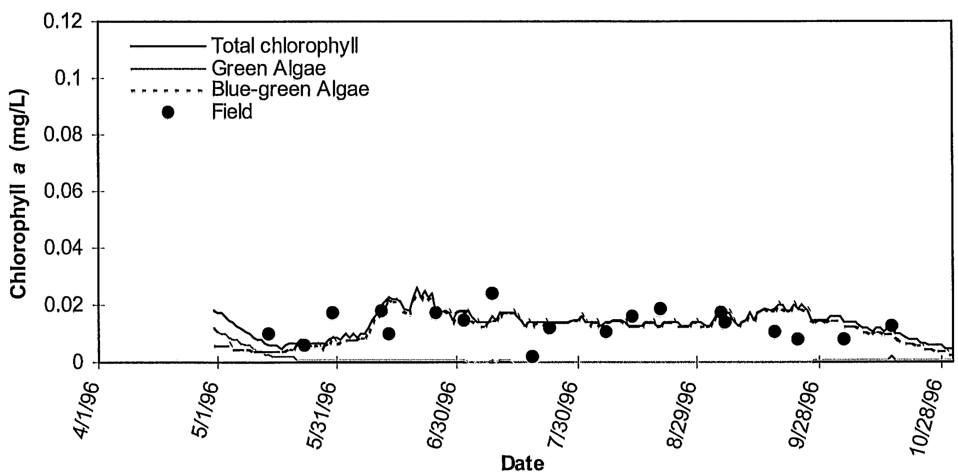

Figure 3.6. Simulated surface chlorophyll *a* (lines) after the calibration of the MINLAKE98 model to the 1996 field data (dots) for Lake McCarrons.

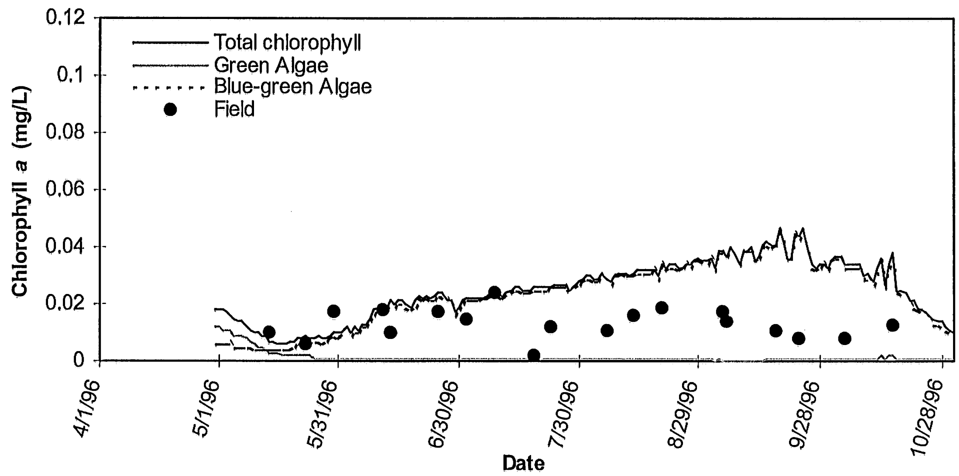

Figure 3.7. Simulated surface chlorophyll *a* (lines) and 1996 field data (dots) for Lake McCarrons using calibration coefficients from 1995.

Table 3.3. Statistical results from the chlorophyll *a* calibration of the MINLAKE98 model to the 1995 and 1996 field data for Lake McCarrons.

	Chlorophyll *a* (mg/L)	
	1995	**1996**
Standard error	0.015	0.012
Maximum error	-0.029	-0.044
Slope of regr. line	0.58	-0.36
Regr. coefficient	-0.13	-0.85
No. of data points	27	30

3.2.2 Validation

The statistical results of the chlorophyll *a* validations for the model calibrated with 1995 data are presented in Table 3.4. The statistical results show that chlorophyll is simulated with standard errors of approximately 0.02 mg/L and maximum errors ≤ 0.045 mg/L. Surface chlorophyll concentrations of the 1996 validation are presented in Figure 3.7. The estimated surface chlorophyll concentrations for 1996 are predicted well for the spring but increasingly overpredicted for the summer and fall. This coincides with an intermittent underprediction of the dissolved oxygen concentrations at a depth of 3 meters.

Table 3.4. Statistical results from the chlorophyll *a* validation of the MINLAKE98 model to the 1996 field data for Lake McCarrons.

	Chlorophyll *a* (mg/L)
	1996
Standard error	0.020
Maximum error	-0.044
Slope of regr. line	0.69
Regr. coefficient	-4.53
No. of data points	30

3.3 Dissolved Oxygen and Total Phosphorus

3.3.1 Calibration

The statistical results of the **dissolved oxygen** calibrations are presented in Table 3.5. The statistical results show that dissolved oxygen is simulated with standard errors ≤ 1.3 mg/L, maximum errors < 6.5 mg/L slopes of 1.01 ± 0.02 and regression coefficients of 0.91 ± 0.02. Dissolved oxygen profiles of the 1995 and 1996 calibrations are presented in Appendices D and E, respectively. The slight depression in measured oxygen concentrations at the thermocline is probably due to the decomposition of algae and not due to ground water infiltration. Simulated and observed dissolved oxygen values at 5 water depths (surface, 3 m, 5 m, 9 m, and 16 m) for 1995 and 1996 are presented in Appendices D and E, respectively. The time series shows that the largest error occurs in the surface water. The saturation DO values for the observed temperatures were calculated and compared with the measured DO values. Several of the measured values show evidence of supersaturation. Some of the oxygen simulation difference in the surface water may be attributed to the 'snapshot' observation of the dissolved oxygen concentration compared to the models estimate of the daily average concentration. The simulated dissolved oxygen values for 1996 are at saturation concentration. Not all of the difference can be attributed to 'snapshot' versus daily average concentrations for 1995 as the simulated DO is frequently slightly less than saturation. Using saturated DO levels in the inflow seems to be reasonable.

The statistical results of the **total phosphorus** calibrations are presented in Table 3.6. The statistical results show that total phosphorus is simulated with standard errors < 0.25 mg/L, maximum errors < 0.65 mg/L, slopes of 0.92 ± 0.02 and regression coefficients of 0.76 ± 0.06. Total phosphorus profiles of the 1995 and 1996 calibrations are presented in Appendices D and E. Simulated and observed total phosphorus values at 5 water depths (surface, 3 m, 5 m, 9 m, and 16 m) for 1995 and 1996 are presented in Appendices D and E. The total phosphorus simulation appears to be reasonable.

Table 3.5. Statistical results from the dissolved oxygen calibration of the MINLAKE98 model to the 1995 and 1996 field data for Lake McCarrons.

	Dissolved Oxygen (mg/L)	
	1995	**1996**
Standard error	1.31	1.00
Maximum error	6.07	5.34
Slope of regr. line	1.03	1.01
Regr. coefficient	0.89	0.93
No. of data points	405	400

Table 3.6. Statistical results from the total phosphorus calibration of the MINLAKE98 model to the 1995 and 1996 field data for Lake McCarrons.

	Total Phosphorus (mg/L)	
	1995	**1996**
Standard error	0.14	0.21
Maximum error	0.40	-0.63
Slope of regr. line	0.90	0.94
Regr. coefficient	0.82	0.70
No. of data points	87	77

3.3.2 Validation

The statistical results of the dissolved oxygen validations (with calibration coefficients determined from the 1995 calibration) are presented in Table 3.7. The statistical results show that dissolved oxygen is simulated with standard errors < 1.4 mg/L, maximum errors < 7.5 mg/L, slopes of 1.13 and regression coefficients of 0.88. Dissolved oxygen profiles of the 1996 validations are presented in Appendix F. Simulated and observed dissolved oxygen values at 5 water depths (surface, 3 m, 5 m, 9 m, and 16 m) for 1996 are presented in Appendix E. Overall the 1995 coefficients produce a good simulation of the 1996 observed values. The majority of the errors occurs in the surface mixed layer. Some of these errors are due to supersaturation. Other errors occurring at 3 m depth underpredict the dissolved oxygen concentration. It is unclear why the dissolved oxygen is underpredicted at this depth as the temperature is simulated well.

Table 3.7. Statistical results from the dissolved oxygen validation of the MINLAKE98 model to the 1996 field data for Lake McCarrons.

	Dissolved Oxygen (mg/L)
	1996
Standard error	1.38
Maximum error	-7.38
Slope of regr. line	1.13
Regr. coefficient	0.88
No. of data points	400

The statistical results of the total phosphorus validations with calibration coefficients determined from the 1995 calibration are presented in Table 3.8. The statistical results show that total phosphorus is simulated with standard errors around 0.2 mg/L, maximum error of 0.7 mg/L, slope of 0.85 and regression coefficients of 0.69. Total phosphorus profiles of the 1996 validations are presented in Appendix F. Simulated and observed total phosphorus values at 5 water depths (surface, 3 m, 5 m, 9 m, and 16 m) for 1996 are also presented in Appendix F. The simulation of the 1996 values is good for most of the season but starts to overpredict the phosphorus concentration in the upper layers of the lake starting in August.

Table 3.8. Statistical results from the total phosphorus validation of the MINLAKE98 model to the 1996 field data for Lake McCarrons.

	Total Phosphorus (mg/L)
	1996
Standard error	0.21
Maximum error	0.70
Slope of regr. line	0.85
Regr. coefficient	0.69
No. of data points	77

4. MODELING OF CONTROL STRATEGIES FOR PRODUCTIVITY

4.1 Phosphorus Controls

Four methods to reduce primary productivity through phosphorus control in Lake McCarrons were simulated. In the first case "no inflow" is added to the lake. This simulates the effect of a complete diversion of the wetland outflow around the lake or through the lake, similar to Lake Elmo. In the second case there is "no phosphorus in the inflow." This simulates the flow through an ideal wetland where all of the phosphorus is removed from the inflow. The third case simulates "phosphorus treatment in the spring" which reduces the initial concentration of phosphorus in the lake to 0 mg/L. The fourth case simulates "no recycling of phosphorus from the sediment" by preventing sediment phosphorus release.

4.1.1 "No Inflow" Scenario

The model was run with no surface water input from the watershed, except precipitation onto the lake. No outflow was simulated. As 90% of the runoff from the watershed goes through the wetland, this simulation does not account for the 10% overland runoff that flows directly into the lake. (The 10% direct runoff is also not simulated for the existing conditions.) The surface chlorophyll *a* concentration for the existing condition and the "no inflow" scenario for 1995 and 1996 are presented in Figures 4.1 and 4.2, respectively. The plots for 1995 and 1996 show very little change in the chlorophyll concentration due to "no inflow" conditions. The very slight changes indicate that the concentration of phosphorus in the lake is high enough at the beginning of the season so that the addition of more phosphorus by the inflow has little impact on summer productivity.

4.1.2 "No Phosphorus in the Inflow" Scenario

The model was run with both inflow and outflow, however, the phosphorus concentration in the inflow was set to 0 mg/L. This would be the case for an ideal wetland where all of the nutrients are removed. The surface chlorophyll *a* concentration for the existing condition and the "no phosphorus in the inflow" condition for 1995 and 1996 are presented in Figures 4.3 and 4.4, respectively. The plot for 1995 shows a small decrease in the chlorophyll concentration (productivity) in the fall while the 1996 plot shows an almost negligible decrease in the chlorophyll concentration in the fall. The simulation of only a slight reduction or no reduction indicates that the volume of water from the inflow although, devoid of phosphorus, is not sufficient enough to consistently dilute the phosphorus concentration in the surface mixed layer to reduce the algal productivity.

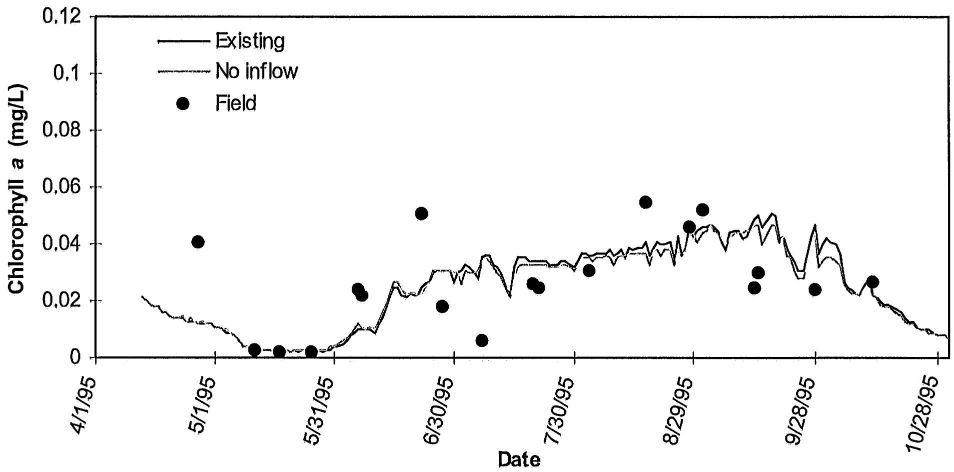

Figure 4.1. Surface chlorophyll *a* in Lake McCarrons with no inflow - 1995.

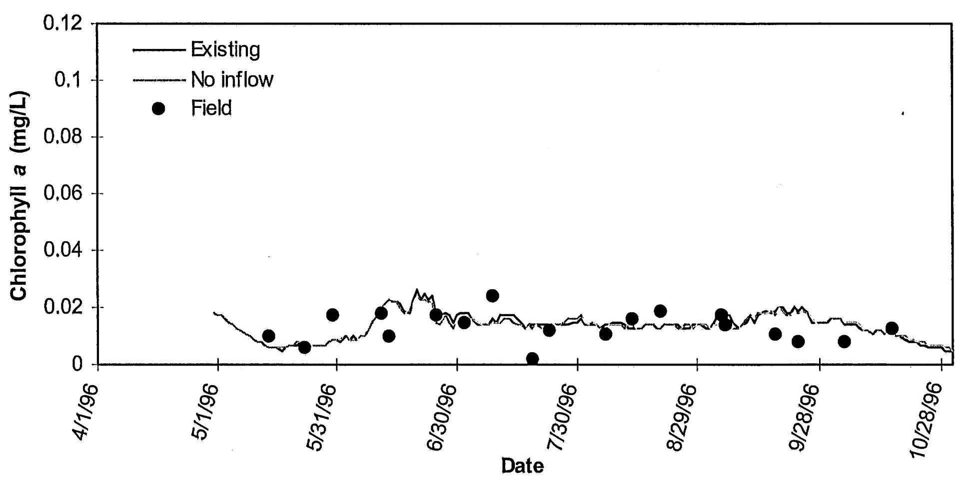

Figure 4.2. Surface chlorophyll *a* in Lake McCarrons with no inflow - 1996.

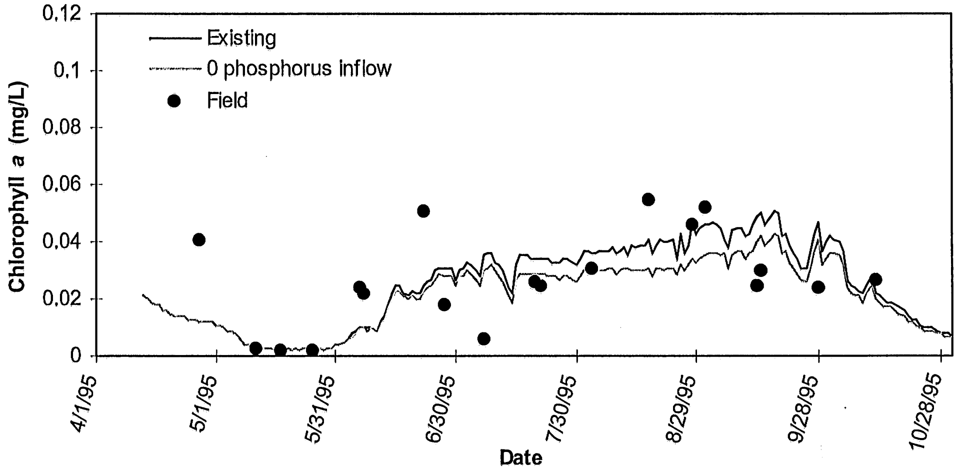

Figure 4.3. Surface chlorophyll *a* in Lake McCarrons with no phosphorus in the inflow - 1995.

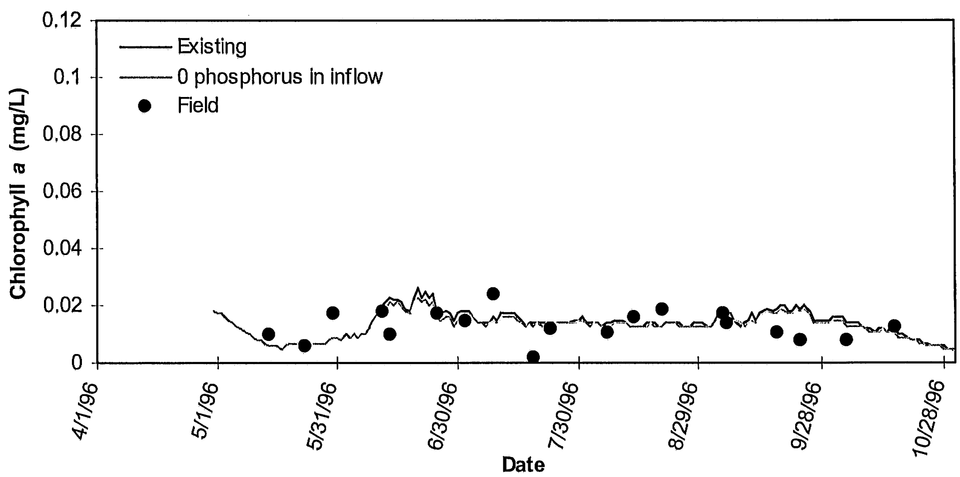

Figure 4.4. Surface chlorophyll *a* in Lake McCarrons with no phosphorus in the inflow - 1996.

4.1.3 "Phosphorus Treatment in the Spring" Scenario

This scenario simulates the treatment of the water column to reduce the phosphorus concentration to 0 mg/L in the spring. This can be done i.g. by precipitation with alum. The surface chlorophyll *a* concentration for the existing condition and the phosphorus treatment in the spring condition for 1995 and 1996 are presented in Figures 4.5 and 4.6, respectively. The spring time phosphorus treatment appears to reduce the productivity during the entire open water season. Productivity is reduced significantly in the spring and well into the summer for the 1995 simulation. The spring phosphorus treatment in 1996 reduces the productivity in the spring, but does not have as significant an impact in summer as in 1995. In 1996 the existing chlorophyll concentration is already less than half that of the 1995 concentration; this may be why the lake phosphorus treatment in the spring does not have as significant an impact. This sort of phosphorus control treatment would need to be applied ever spring.

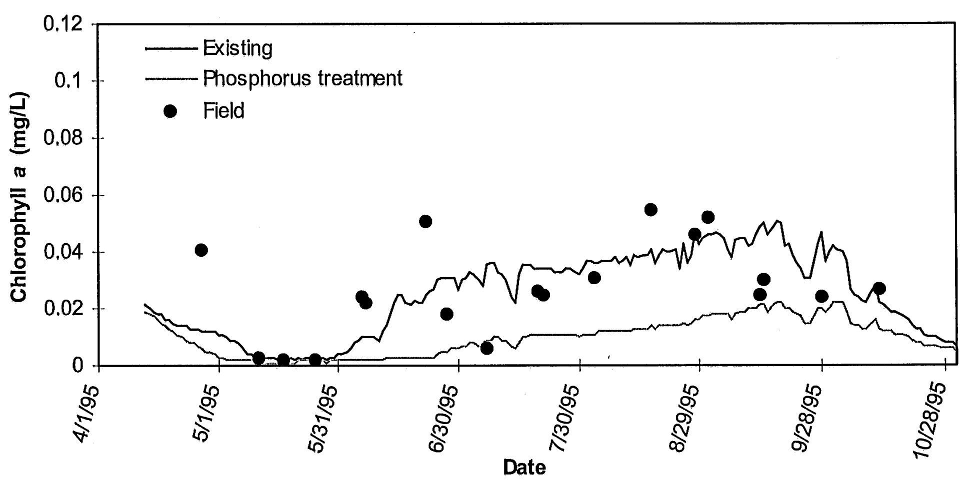

Figure 4.5. Surface chlorophyll *a* in Lake McCarrons with phosphorus treatment in the spring - 1995.

4.1.4 "No Sediment Phosphorus Release" Scenario

This scenario simulates the treatment of the lake sediment to prevent the release of phosphorus. The surface chlorophyll *a* concentration for the existing condition and the "no phosphorus sediment release" condition for 1995 and 1996 are presented in Figures 4.7 and 4.8, respectively. This treatment produces a slight reduction in algal productivity in the fall which is as expected. The phosphorus released to the hypolimnion during the summer does not impact the epilimnion until the fall turnover. It is difficult to predict how long the sediment treatment would be effective. Assuming a stable sediment, a sediment treatment may need to be applied for a few years to achieve an ongoing algal productivity reduction. If external phosphorus input from the watershed is substantial, sediment treatment would need to be applied frequently.

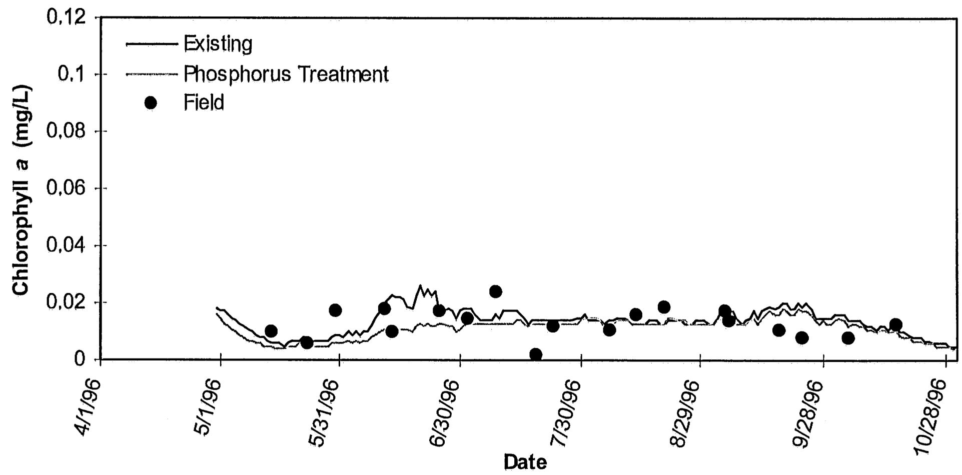

Figure 4.6. Surface chlorophyll *a* in Lake McCarrons with phosphorus treatment in the spring - 1996.

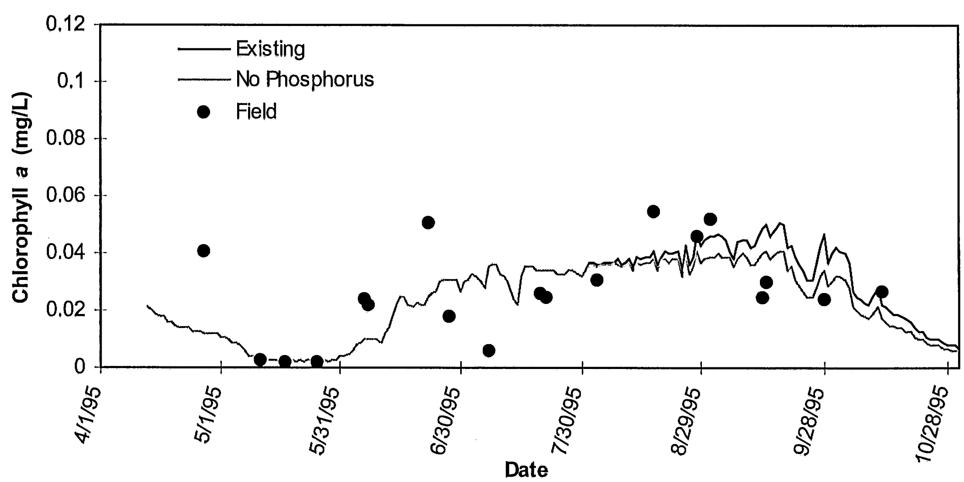

Figure 4.7. Surface chlorophyll *a* in Lake McCarrons with no phosphorus release from the sediment - 1995.

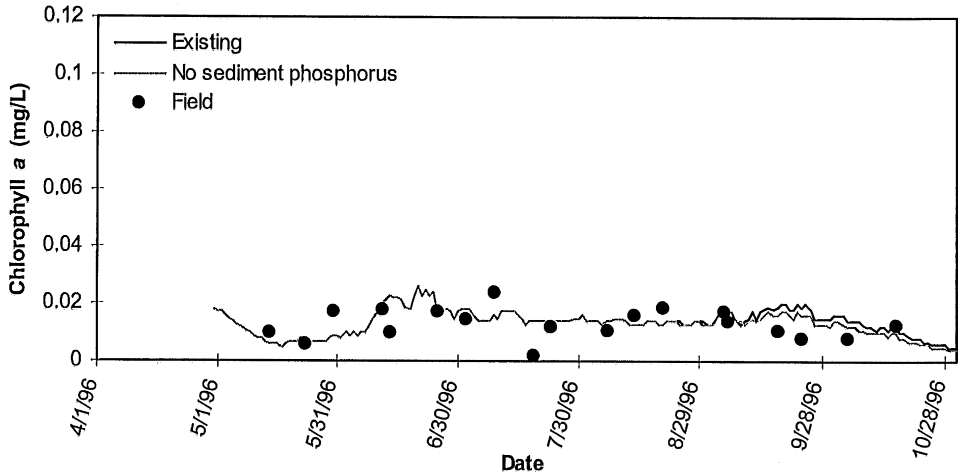

Figure 4.8. Surface chlorophyll *a* in Lake McCarrons with no phosphorus release from the sediment - 1996.

4.2 Mixed Layer Deepening

Previously published work by Denman, Megard, Skoglund, Gulliver and Stefan indicates that standing crops of phytoplankton populations go down when the surface mixed layer depth increases. What keeps the concentrations of the phytoplankton down are selfshading and losses (respiration, grazing, and settling). In a deep mixed layer the total phytoplankton mass in g/m^2 of lake surface area can be large while the concentrations are small. Total loses/day are proportional to a loss rate coefficient times the total mass (assuming first order kinetics). Photosynthetic production is not proportional to that mass because only the upper portion of the population in the water column receives enough light. So photosynthetic production per unit surface area of the water column has a value limited by light, no matter what the mixed layer depth is. On the other hand, losses increase linearly with the mass of the standing crop per unit surface area, and that mass increases linearly with surface mixed layer depth. As the surface mixed layer depth increases the losses increase while the photosynthetic production is finite. This is what reduces the concentrations in the surface mixed layer as the surface mixed layer depth increases.

Mixed layer deepening was applied in the model at the end of the daily simulation as a separate subroutine which increased the mixed layer depth to the specified depth (4 m, 6 m, and 8 m) as needed. To calculate new average concentration of materials in the new surface mixed layer, the entire mass of material (algae) in the layers comprising the new surface mixed layer was summed and then divided by the entire volume of the mixed layer.

Figure 4.9 shows the productivity (chlorophyll *a*) changes by deepening of the mixed layer to 4 m, 6m, and 8m for 1995. These results are as expected and similar to what other researchers have found when the mixed layer is deepened. The simulation shows that increasing the mixed layer to 4 m depth decreases the surface concentration on average by a little over 10%. The reduction is 50% or more at surface mixed layer depth of 8 m. Deepening of the mixed layer will tend to average the productivity over time and remove some of the growth spikes and crashes. The reductions shown in Fig. 4.9 are over the entire time simulated, mid-April through October.

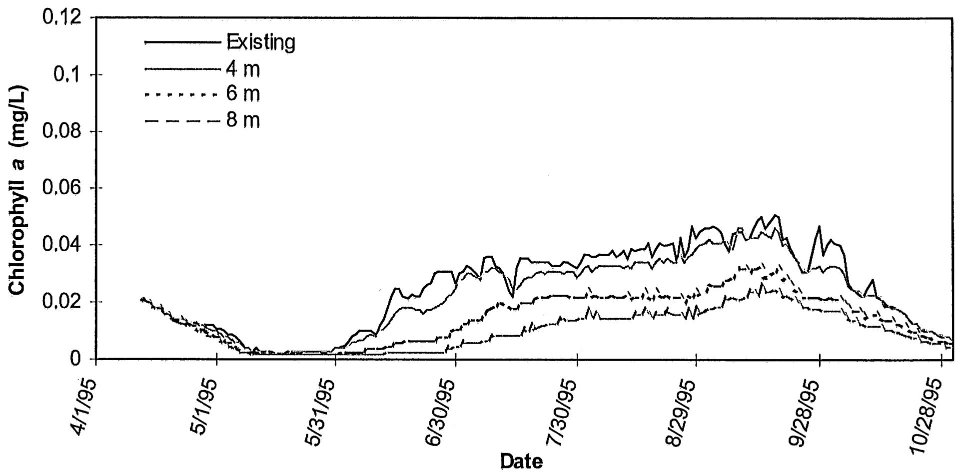

Figure 4.9. Surface chlorophyll *a* in Lake McCarrons with mixed layer deepening - 1995.

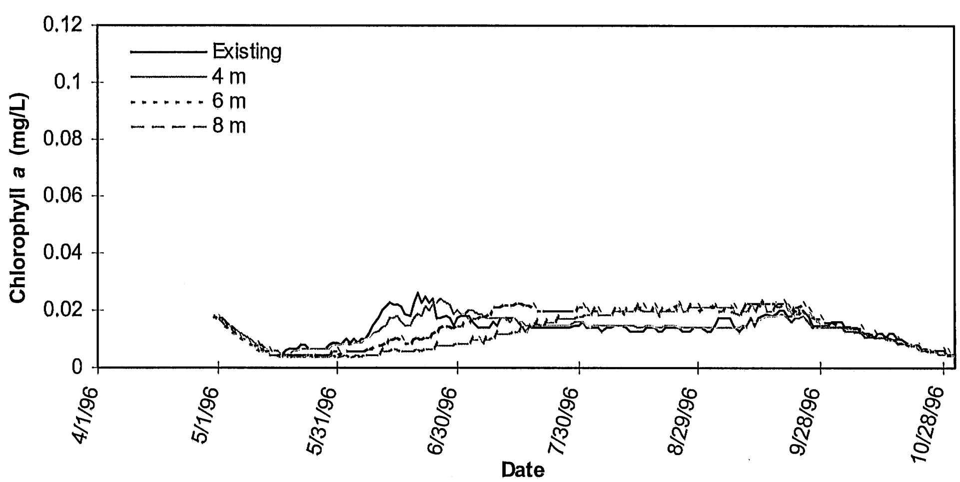

Figure 4.10. Surface chlorophyll *a* in Lake McCarrons with mixed layer deepening - 1996.

Figure 4.10 shows the productivity (chlorophyll a) changes by deepening of the mixed layer to 4 m, 6m, and 8m for 1996. The simulation shows that increasing the mixed layer to 4 m depth has very little impact on the overall algal concentration. As for 1995, deepening of the mixed layer tends to remove some of the growth spikes and crashes. Increasing the mixed layer to 6 m depth appears to increase productivity by around 10% overall; increasing the mixed layer to 8 m depth decreases the surface productivity in early summer, but not in August or September. This is because when phytoplankton concentrations and hence selfshading are already low, the surface mixed layer depth is less than the photic depth The reduction in the spring is offset by the increase in the summer. So, overall the reductions in overall standing algal crops by deepening of the surface mixed layer are less clear in the 1996 simulations when the existing concentrations were already lower than in 1995 when they were high.

6. SUMMARY AND CONCLUSIONS

The surface inflow during the summer does not seem to add much to the growth of the phytoplankton. This may indicate that there is already enough phosphorus present from the beginning of the season, so that any addition of phosphorus during the summer does not do much for plant growth. This would imply that the warming of the water in the wetland has no substantial negative consequence for algal blooms in the lake in summer.

The results of the simulation of a whole-lake phosphorus treatment in the spring indicate that the removal of phosphorus in the spring will impose a nutrient limitation for several months to follow. This is therefore a viable method for control of phytoplankton growth in the lake in summer.

Sediment treatment, e.g. with bentonite or by the RIPLOX method would prevent or reduce chemical recycling of phosphorus connected with iron. It would reduce internal phosphorus loading of the lake resulting in a gradual reduction of algae growth potential, provided that the external phosphorus loading from the watershed is small enough. During the summer months, sedimentary phosphorus release cannot contribute to the growth of algae near the lake surface because of the strong stratification of the lake.

Mixed layer deepening has substantial potential for productivity control. If mixed layer deepening is the method chosen for productivity control a mechanism for monitoring the mixed layer depth and a pneumatic or hydraulic mixing device have to be installed in the lake.

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APPENDIX A. THE N:P RATIO IN LAKE MCCARRONS

The nitrogen to phosphorus ratios (N:P) for Lake McCarrons were computed using total nitrogen and total phosphorus. (Concentrations for the bioavailable forms are not available.) The total nitrogen was estimated using the sum of total kjeldahl nitrogen (which consists primarily of organic nitrogen and ammonia) and nitrate+nitrite measurements. The average TN:TP ratio for 1993 to 1997 is 29 ± 13 (Table 1). Figure 1 presents the individual TN:TP ratios for 1993 to 1997. Ratios of N:P greater than 20 are considered to reflect phosphorus limited systems and ratios of N:P less than 5 are considered to reflect nitrogen limited systems (Thomann and Mueller, 1987 p.401). Figure A.1 shows a general trend of an increasingly phosphorus limited system. The lowest measured TN:TP ratios increase with time (Table A.1). Lake McCarrons is currently a phosphorus limited lake.

Table A.1. Total nitrogen to total phosphorus ratios in Lake McCarrons for 1993 to 1997

Year	Mean ± Std Deviation	Lowest Value
1993	24 ± 13	4
1994	31 ± 13	8
1995	31 ± 14	11
1996	31 ± 11	14
1997	33 ± 13	16
Mean	29 ± 13	

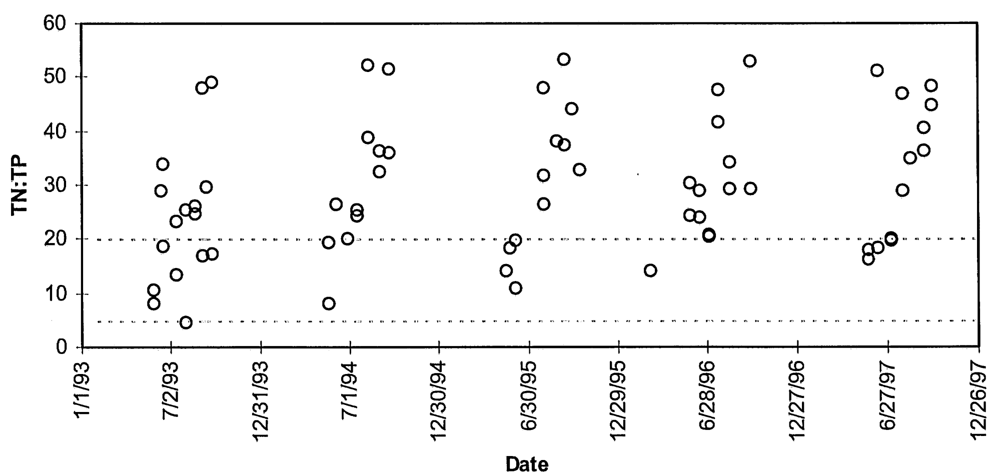


Figure A.1. Total nitrogen to total phosphorus ratios in Lake McCarrons for 1993 to 1997.

APPENDIX B. MINLAKE98 CALIBRATION COEFFICIENTS

Table B.1. Table of coefficients for simulation of Lake McCarrons using MINLAKE98.

Coefficient	Abreviation	Units	1995	1996
Type of model simulation	model	--	1	1
Number of algal classes	nclass	--	2	2
Flag for silica simulation	idiatom	--	0	0
Flag for nitrogen simulation	nitro	--	0	0
Number of iterations in the biological nutrient routines	iter	--	1	1
Total number of field data days	ndays	d	17	19
Field data year	kyear	y	1	1
Minimum layer thickness	dzll	m	0.5	0.5
Maximum layer thickness	dzul	m	1	1
Surface radiation absorption	beta	--	0.3	0.3
Emissivity of water	emiss	--	0.97	0.97
Light extinction of water	xk1	1/m	0.7	0.5
Light extinction of chlorophyll	xk2	m^2/g chla	16	14
Wind function	wcoef	--	0.9	0.9
Wind sheltering	wstr	--	.0.2	0.1
Wind function open season	wcfsf	--	0.8	0.7
Wind sheltering open season	wssf	--	0.3	0.1
Width of the inflow channel	wchannel	m	3	3
Maximum width of the lake perpendicular to the inflow channel	wlake	m	412	412
Elevation of lake bottom above mean sea level	dbl	m	239.3	239.3
Lake stage	st	m	256.6	256.6
Slope of inflow channel	s	--	0.01	0.01
Mannings roughness coef. for density currents	ft		0.035	0.035
Elevation of outflow channel bottom	elcb	m	256.3	256.3
Side slope of outflow channel	alpha	---	1	1
Bottom width of outflow channel	bw	m	1	1
Number of layers	mbot	--	17	19
Number of months in the first year	nm	--	7	7
Number of inflows in the inflow data file	inflow	1	1	1
Julian day	jdy	--	103	121
Initial month of the simulation	month	--	4	4
First day of the simulation	istart	--	13	30
Year at the start of the simulation	myear	--	1995	1996
Detrital decay rate	bodk20	1/d	0.05	0.05

Coefficient	Abreviation	Units	1995	1996
Sediment oxygen depletion rate	sb20	g/m^2 d	2	2
Sediment phosphorus release rate	brr	g/m^2 d	0.029	0.02
Settling rate of detritus	fvchla	m/d	0.04	0.04
Mass yield ratio of chlorophyll to dissolved oxygen	ycho2	mg chla/ mg DO	0.083	0.083
Mass yield ratio of chlorophyll to BOD	ycbod	mg chla/ mg BOD	0.0083	0.0083
Mass yield ratio of phosphorus to BOD	ypbod	mg P/ mg BOD	0.0091	0.0091
Mass yield ratio of phosphorus to zooplankton	ypzp	mg/ind.	0	0
Mass yield ratio of zooplankton to oxygen	yzdo	mg O^2/ mg Zoo	1.04	1.04
Average mass of individual zooplankton	yzw	mg/ind.	0.003	0.003
Mass yield ratio of phosphorus to chlorophyll	ypchla	mg P/ mg Chla	0.7	0.8
Maximum growth rate of algae #1	growmax (1)	1/d	0.6	0.4
Maximum growth rate of algae #2	growmax(2)	1/d	1.4	0.9
Temperature at which growth is reduced 90%	tmax(1)	°C	35	35
	tmax(2)	°C	35	35
Optimal temperature for growth	topt(1)	°C	20	20
	topt(2)	°C	25	25
Algal respiration rate	xkr1(1)	1/d	0.06	0.04
	xkr1(2)	1/d	0.12	0.12
Algal mortality rate	xkm(1)	1/d	0.06	0.04
	xkm(2)	1/d	0.10	0.10
Half saturation for phosphorus uptake	hscpa(1)	mg/L	0.02	0.02
	hscpa(2)	mg/L	0.03	0.005
Settling velocity of algae	fvchla(1)	m/d	0.01	0.01
	fvchla(2)	m/d	0.01	0.01
Minimum temperature at which growth is reduced by 90%	tmin(1)	°C	0	0
	tmin(2)	°C	11	12
Light limitation	hscl(1)	$\mu E/m^2$ s	100	100
	hscl(2)	$\mu E/m^2$ s	400	400
Light inhibition	hsc2(1)	$\mu E/m^2$ s	700	700
	hsc2(2)	$\mu E/m^2$ s	1000	1000
Zooplankton population	zp	$\#/m^3$	800	900
Minimum zooplankton population for predation to occur	zpmin	$\#/m^3$	100	100
Minimum seasonal zooplankton predation rate	prmin	1/d	0.05	0.05
Maximum seasonal daytime predation rate on zooplankton	prmax	1/d	0.7	0.7
Predation rate during vertical migration	predmin	1/d	0.03	0.03
Minimum light intensity for zooplankton predation	ximin		0	0

Coefficient	Abreviation	Units	1995	1996
		μE/m² s		
Maximum light intensity for zooplankton predation	ximax	μE/m² s	0.1	0.1
Julian day for the end of the minimum predation preiod	minday	--	130	130
Julian day for beginning of maximum predation period	maxday	--	160	160
Zooplankton respiration rate	xkrzp	1/ind. D	0.002	0.002
Zooplankton reproduction rate	repro	1/d	0.02	0.02
Grazing assemmilation	asm	--	0.5	0.5
Temperature coef. zooplankton respiration	thrzp	--	1.06	1.06
Maximum zooplankton grazing rate	grazmax(1)	mg chla/ ind d	0.01	0.01
	grazmax(2)	mg chla/ ind d	0	0
Half saturation for grazing on chlorophyll	hscgraz(1)	mg/L	0.0001	0.0001
	hscgraz(2)	mg/L	0.0001	0.0001
Minimum chlorophyll for grazing to occur	chlamin(1)	mg/L	0.001	0.001
	chlamin(2)	mg/L	0.001	0.001
Percentage of surface area which contributes to mixing	emcoe(1)	--	0.3	0.2
Maximum specific photosynthetic oxygen production rate	pomax		8	8
Constant for computing kw fro CZs/Zs	emcoe(3)		-1.8	-1.8
Number of depth for time series plots	ndepth	--	5	5
Depths for time series	fdth(1)	m	0	0
	fdth(2)	m	3	3
	fdth(3)	m	5	5
	fdth(4)	m	9	9
	fdth(5)	m	16	16
Year of times series	idnum(6)	--	1995	1996
Total number of years to be simulated	nytot	y	1	1
Number of months in the last year to be simulated	nmfin	month	9	9
Total depth of sediment	zslt	m	10	10
Number of sediment layers	izslt	--	11	11
Kb thermal diffusivity of sediment	ahtbtm	m²/d	0.035	0.035
Density*heat capacity of sediment	srcp	kcal/ kg °C	550	550
Mean sediment temperature	tslmean	°C	4	4
Exponential function factor to increase temperature gradient	etab	--	2	2
Initial bottom water temperature	t2mbot	°C	4	4
Gradiant at z=0	fakw	--	1	1

APPENDIX C. ESTIMATION OF WETLAND OUTFLOW TEMPERATURE

The temperature of the wetland outflow into Lake McCarrons was not measured for 55 out 202 days of simulation for 1995 (4/13/95-5/31/95; 8/6-11/95) and for 4 out of 185 days of simulation for 1996 (8/6-7/96; 8/22/96; 8/30/96). For simulations of Lake McCarrons for those years the missing wetland outflow temperatures were estimated from the measured air temperature. A linear relationship between the measured air temperature and the measured wetland outflow temperature for 1999 was calculated. The wetland outflow temperature was measured at the weir going from the wetlands to the short creek flowing into Lake McCarrons. The local air temperature was measured with one of the thermistors on the litoral raft. Measurements were recorded every 10 minutes for both instruments. Air temperature was recorded from May 1, 1999 to October 26, 1999 (with data missing from 9/27/99-10/14/99); wetland outflow temperature was recorded from March 26, 1999 to October 18, 1999. Values from May 1, 1999 to October 17, 1999 (excluding September 27 - October 14) were used for determining the linear relationship. Time averaged daily values were calculated for both the air temperature and the wetland outflow temperature and then compared. The linear relationship of daily air temperature to daily wetland outflow temperature is presented in Figure C.1. The linear relationship is: wetland outflow temperature = 0.65 * air temperature + 6.74, with a r-squared value of 0.81. The wetland outflow temperatures for 1995 and 1996 were estimated using the above equation and the air temperature measured at the University of Minnesota in St. Paul for the respective years.

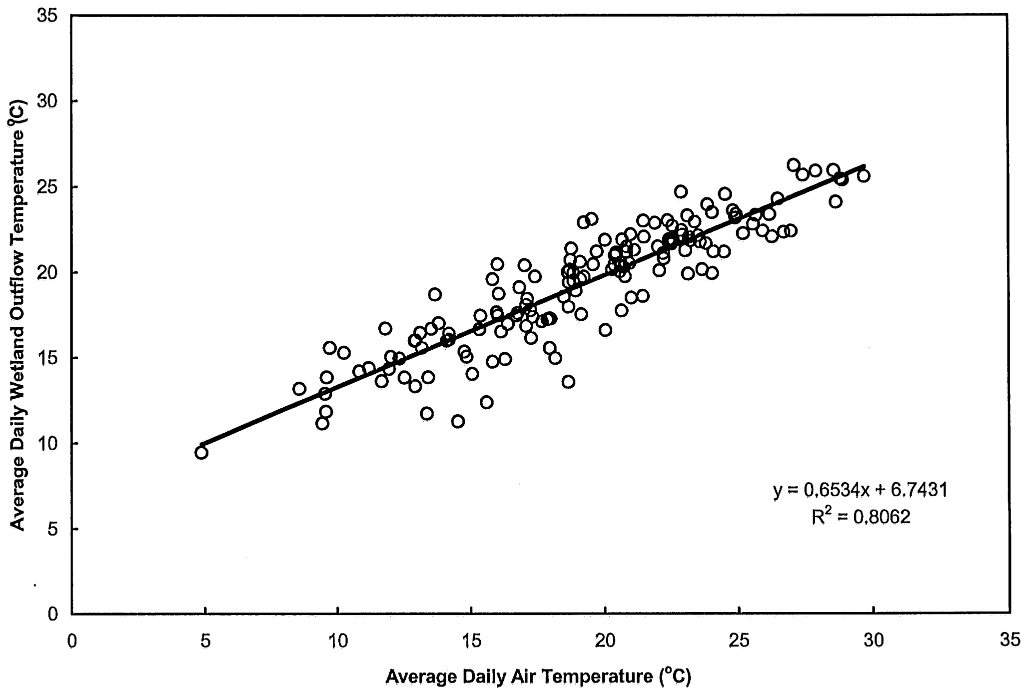


Figure C.1. Linear relationship of the daily air temperature to the daily wetland outflow temperature for Lake McCarrons, 1999.

Appendix D. Calibration of MINLAKE98 for 1995

A comparison of the observed and simulated values is presented in this appendix.

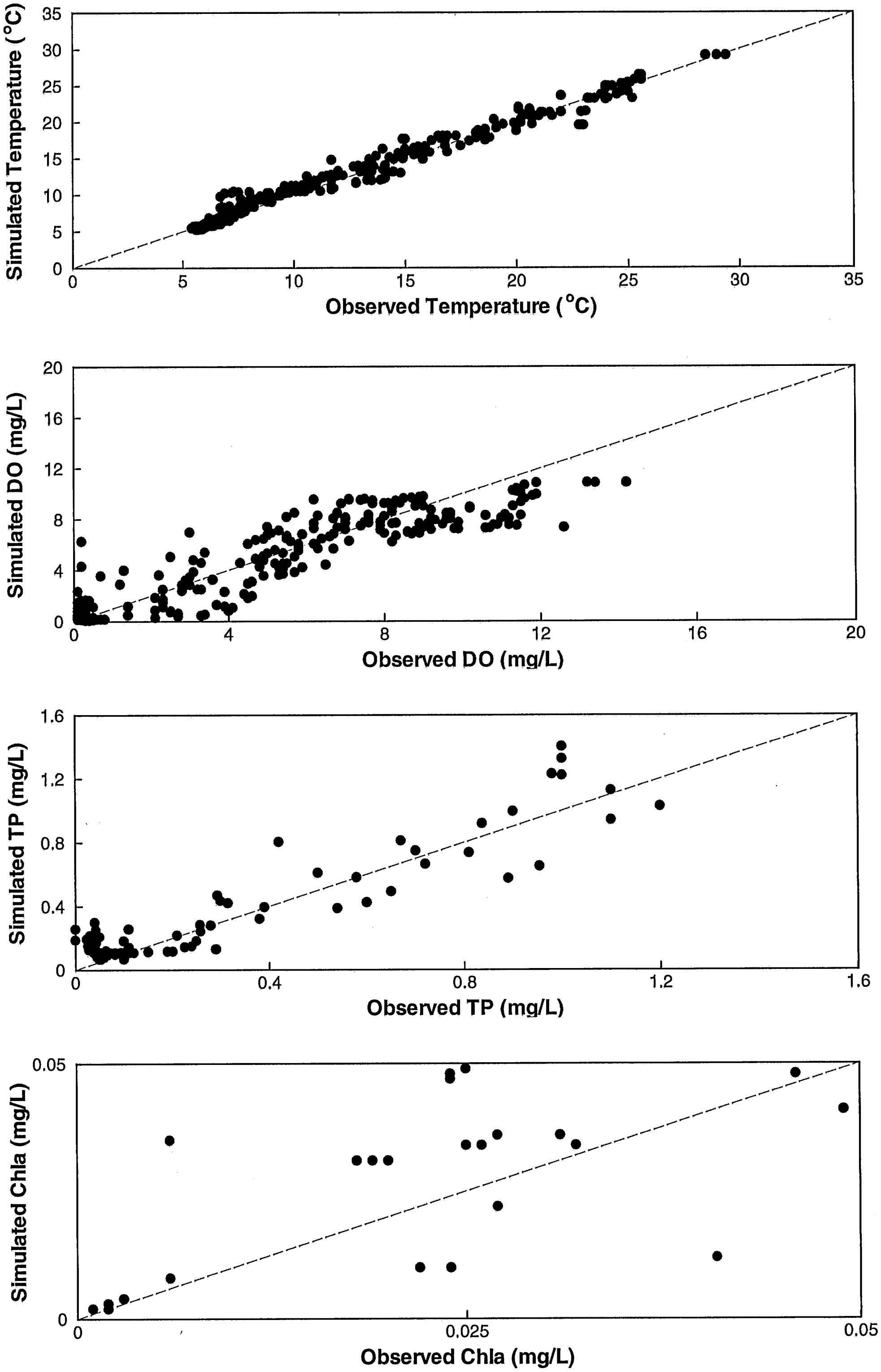


Figure D.1. Comparison of simulated and observed water quality values for Lake McCarrons calibrated for 1995

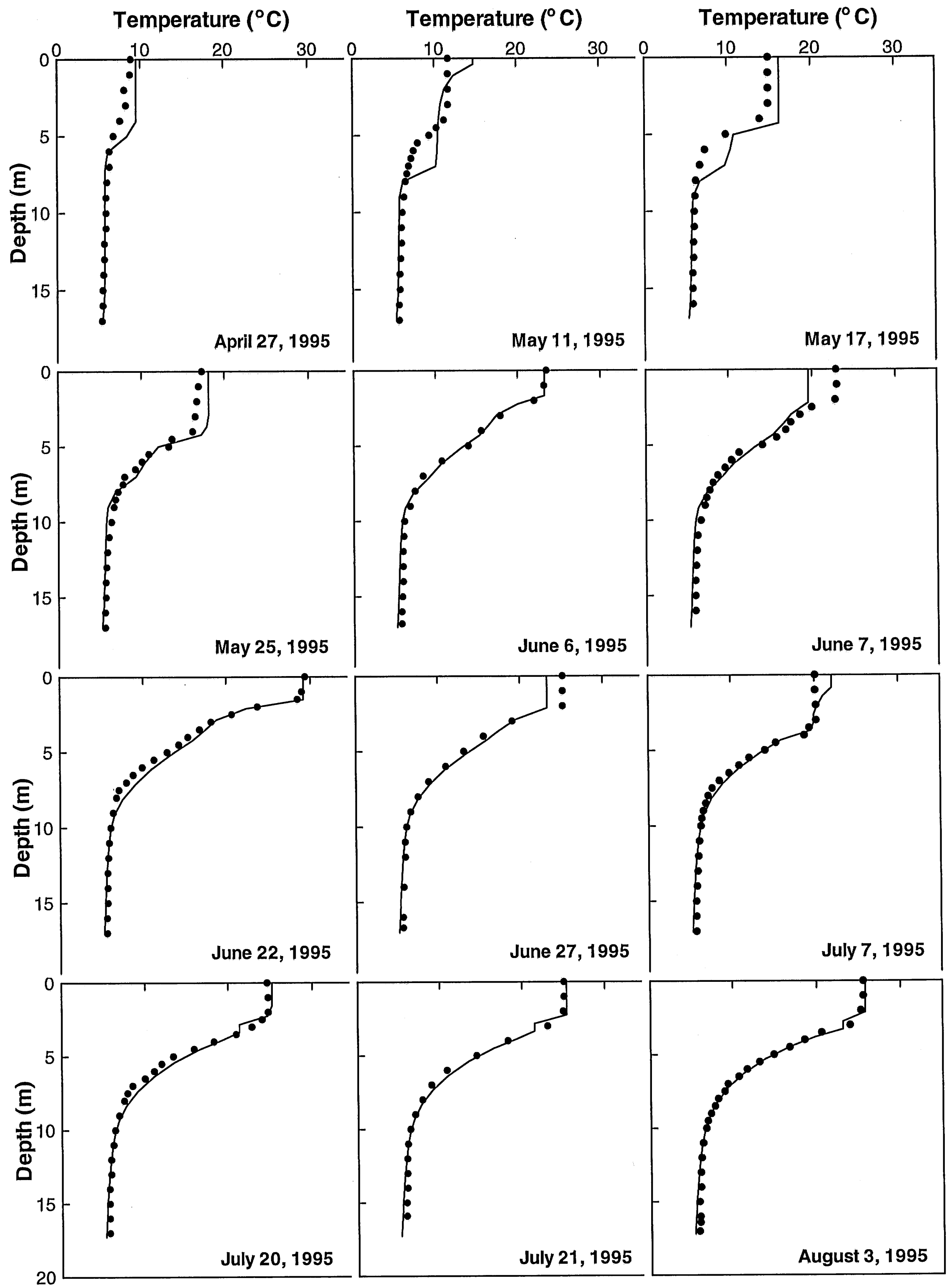


Figure D.2. Simulated (line) and observed (dot) water temperature profiles for Lake McCarrons calibrated for 1995.

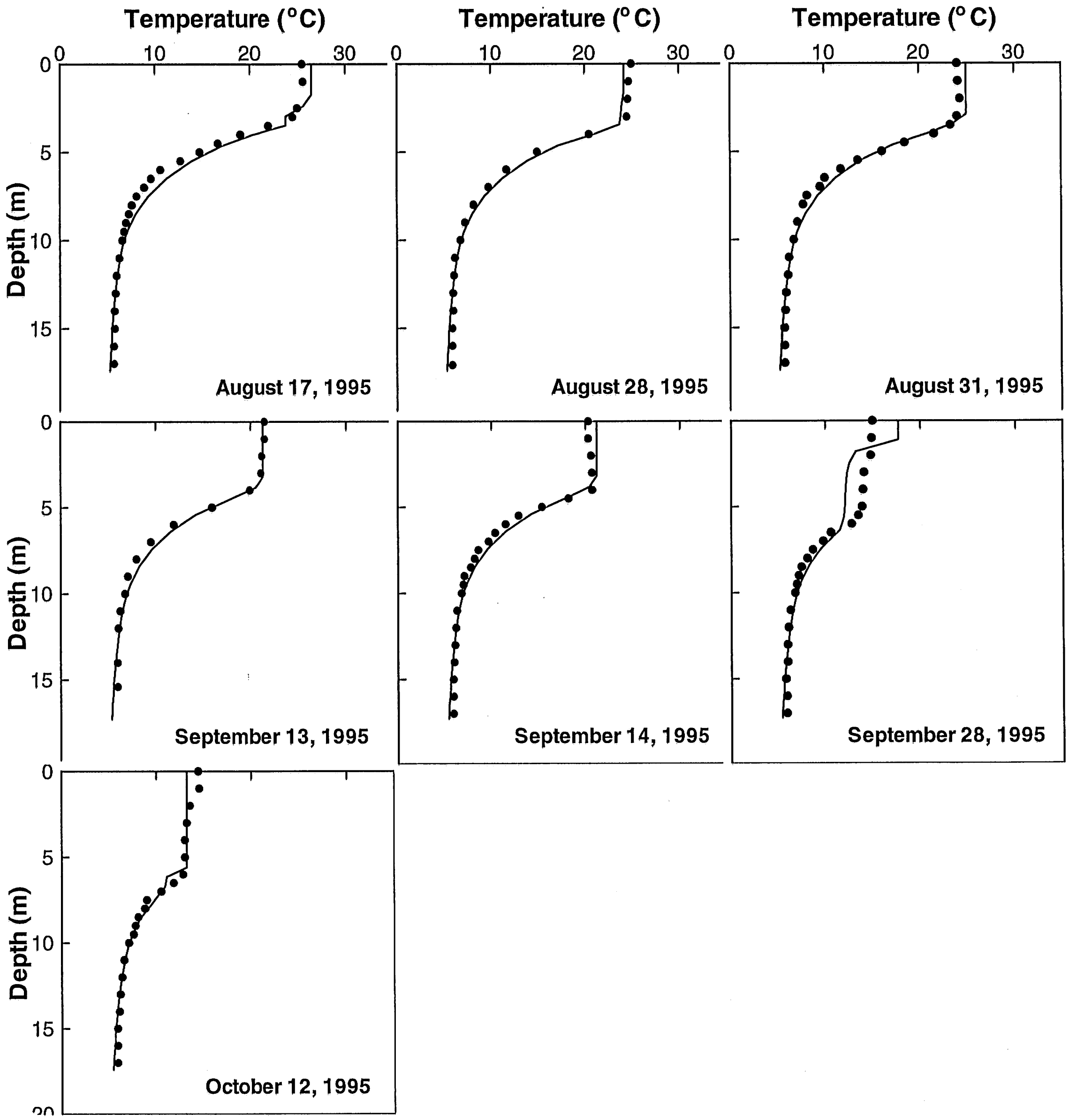


Figure D.2. (cont'd.) Simulated (line) and observed (dot) water temperature profiles for Lake McCarrons calibrated for 1995.

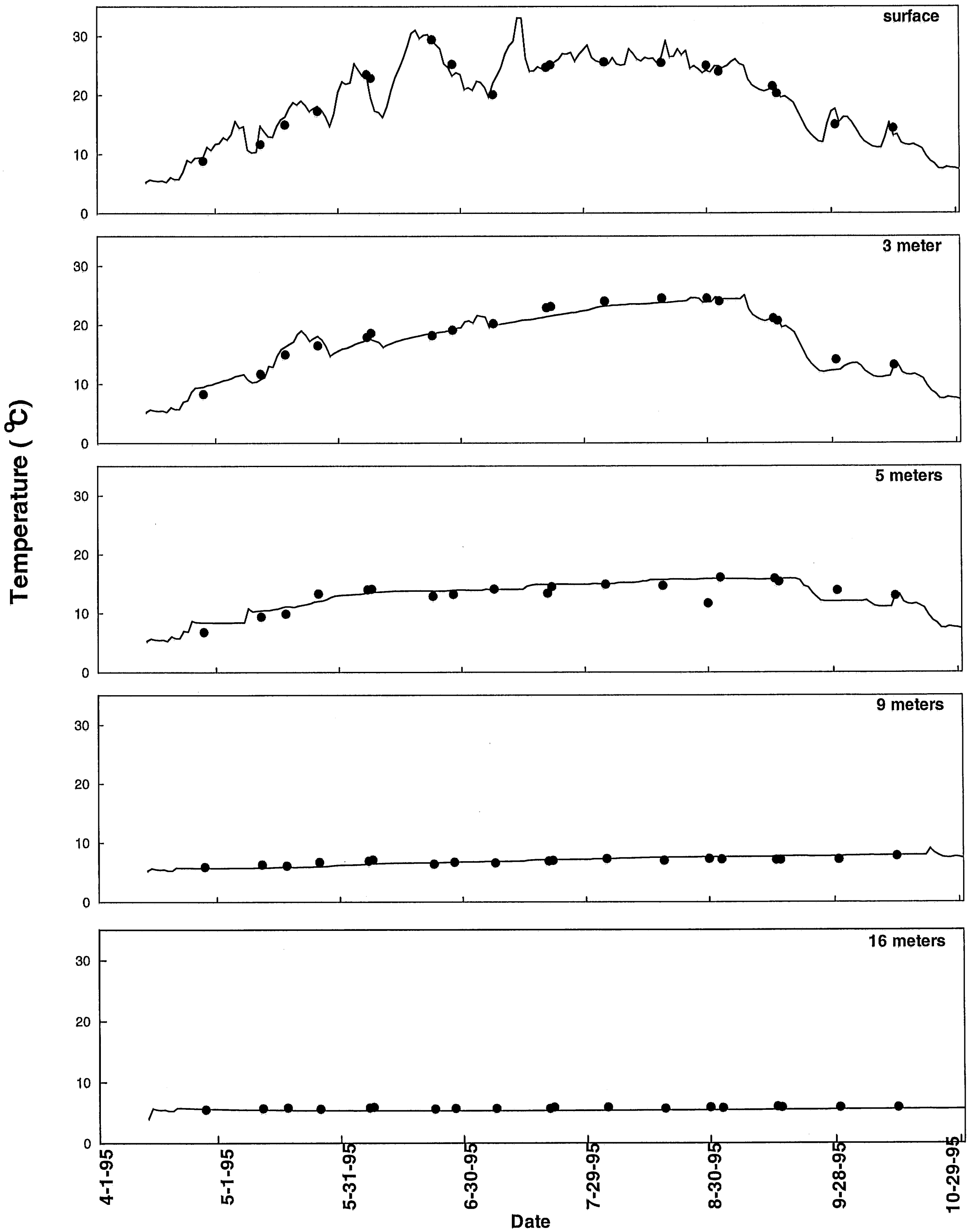


Figure D.3. Simulated (line) and observed (dots) water temperatures at a) surface, b) 3m, c) 5 m, d) 9 m, and e) 16 m below the surface for Lake McCarrons, April to October 1995.

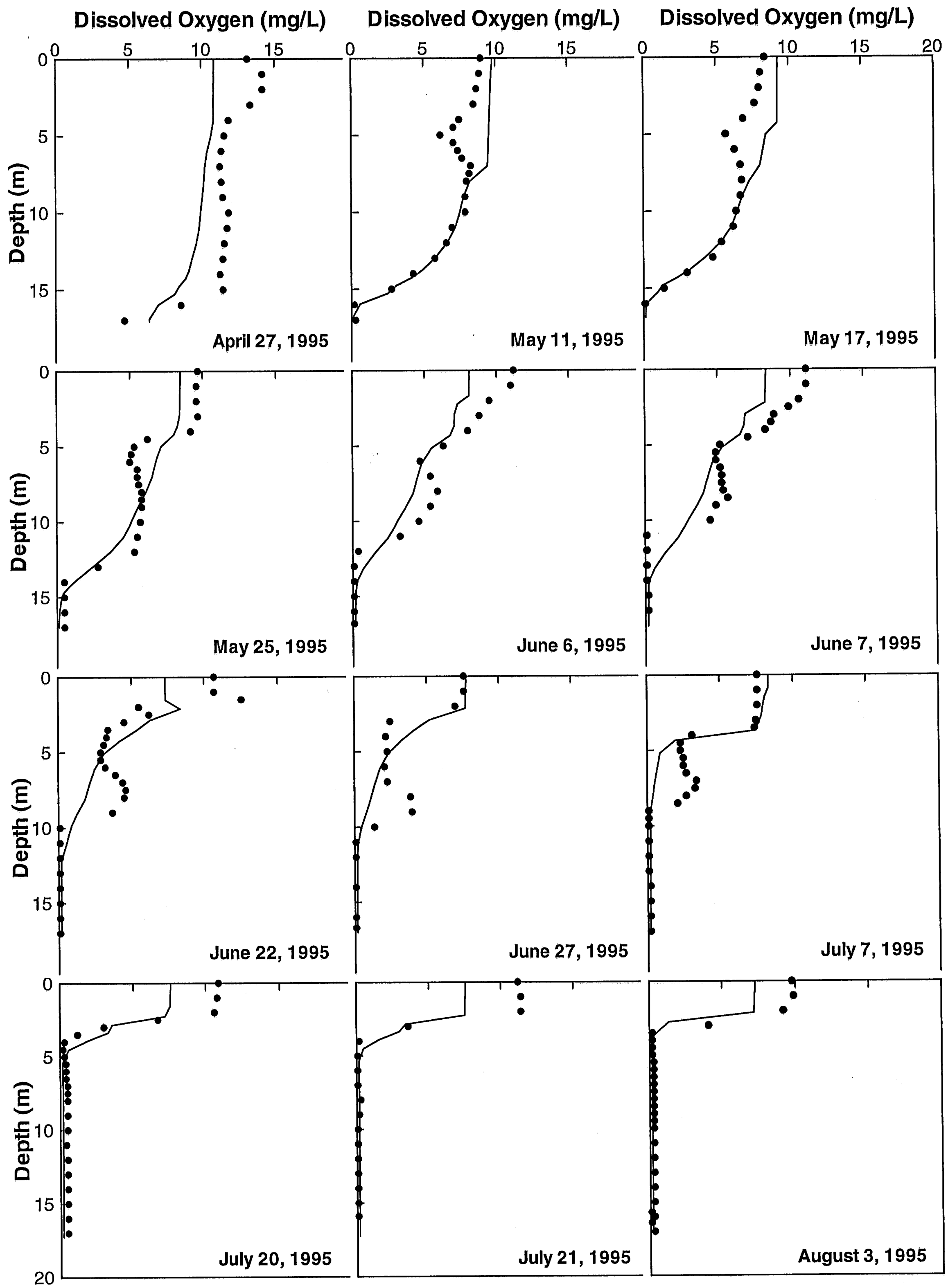


Figure D.4. Simulated (line) and observed (dot) dissolved oxygen profiles for Lake McCarrons calibrated for 1995.

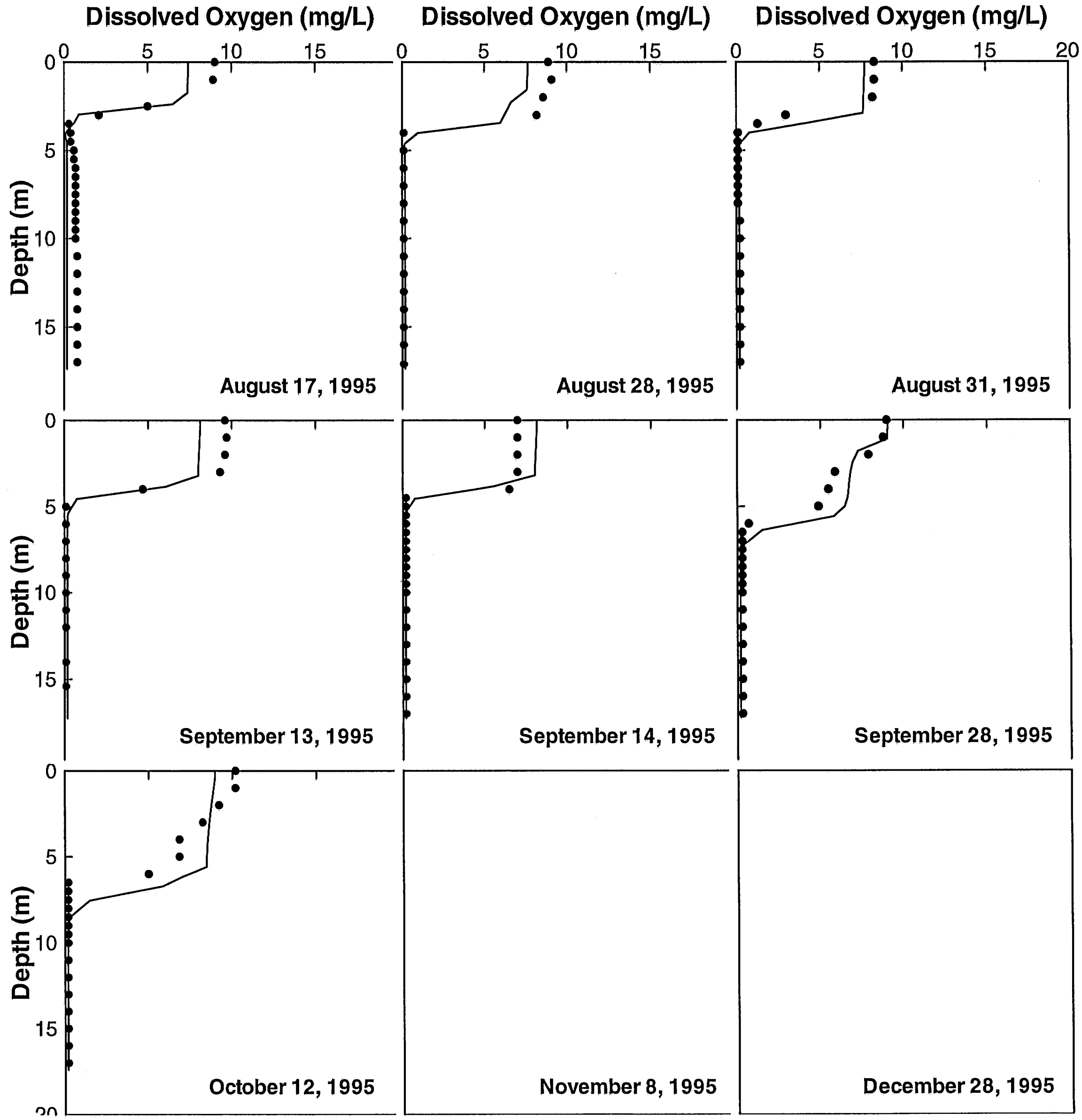


Figure D.4. (cont'd). Simulated (line) and observed (dot) dissolved oxygen profiles for Lake McCarrons calibrated for 1995.

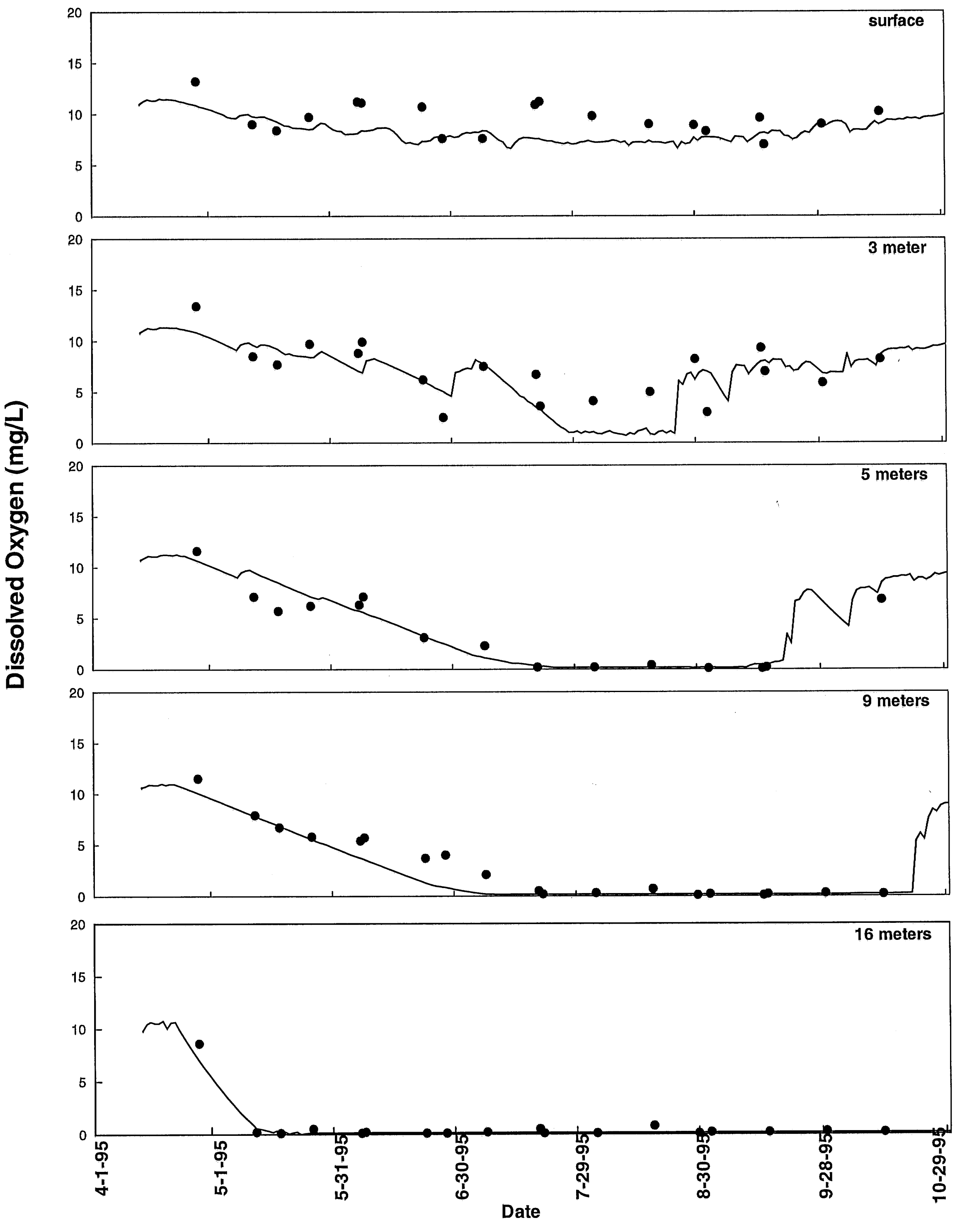
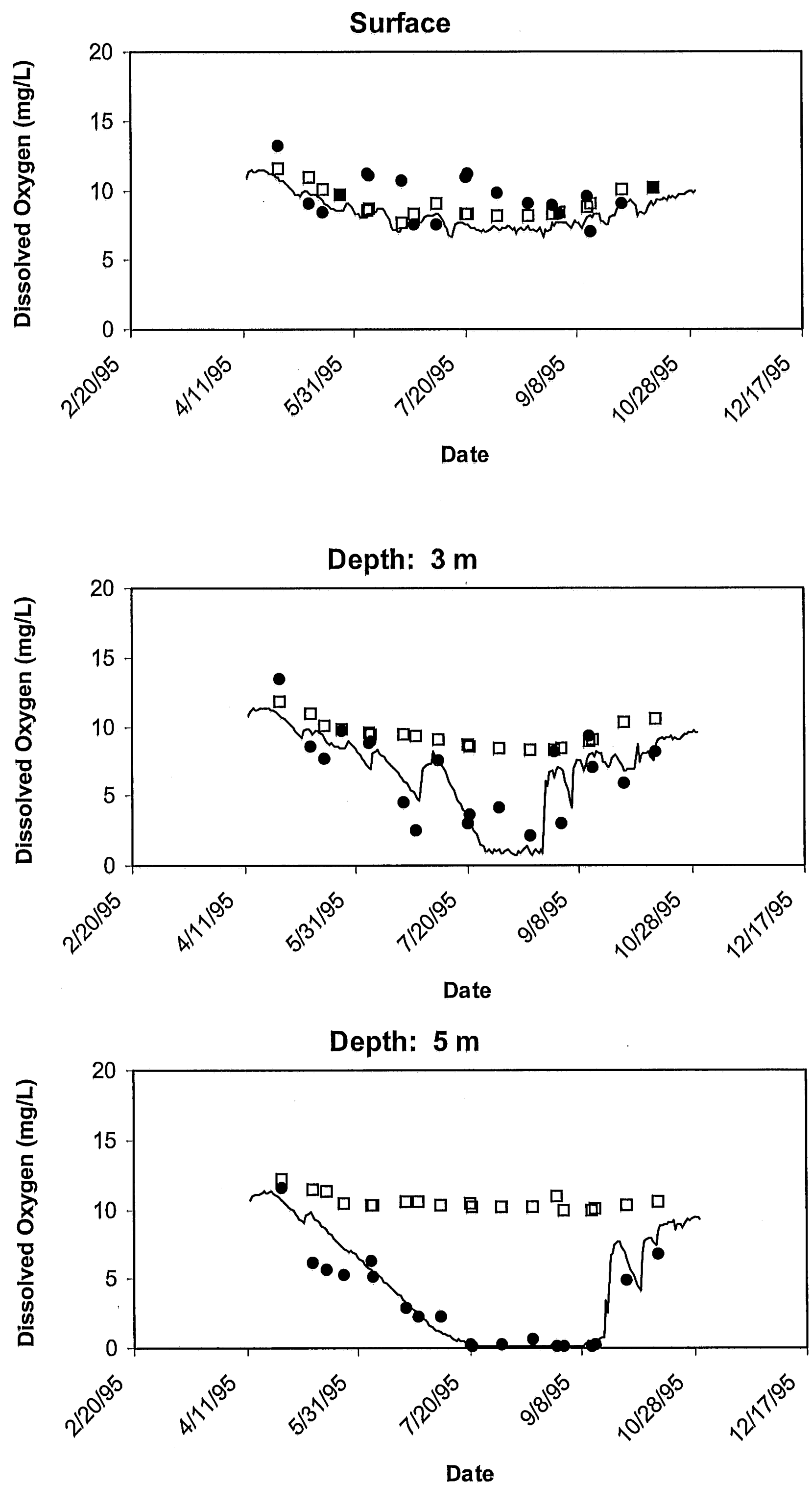


Figure D.5. Simulated (line) and observed (dots) dissolved oxygen at a) surface, b) 3m, c) 5 m, d) 9 m, and e) 16 m below the surface for Lake McCarrons, April to October 1995.



D.6. Simulated (line), observed (dots) dissolved oxygen, and calculated sasturated oxygen (squares) at a) surface, b) 3 m, c) 5 m below the surface for Lake McCarrons, April to October 1995.

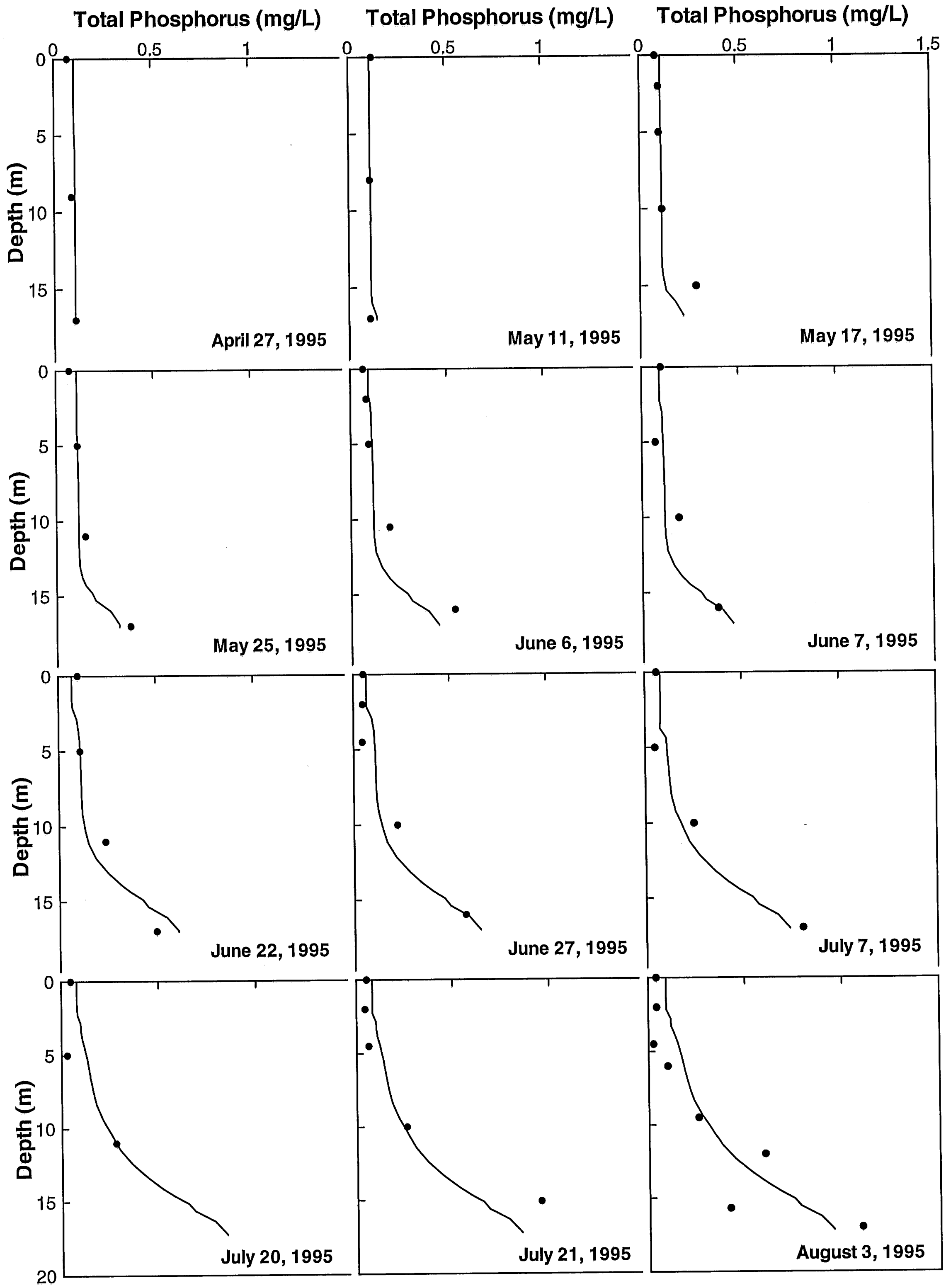


Figure D.7. Simulated (line) and observed (dot) total phosphorus profiles for Lake McCarrons calibrated for 1995.

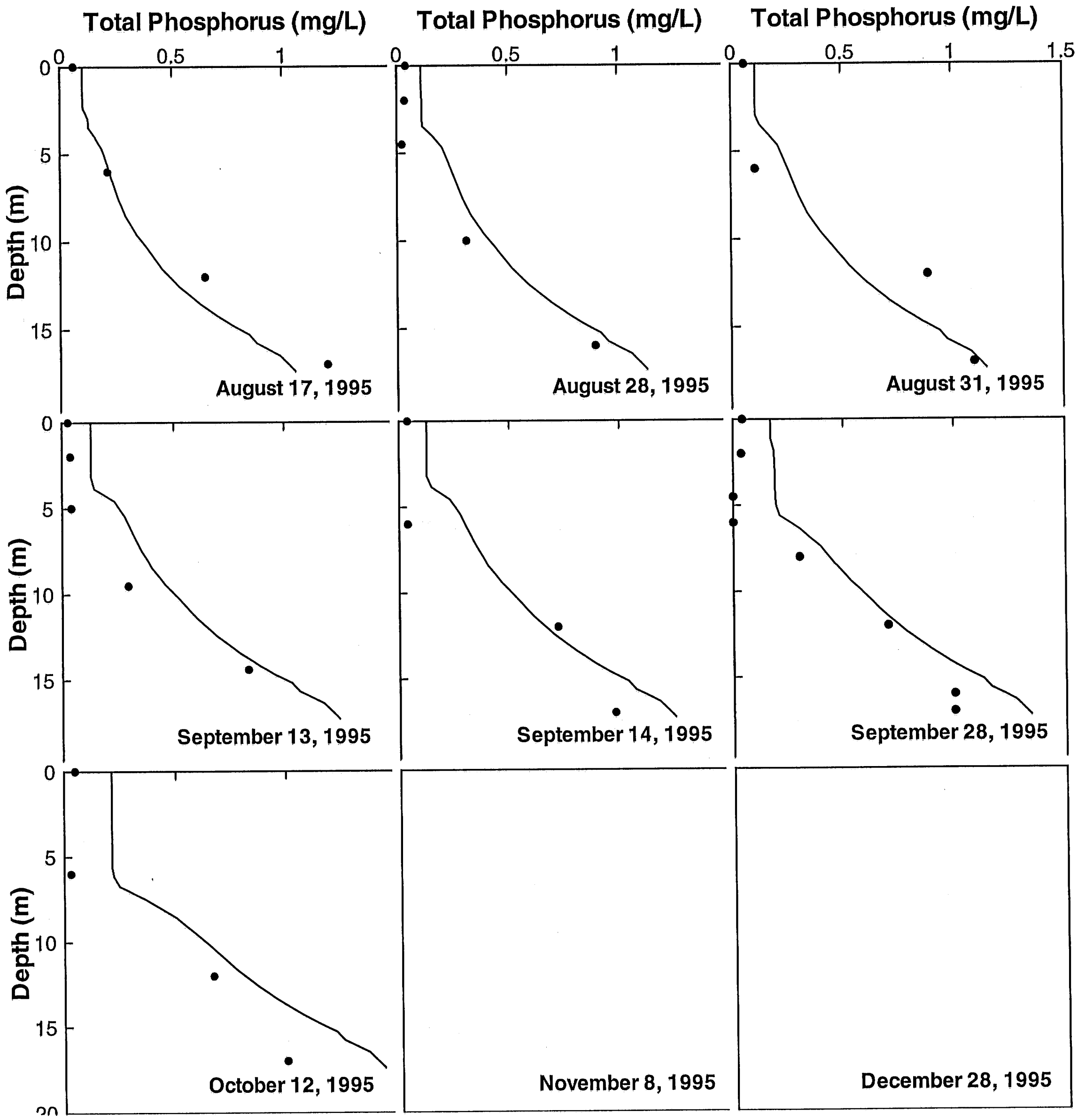


Figure D.7 (cont'd). Simulated (line) and observed (dot) total phosphorus profiles for Lake McCarrons calibrated for 1995.

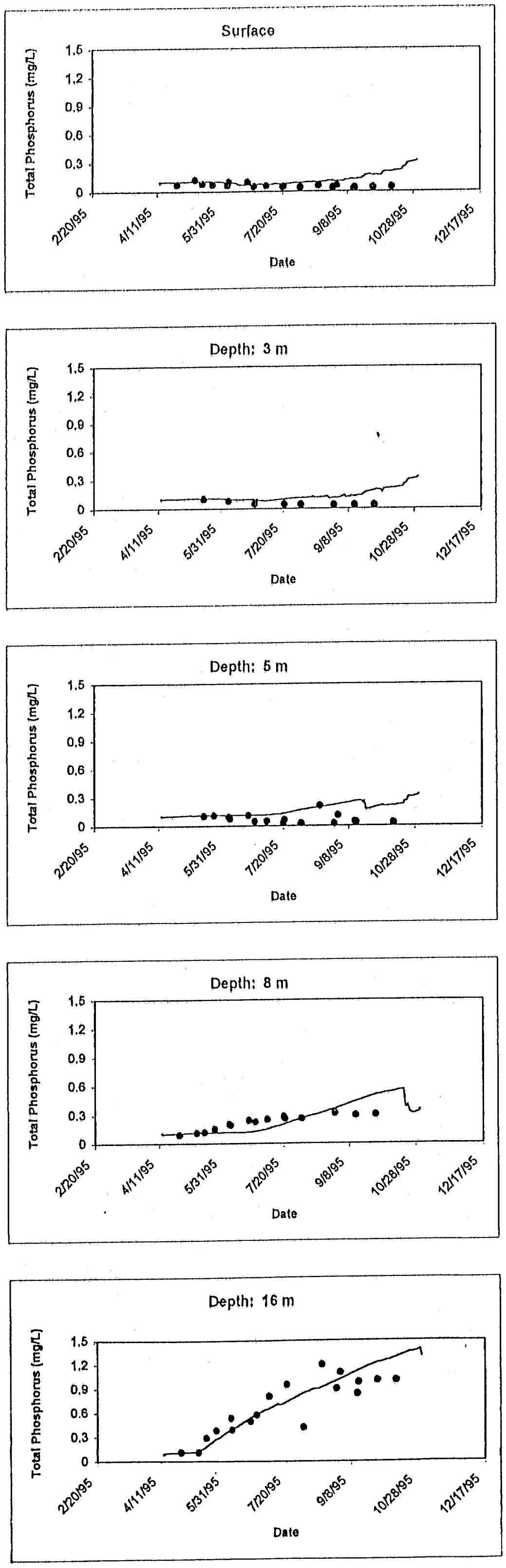


Figure D.8. Simulated (line) and observed (dots) total phosphorus at a) surface, b) 3m, c) 5 m, d) 9m, and e) 16 m below the surface for Lake McCarrons, April to October 1995.

Appendix E. Calibration of MINLAKE98 for 1996

A comparison of the observed and simulated values is presented in this appendix.

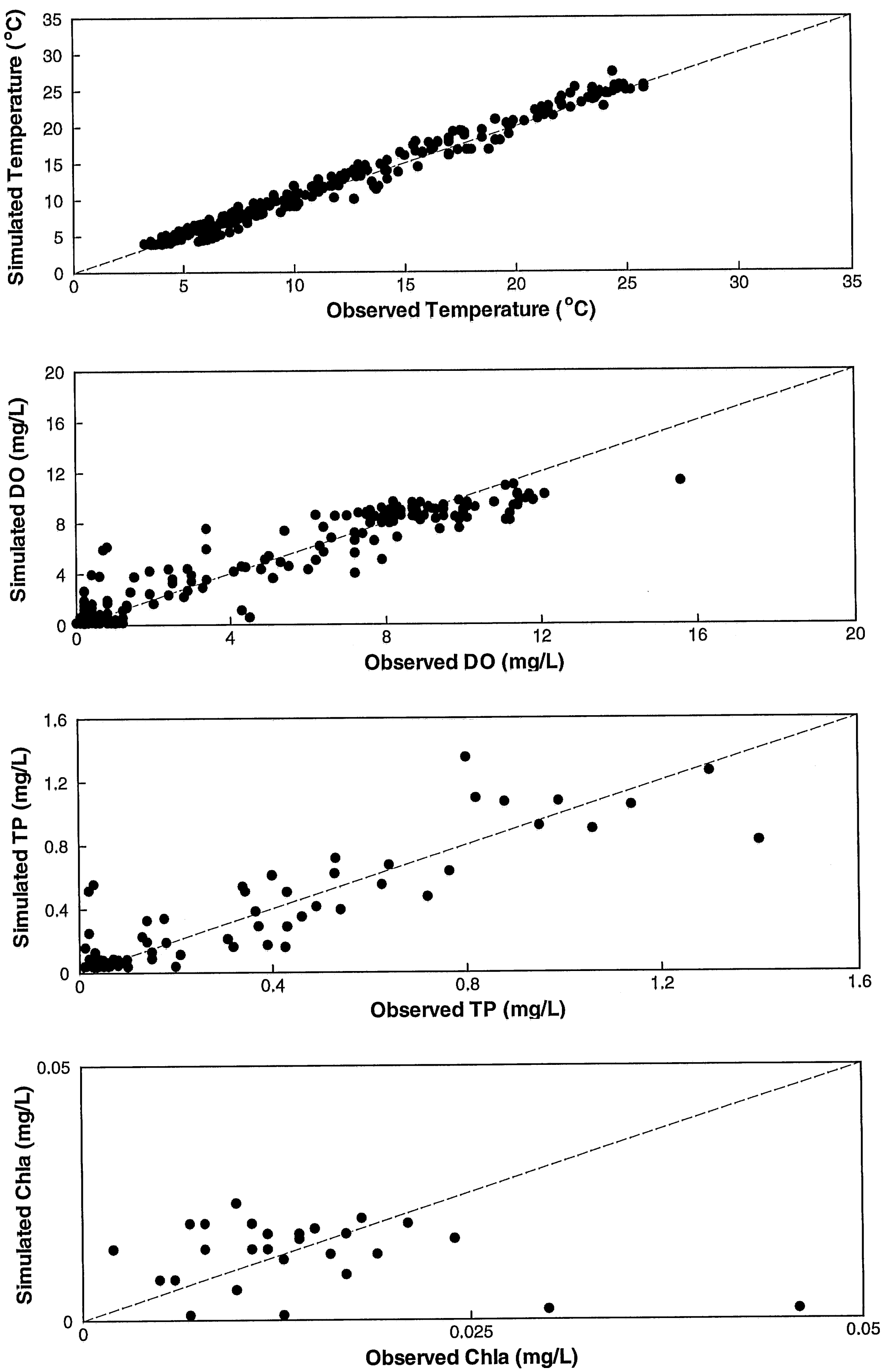


Figure E.1. Comparison of simulated and observed water quality values for Lake McCarrons calibrated for 1996.

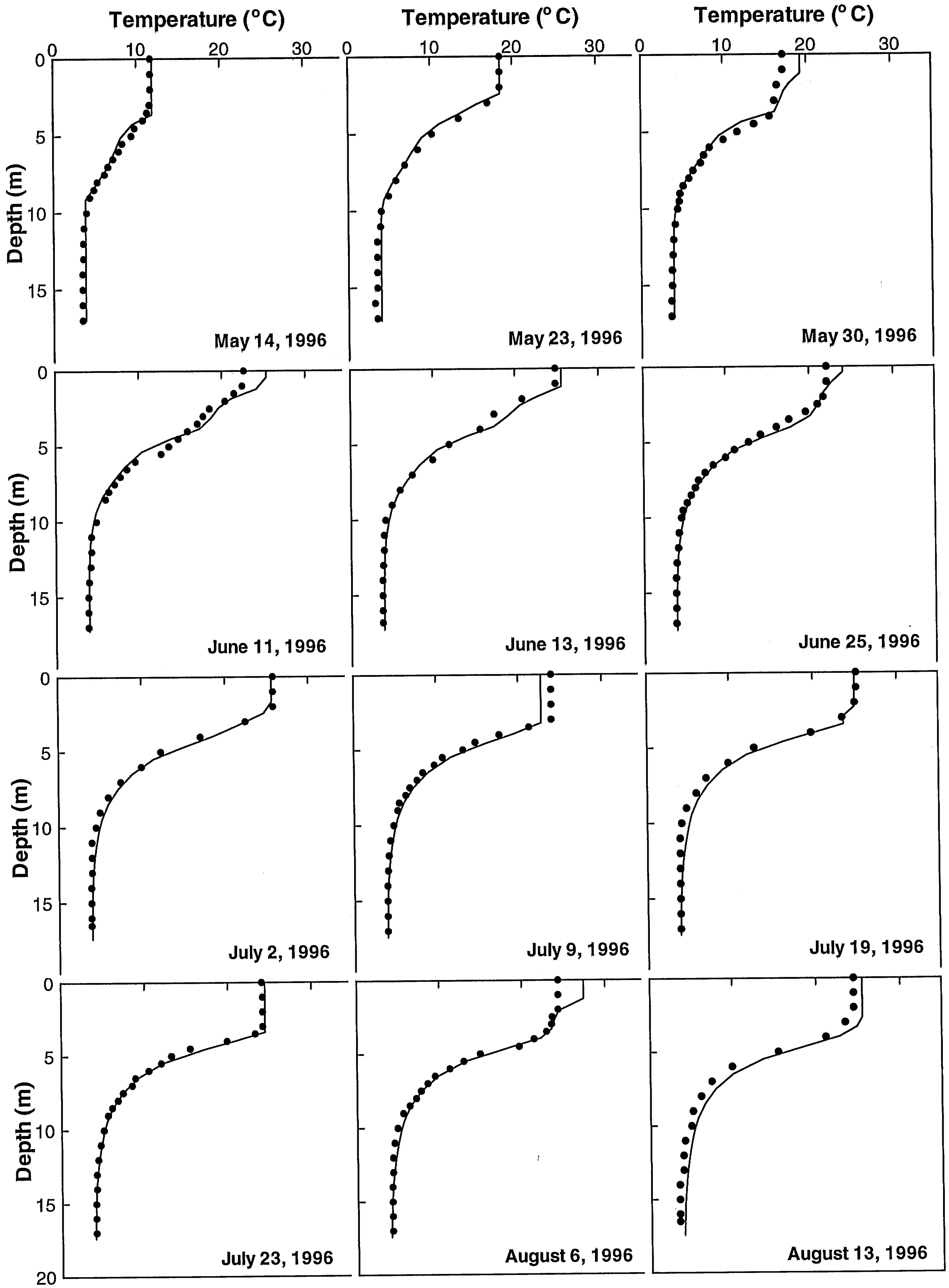


Figure E.2. Simulated (line) and observed (dot) water temperature profiles for Lake McCarrons calibrated for 1996.

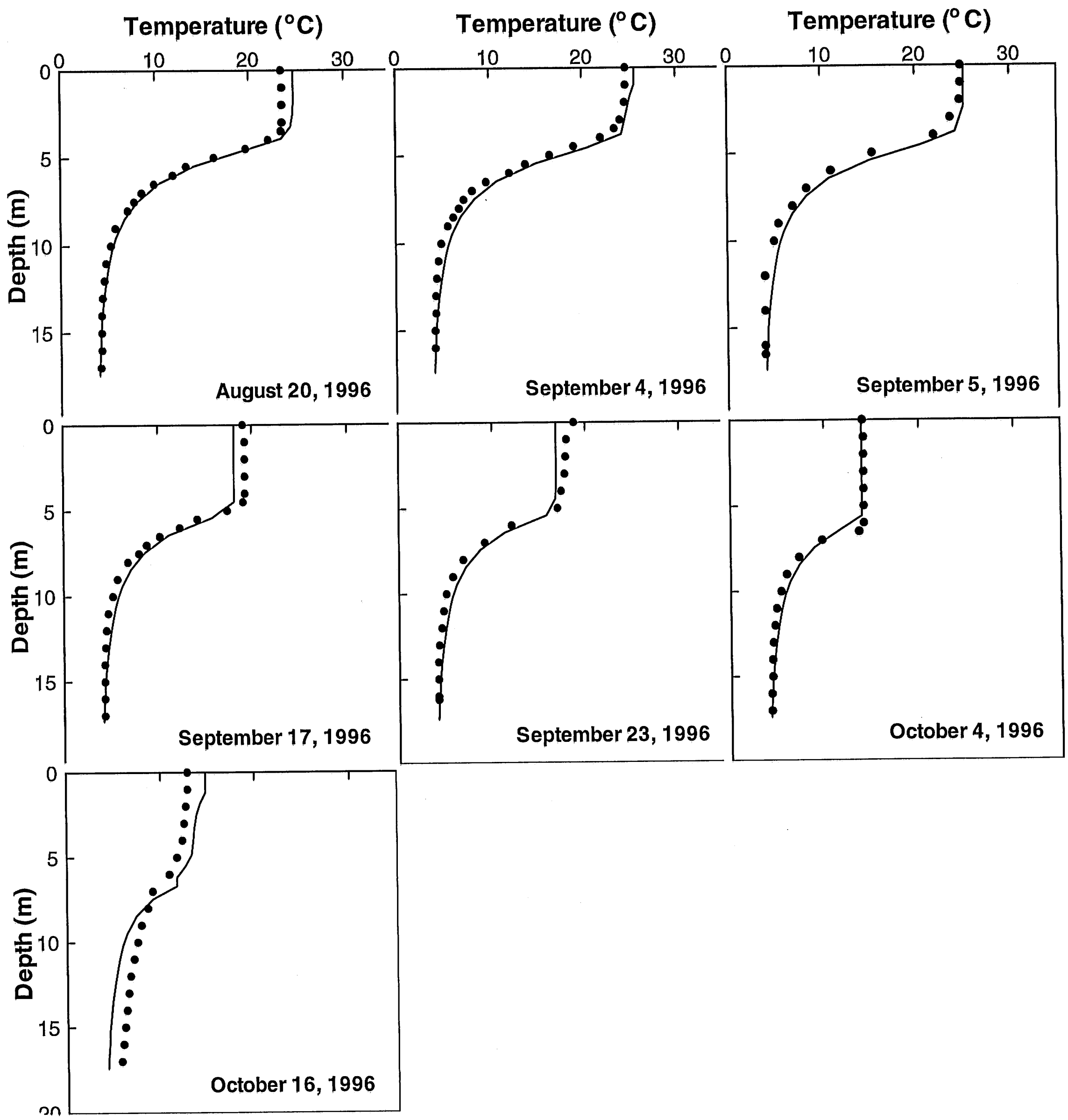


Figure E.2 (Cont'd.). Simulated (line) and observed (dot) water temperature profiles for Lake McCarrons calibrated for 1996.

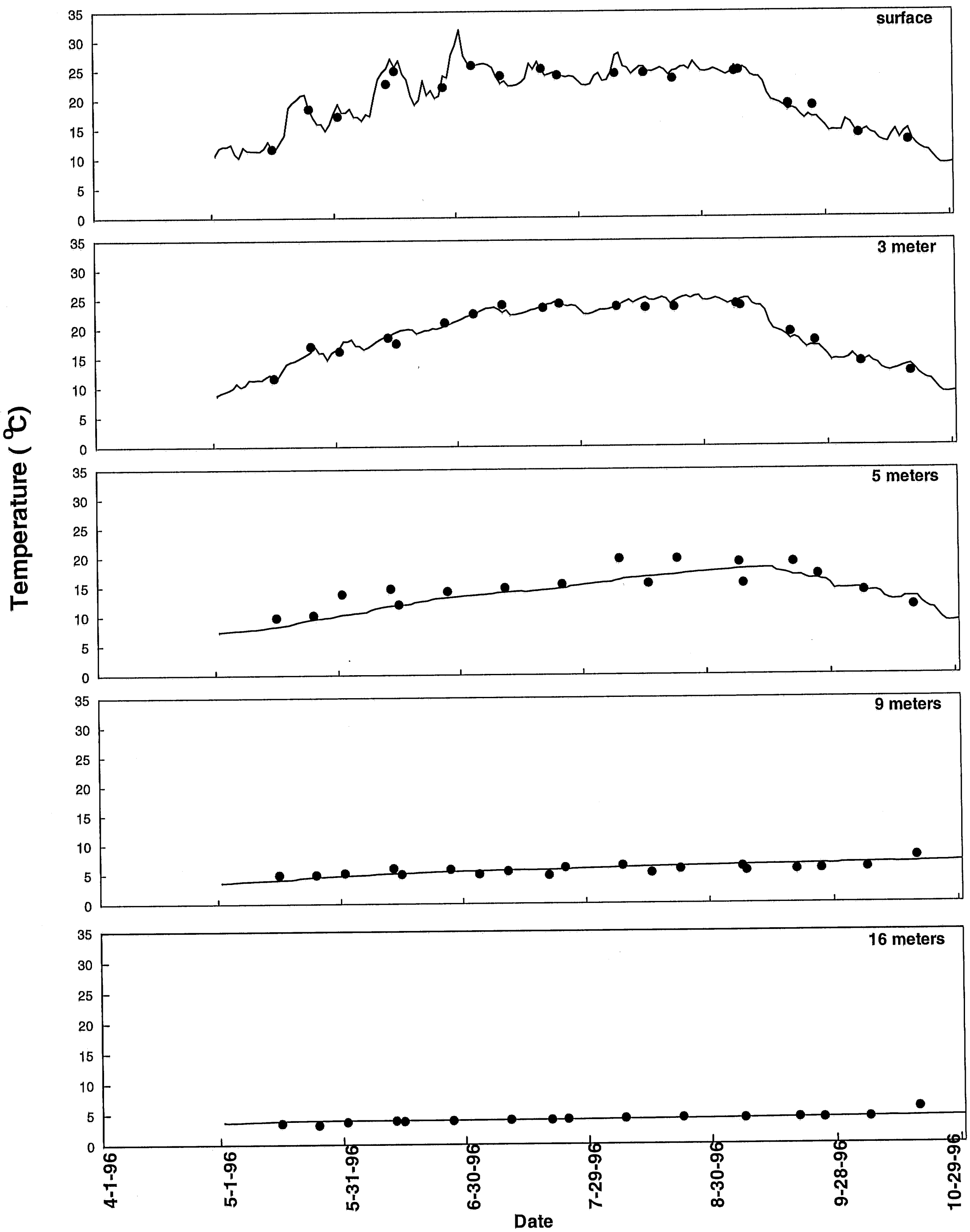


Figure E.3. Simulated (line) and observed (dots) water temperatures at a) surface, b) 3 m, c) 5 m, d) 9 m, and e) 16 m below the surface for Lake McCarrons, April to October 1996.

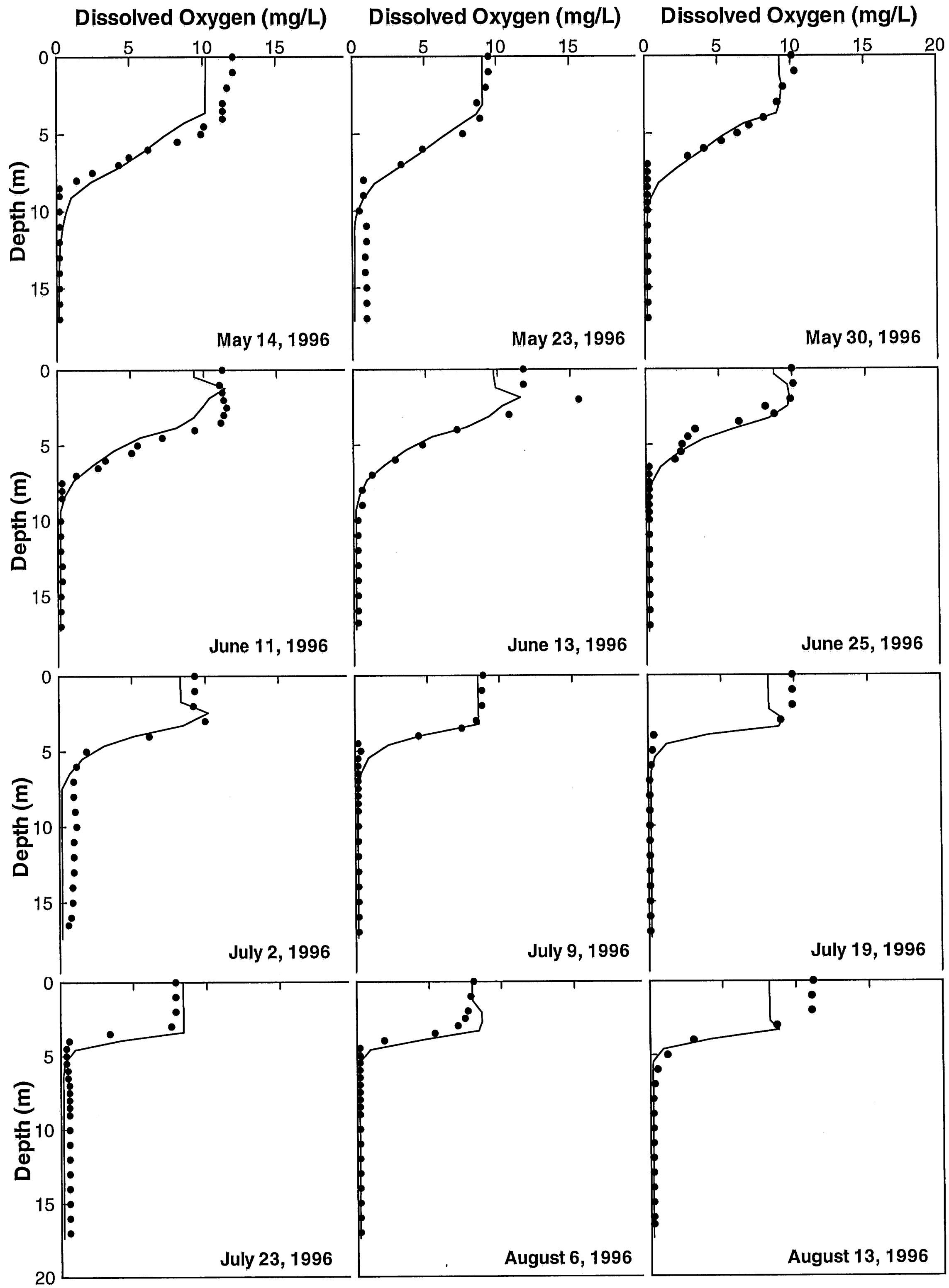


Figure E.4. Simulated (line) and observed (dot) dissolved oxygen profiles for Lake McCarrons calibrated for 1996.

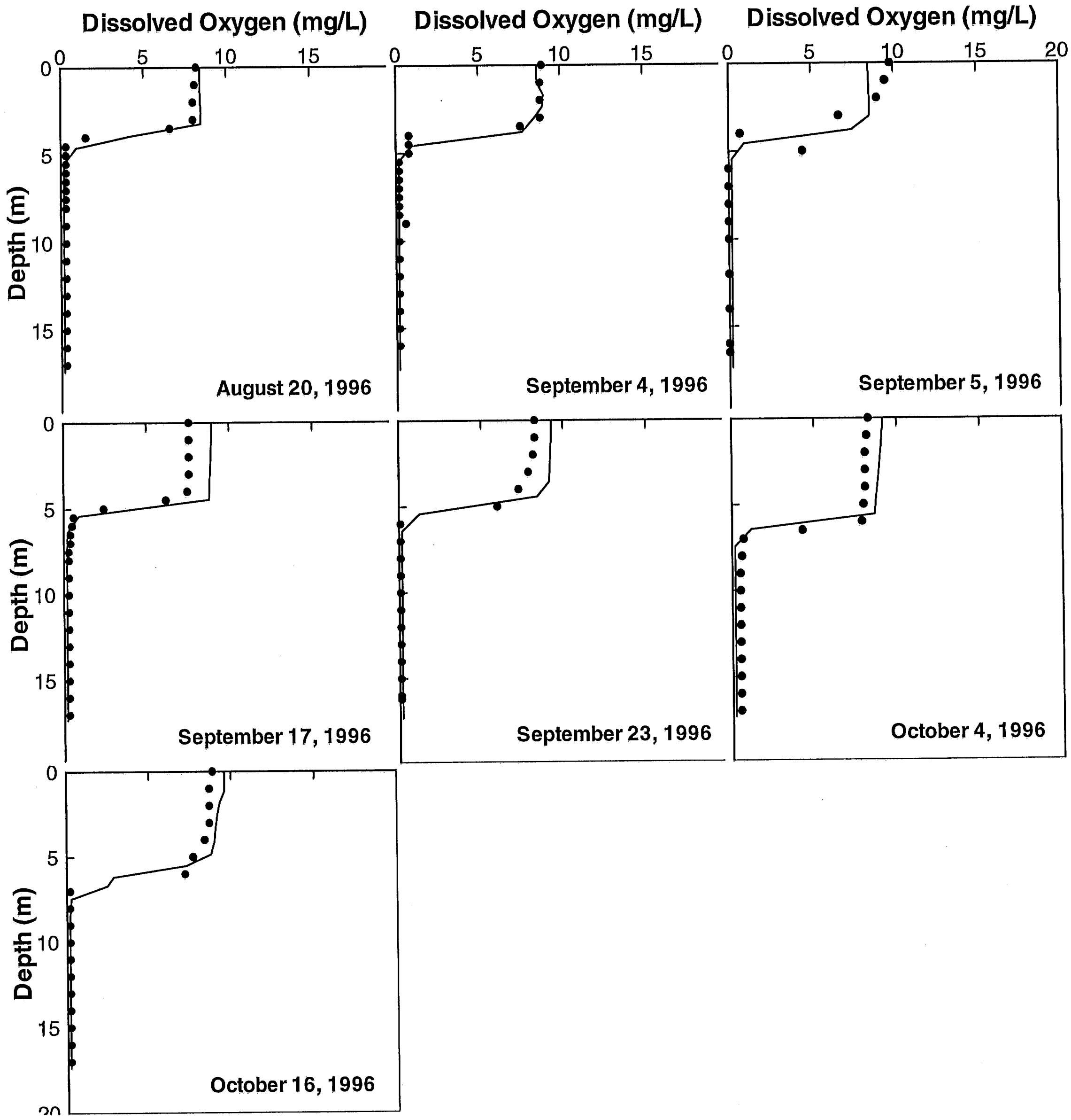


Figure E.4 (cont'd). Simulated (line) and observed (dot) dissolved oxygen profiles for Lake McCarrons calibrated for 1996.

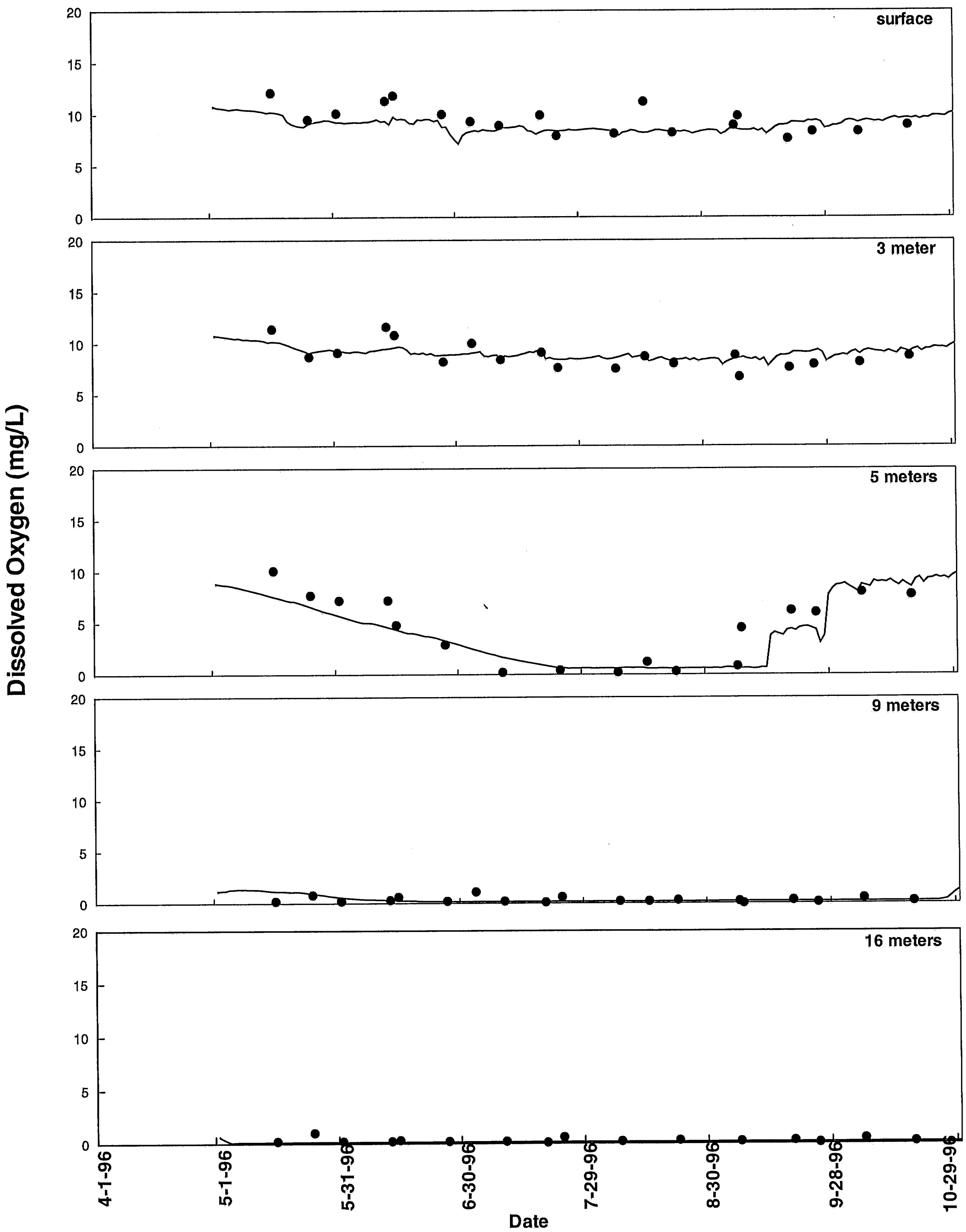


Figure E.5. Simulated (line) and observed (dots) dissolved oxygen at a) surface, b) 3 m, c) 5 m, d) 9 m and e) 16 m below the surface for Lake McCarrons, April to October 1996.

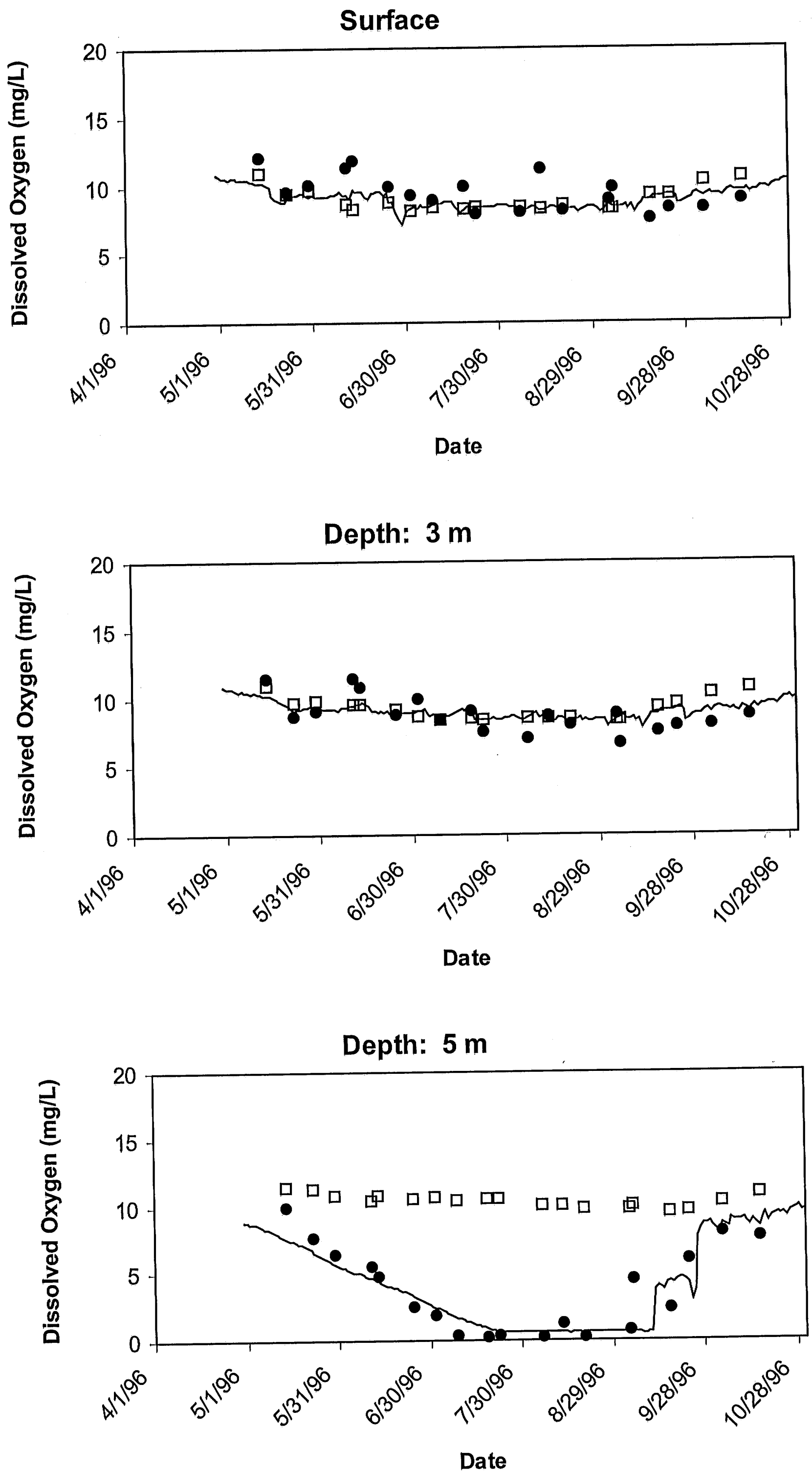


Figure E.6. Simulated (line), observed (dots) dissolved oxygen, and calculated saturated oxygen (squares) at a) surface, b) 3m, c) 5 m below the surface for Lake McCarrons, April to October 1996.

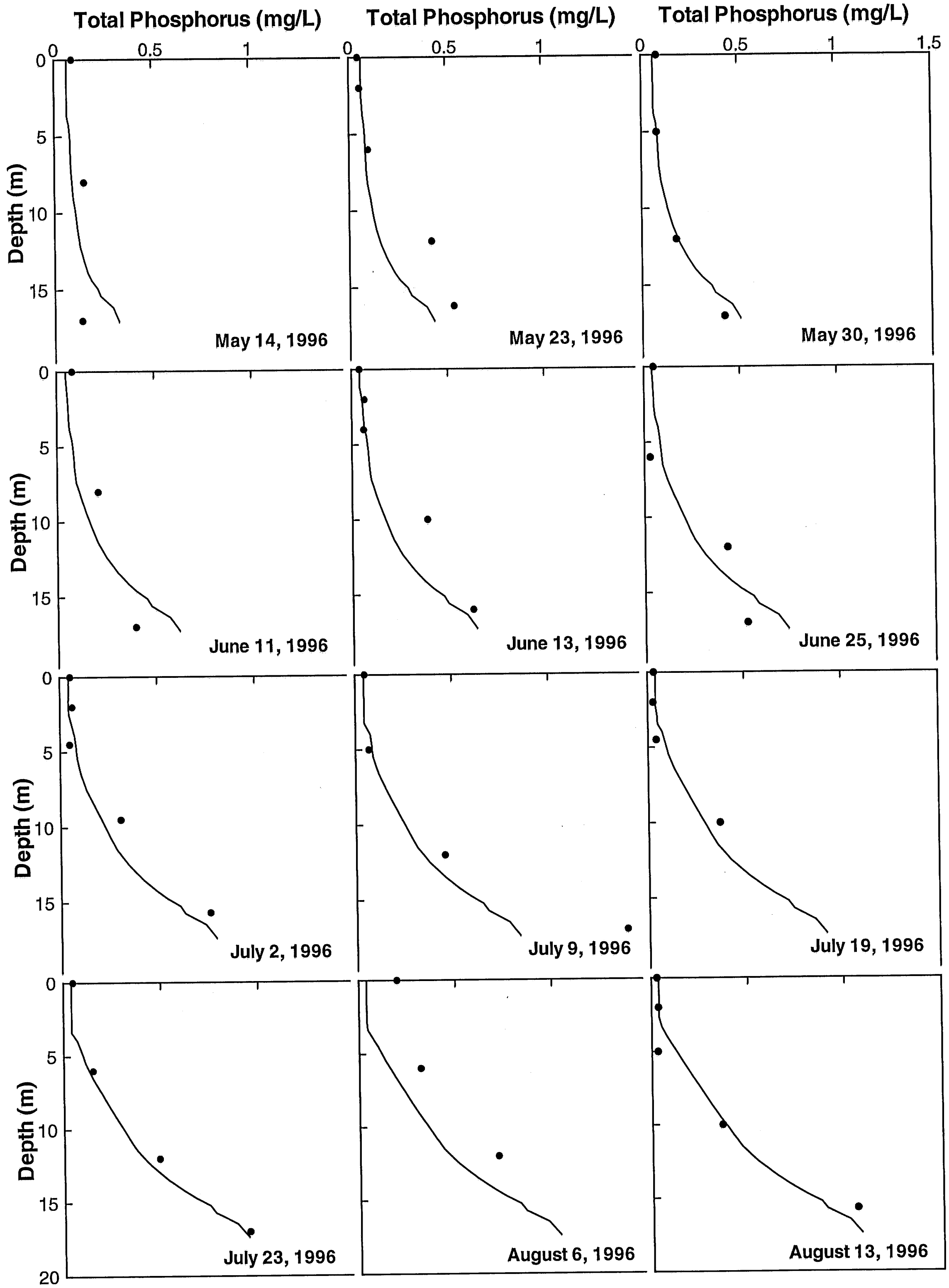


Figure E.7. Simulated (line) and observed (dot) total phosphorus profiles for Lake McCarrons calibrated for 1996.

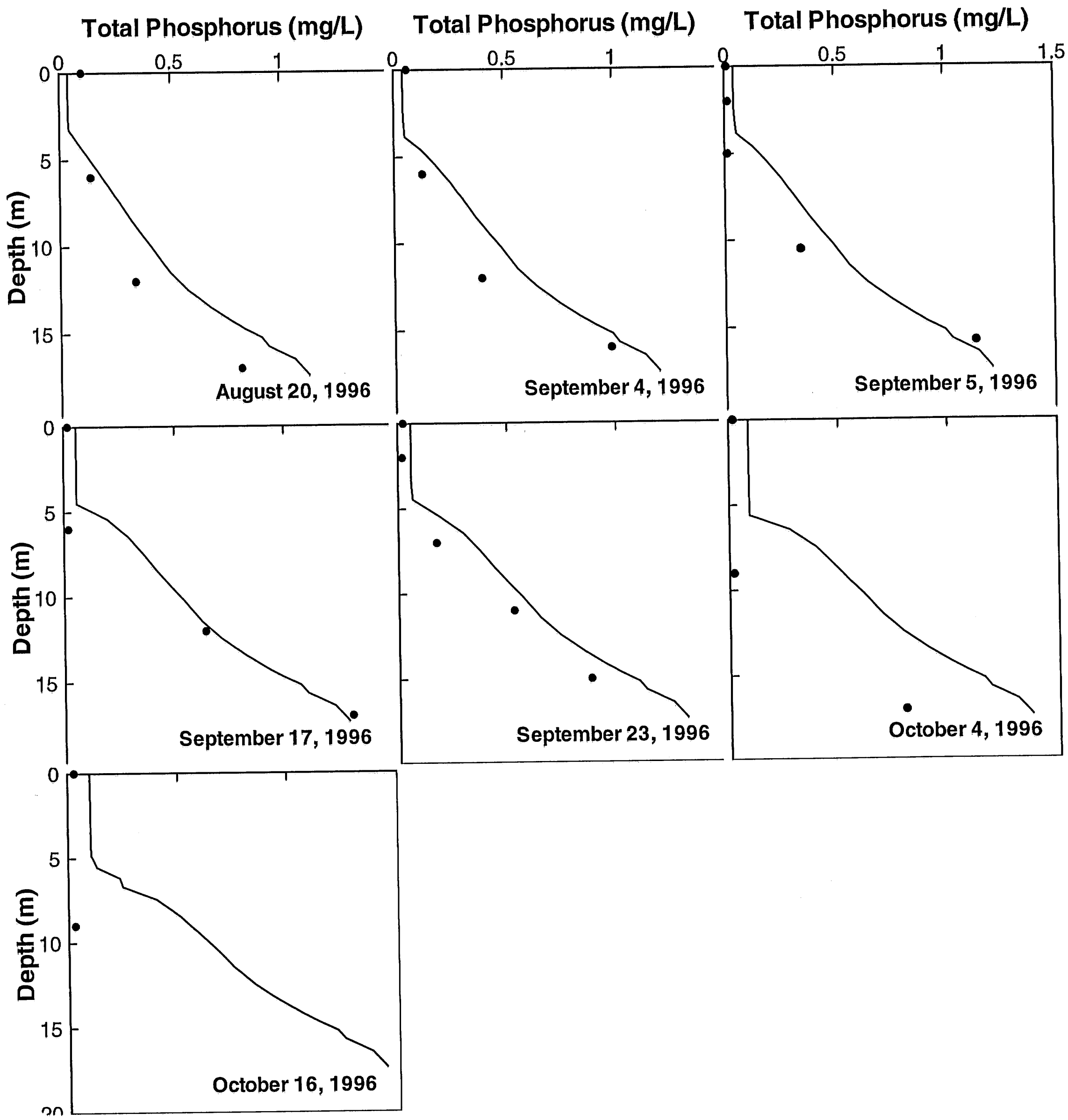


Figure E.7 (cont'd). Simulated (line) and observed (dot) total phosphorus profiles for Lake McCarrons calibrated for 1996.

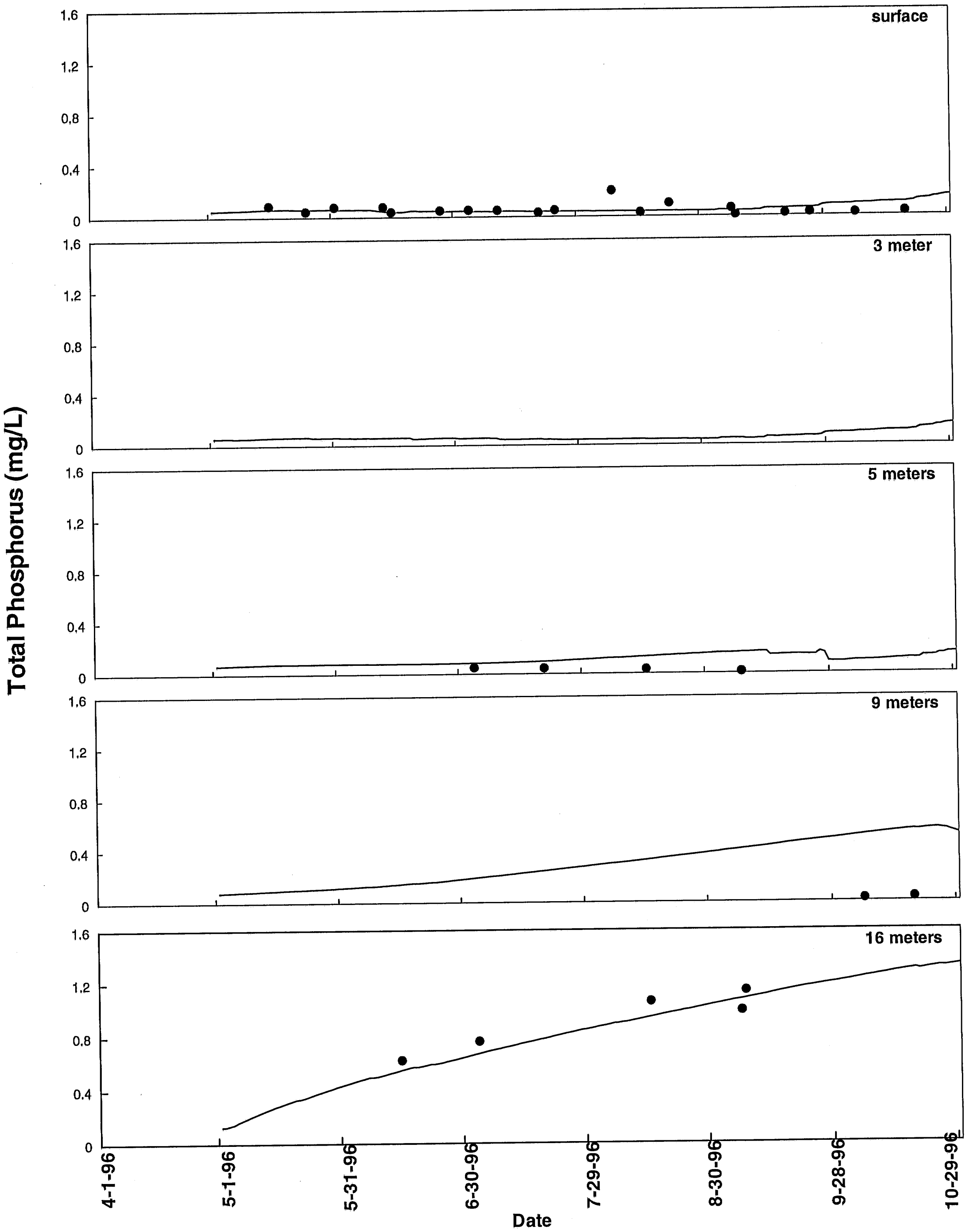


Figure E.8. Simulated (line) and observed (dots) total phosphorus at a) surface, b) 3 m, c) 5 m, d) 9 m and e) 16 m below the surface for Lake McCarrons, April to October 1996.

APPENDIX F. VALIDATION OF MINLAKE98 FOR 1996

A comparison of the observed and simulated values is presented in this appendix. The model has been calibrated with data from 1995 and applied to 1996 conditions with calibration coefficients from 1995.

Figure F.1. Comparison of simulated and observed water quality values for Lake McCarrons for 1996 using 1995 calibration coefficients.

Figure F.2. Simulated (line) and observed (dot) water temperature profiles for Lake McCarrons for 1996 using 1995 calibration coefficients.

Figure F.3. Simulated (line) and observed (dots) water temperatures at a) surface, b) 3 m, c) 5 m, d) 9 m, and e) 16 m below the surface for Lake McCarrons, April to October 1996 using 1995 calibration coefficients.

Figure F.4. Simulated (line) and observed (dot) dissolved oxygen profiles for Lake McCarrons for 1996 using 1995 calibration coefficients.

Figure F.5. Simulated (line) and observed (dots) dissolved oxygen at a) surface, b) 3 m, c) 5 m, d) 9 m, and e) 16 m below the surface for Lake McCarrons, April to October 1996 using 1995 calibration coefficients.

Figure F.6. Simulated (line) and observed (dot) total phosphorus profiles for Lake McCarrons validated for 1996 using 1995 calibration coefficients.

Figure F.7. Simulated (line) and observed (dots) total phosphorus at a) surface, b) 3 m, c) 5 m, d) 9 m, and e) 16 m below the surface for Lake McCarrons, April to October 1996, using 1995 calibration coefficients.

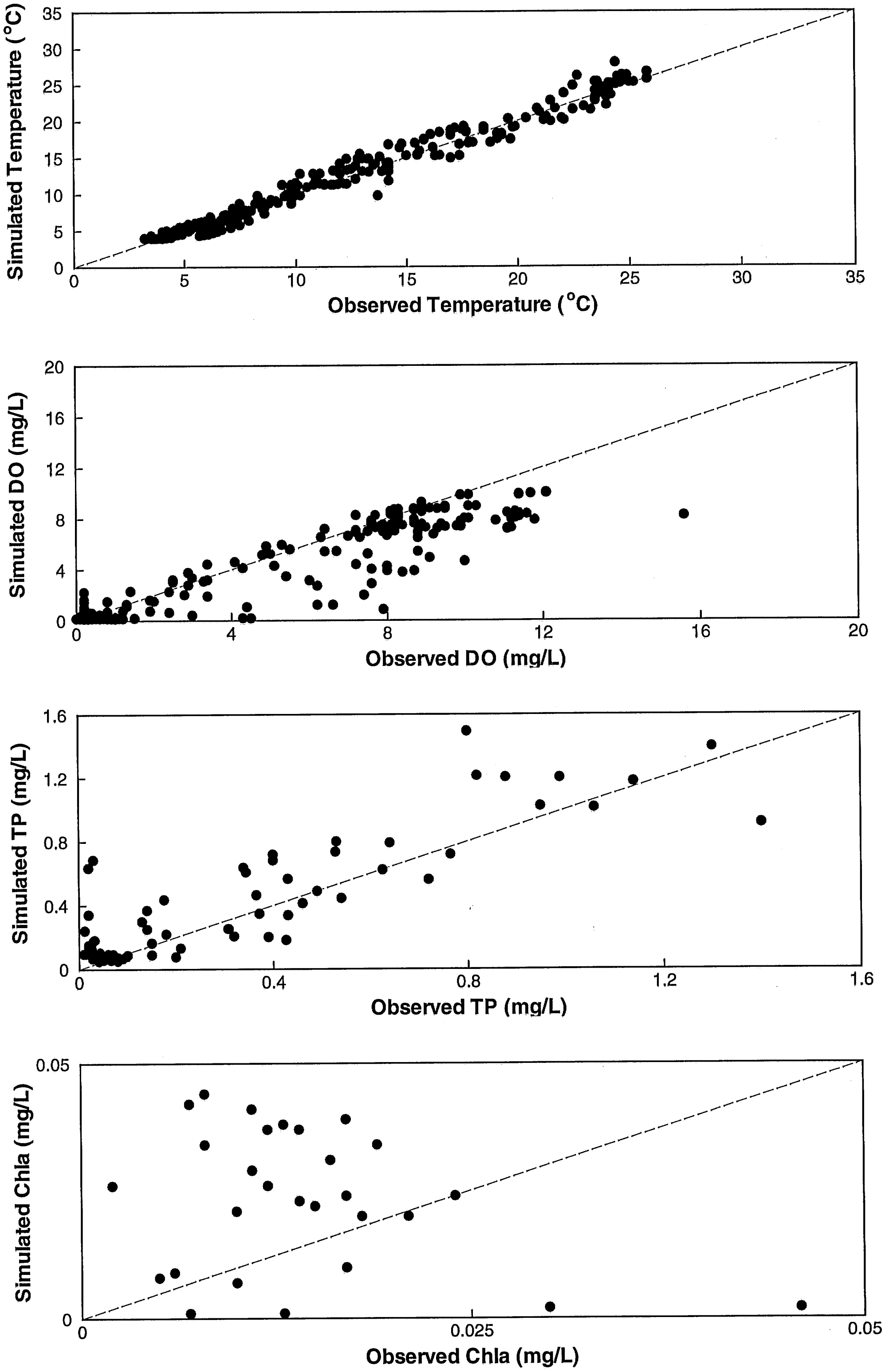


Figure F.1. Comparison of simulated and observed water quality values for Lake McCarrons for 1996 using 1995 calibration coefficients.

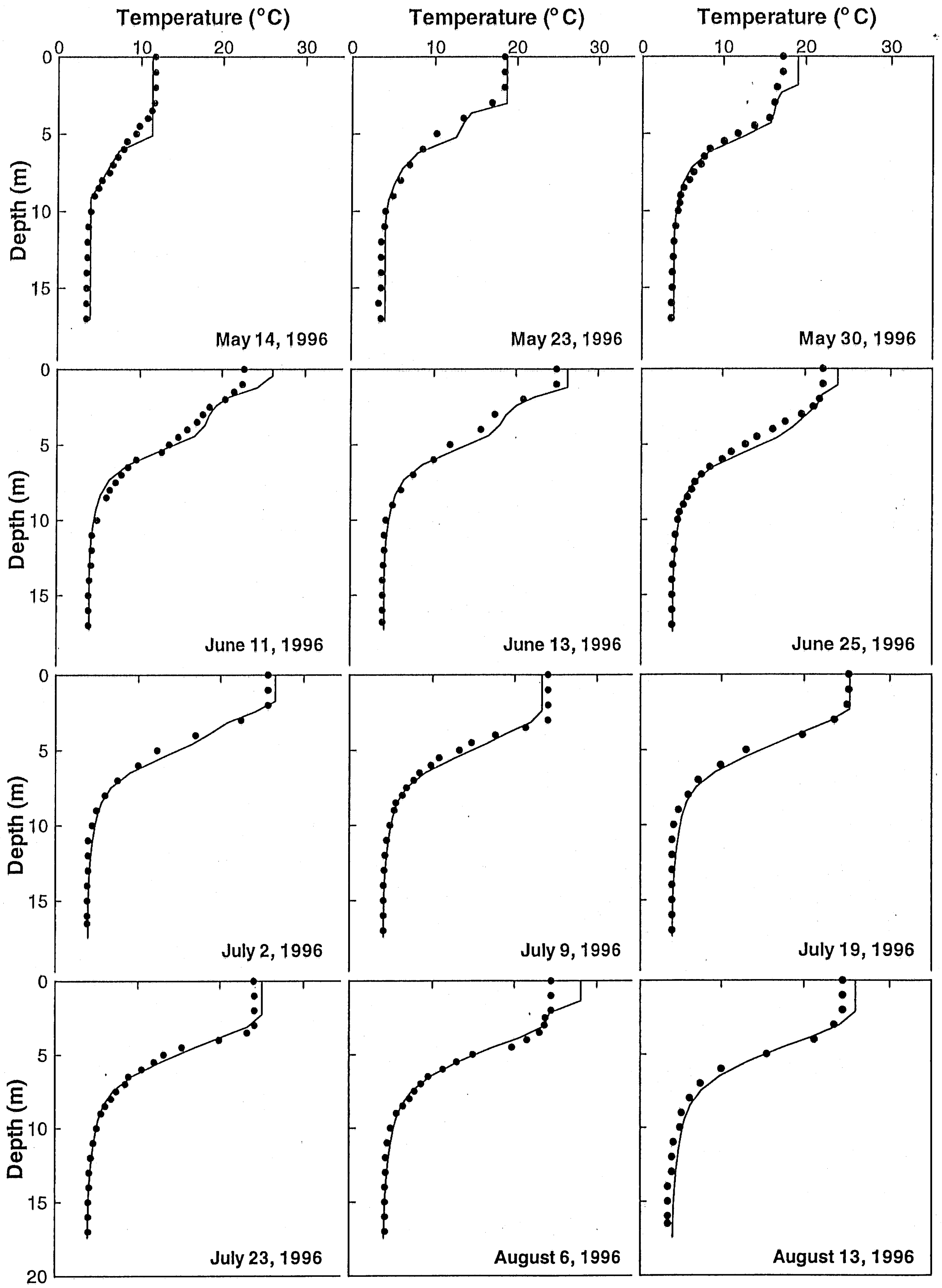


Figure F.2. Simulated (line) and observed (dots) water temperature profiles for Lake McCarrons for 1996 using 1995 calibration coefficients.

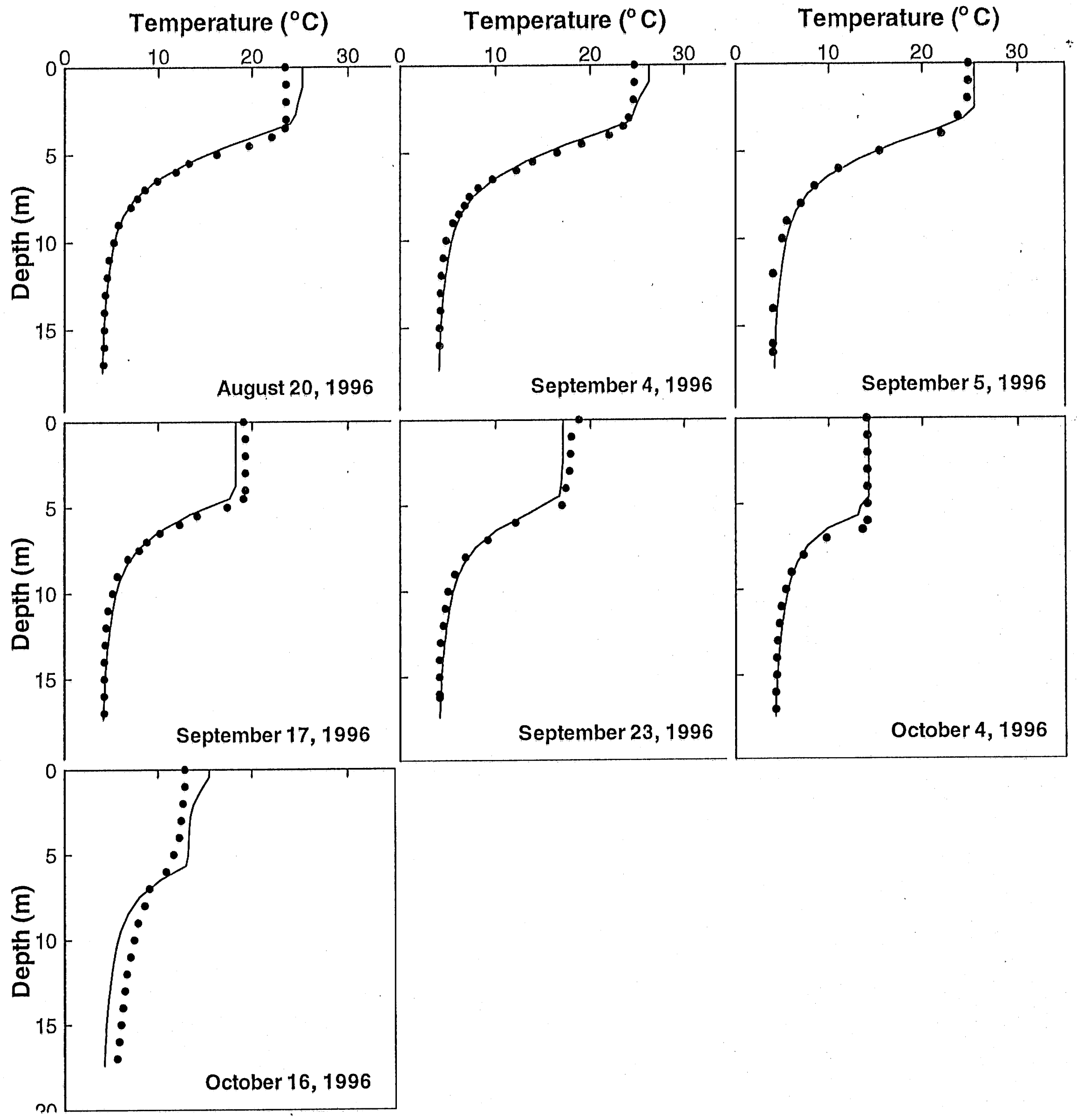


Figure F.2. (Cont'd) Simulated (line) and observed (dots) water temperature profiles for Lake McCarrons for 1996 using 1995 calibration coefficients.

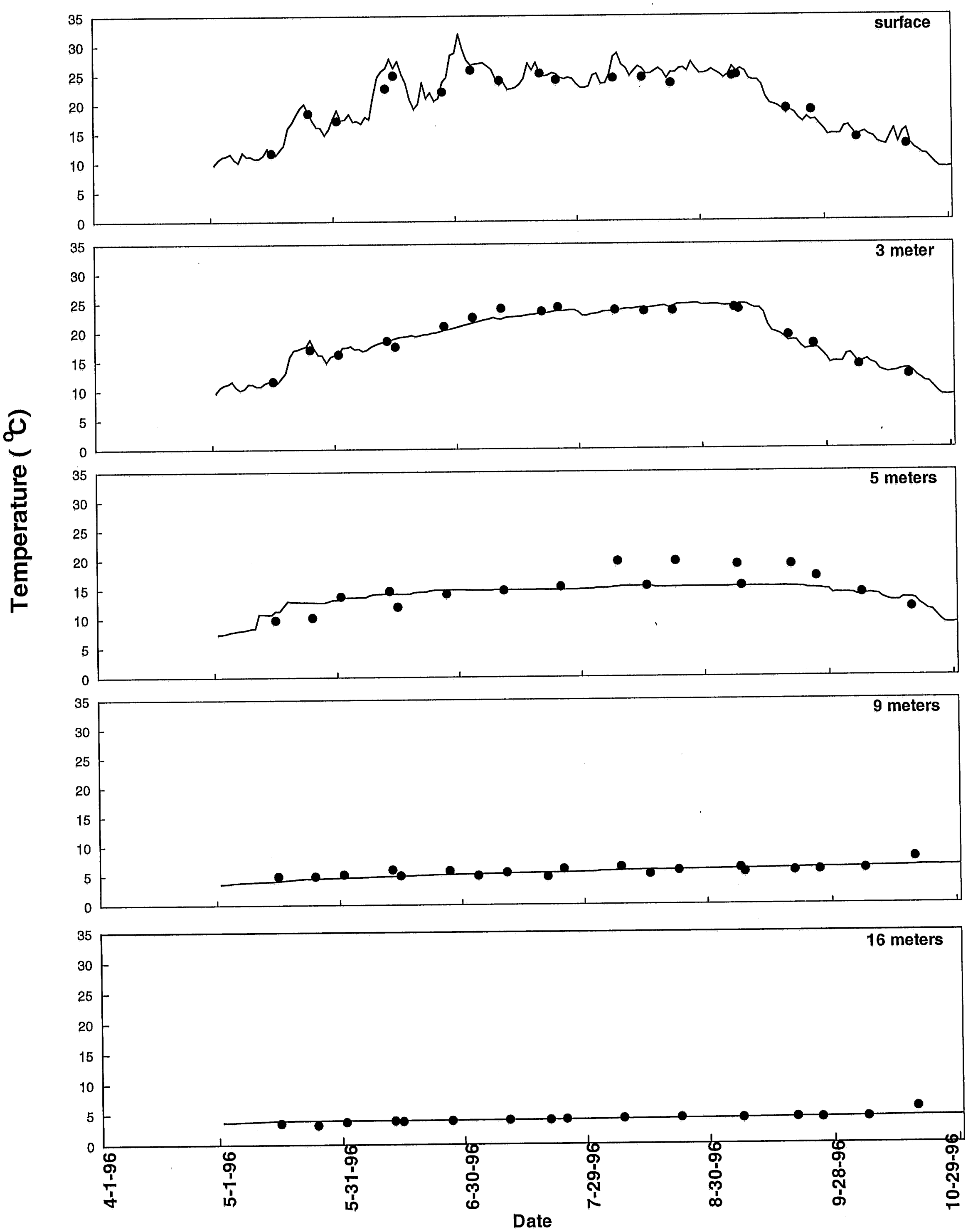


Figure F.3. Simulated (line) and observed (dots water temperatures at a) surface, b) 3 m, c) 5 m, d) 9 m, and e) 16 m below the surface for Lake McCarrons, April to October 1996 using 1995 calibration coefficients.

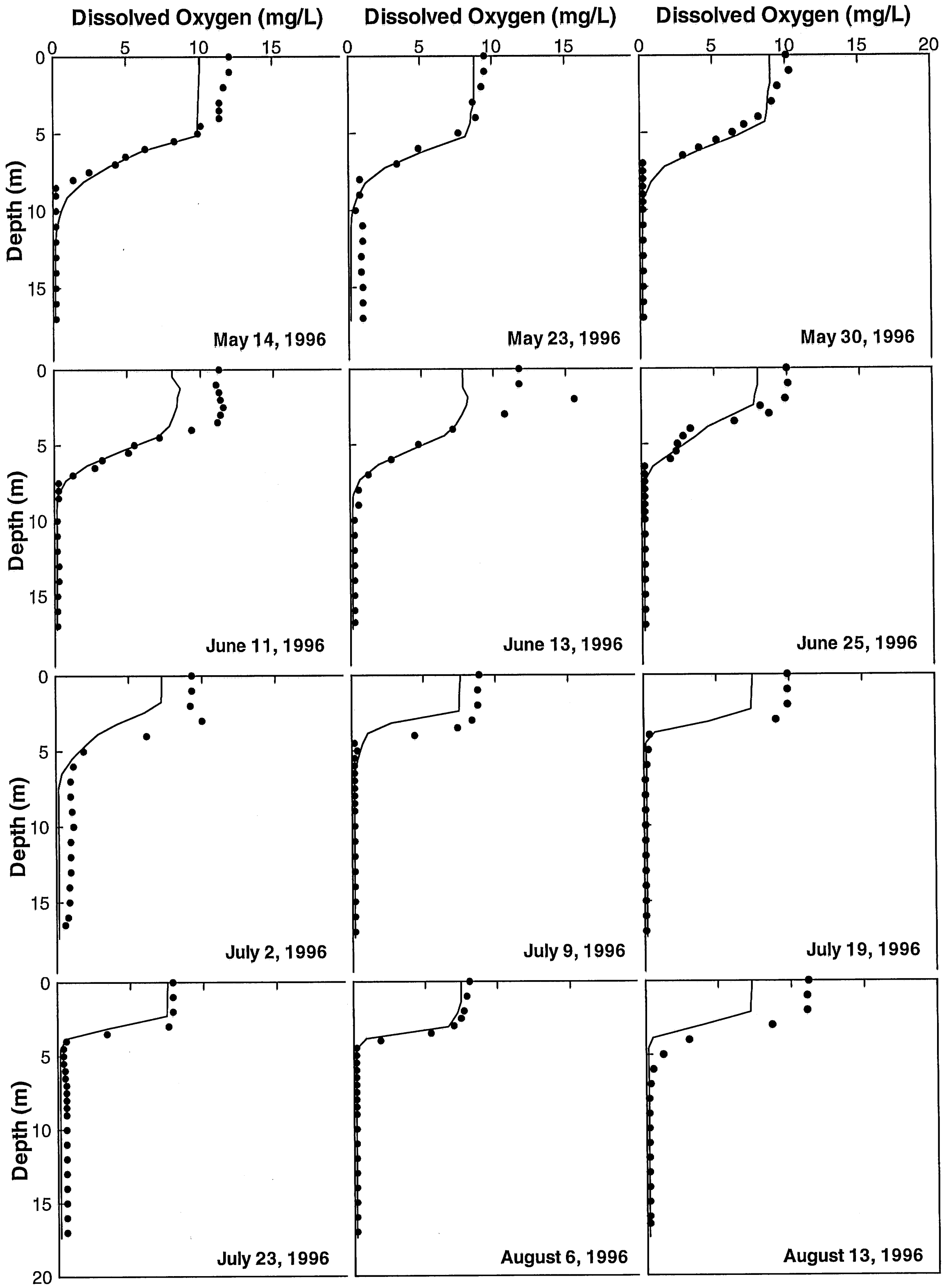


Figure F.4. Simulated (line) and observed (dot) dissolved oxygen profiles for Lake McCarrons for 1996 using 1995 calibration coefficients.

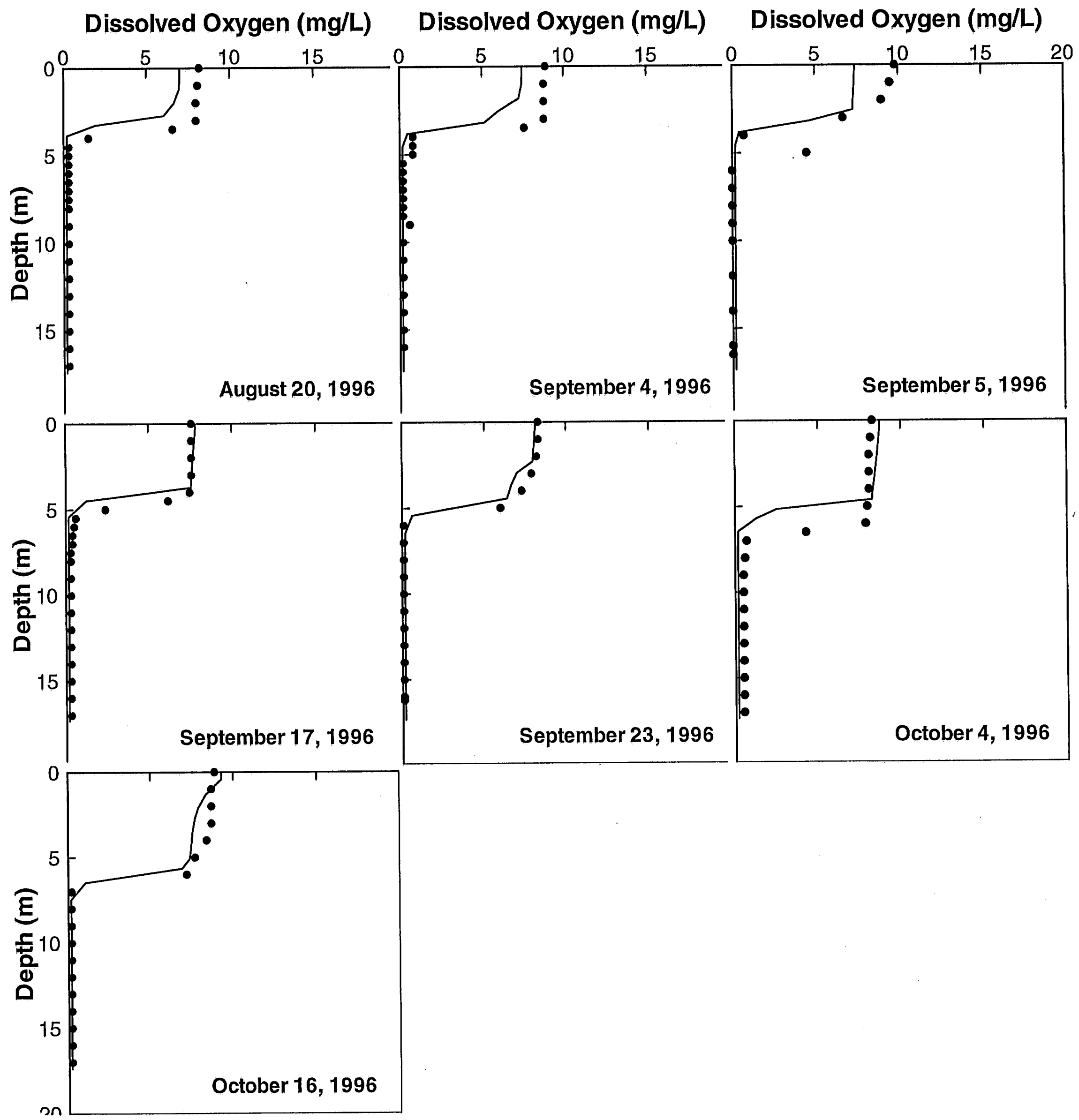


Figure F.4 (cont'd). Simulated (line) and observed (dot) dissolved oxygen profiles for Lake McCarrons for 1996 using 1995 calibration coefficients.

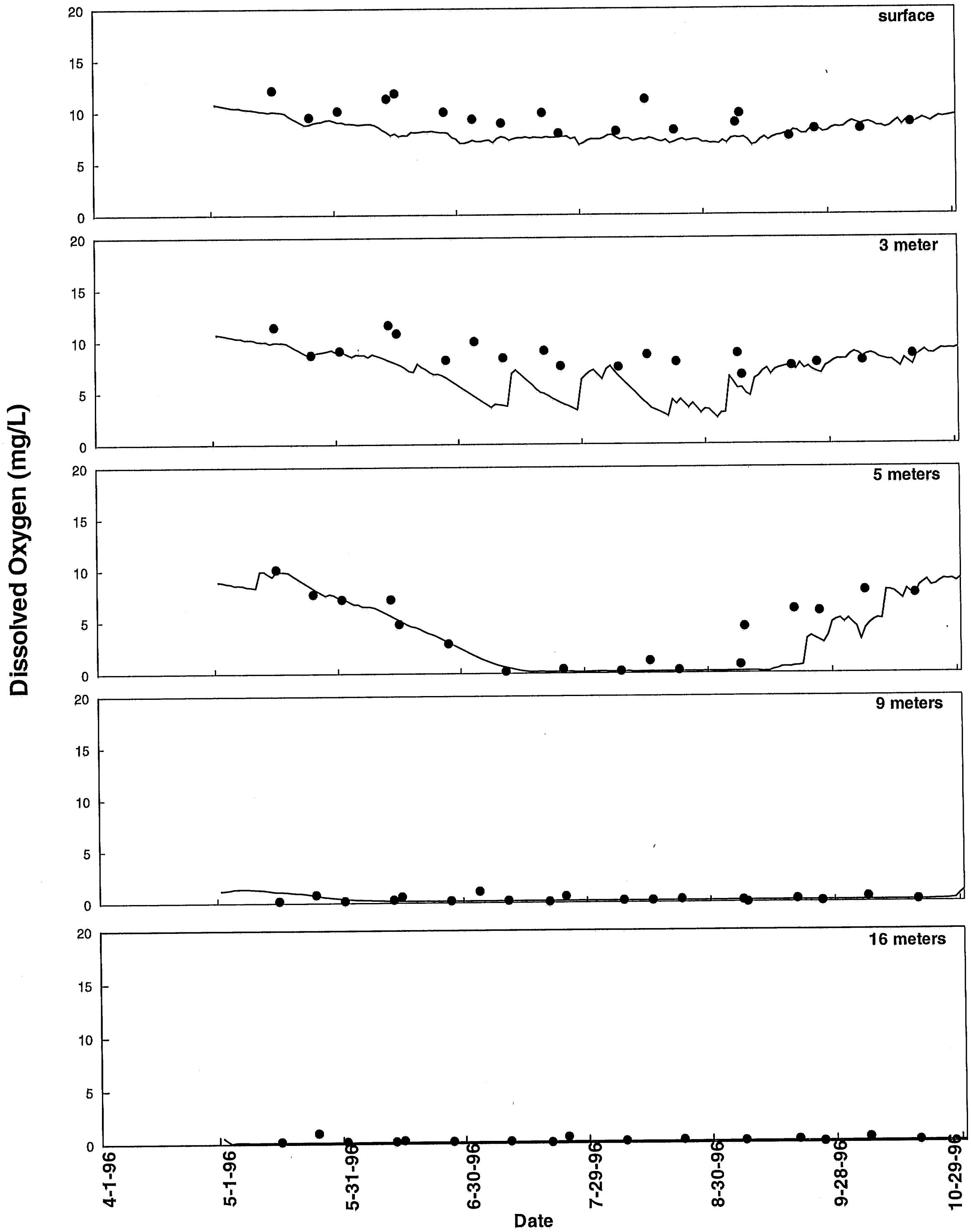


Figure F.5. Simulated (line) and observed (dots) dissolved oxygen at a) surface, b) 3 m, c) 5 m, d) 9 m, and e) 16 m below the surface for Lake McCarrons, April to October 1996 using 1995 calibration coefficients.

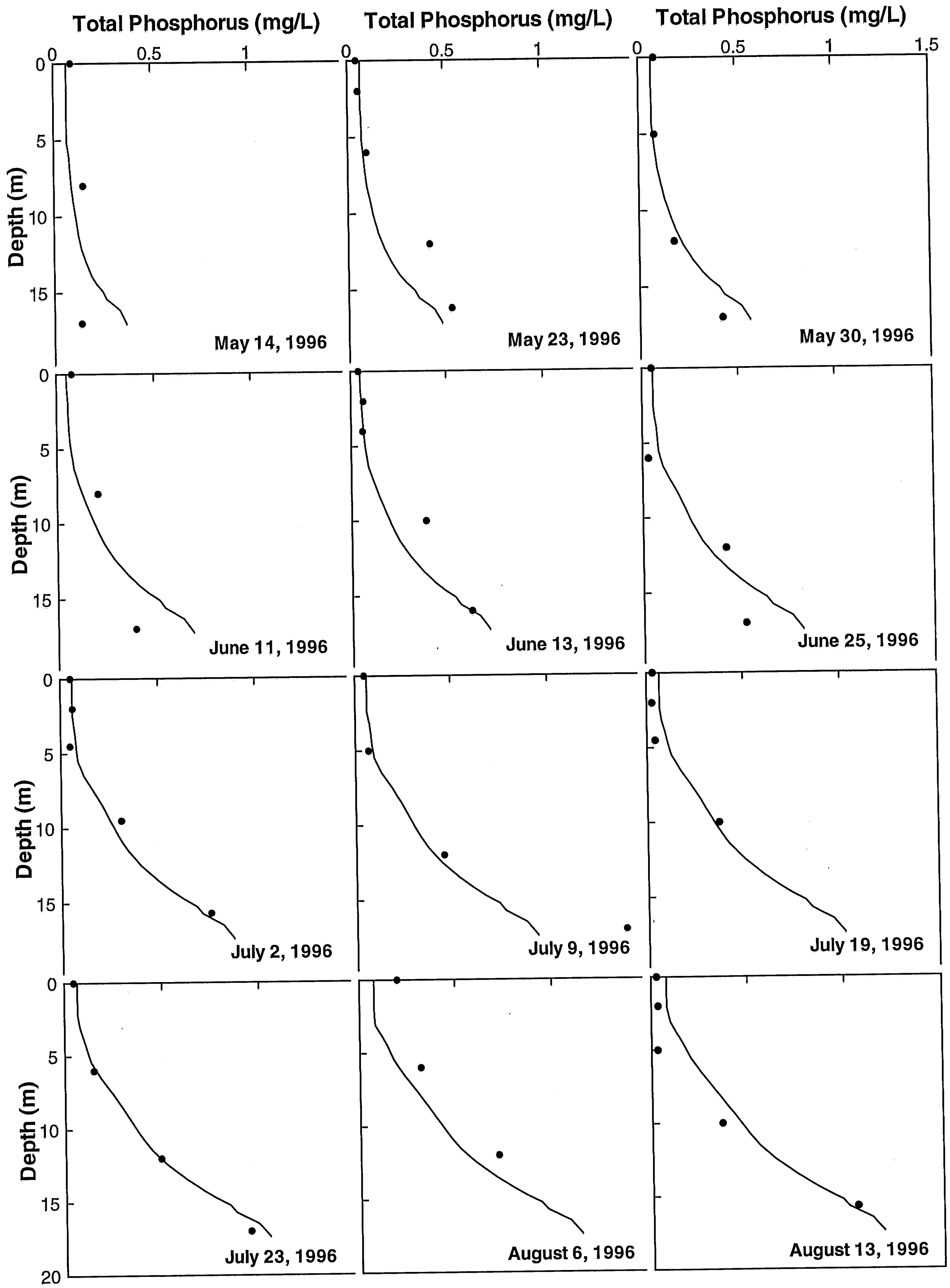


Figure F.6. Simulated (line) and observed (dot) total phosphorus profiles for Lake McCarrons validated for 1996 using 1995 calibration coefficients.

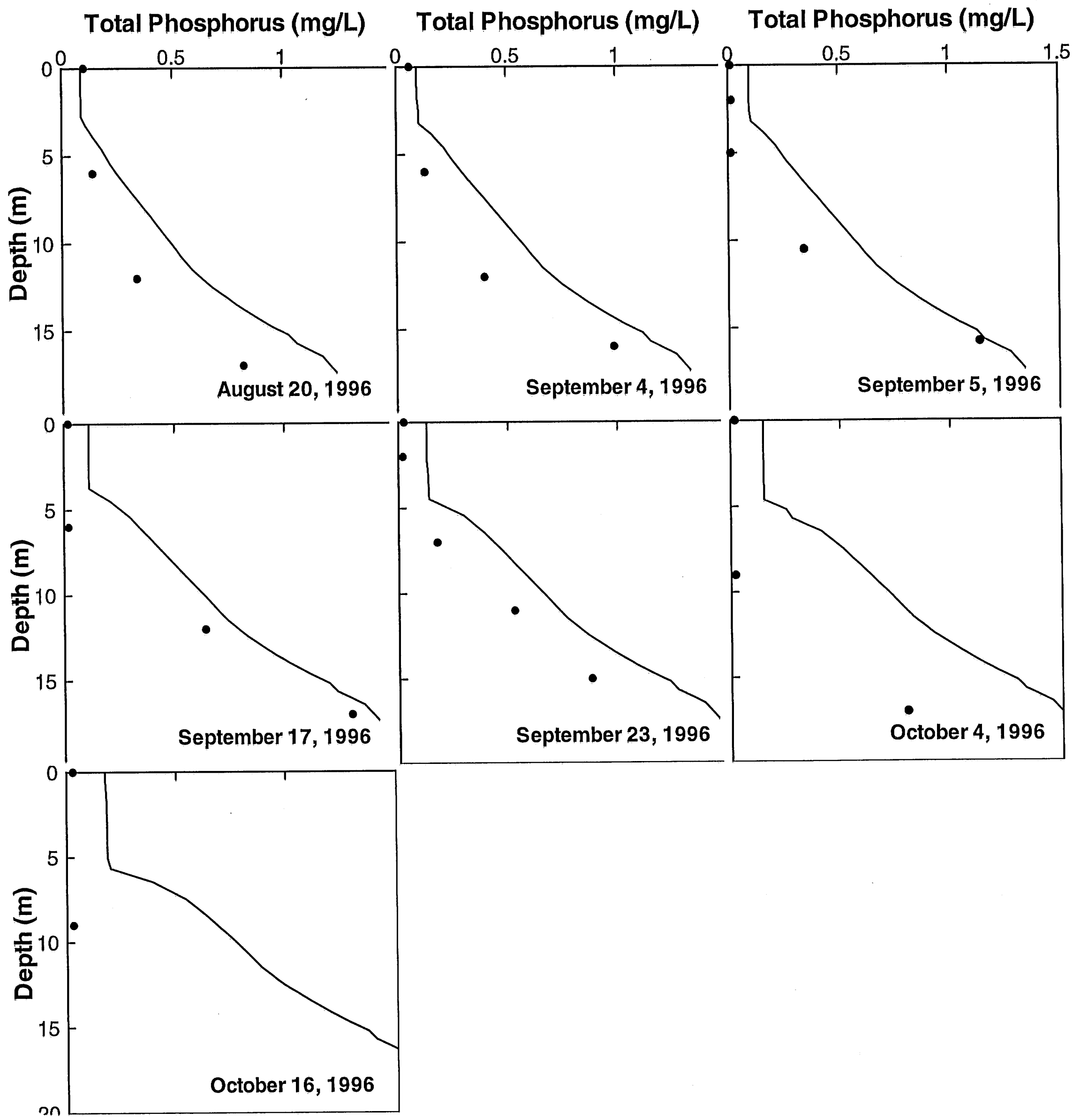


Figure F.6 (cont'd). Simulated (line) and observed (dot) total phosphorus profiles for Lake McCarrons validated for 1996 using 1995 calibration coefficients.

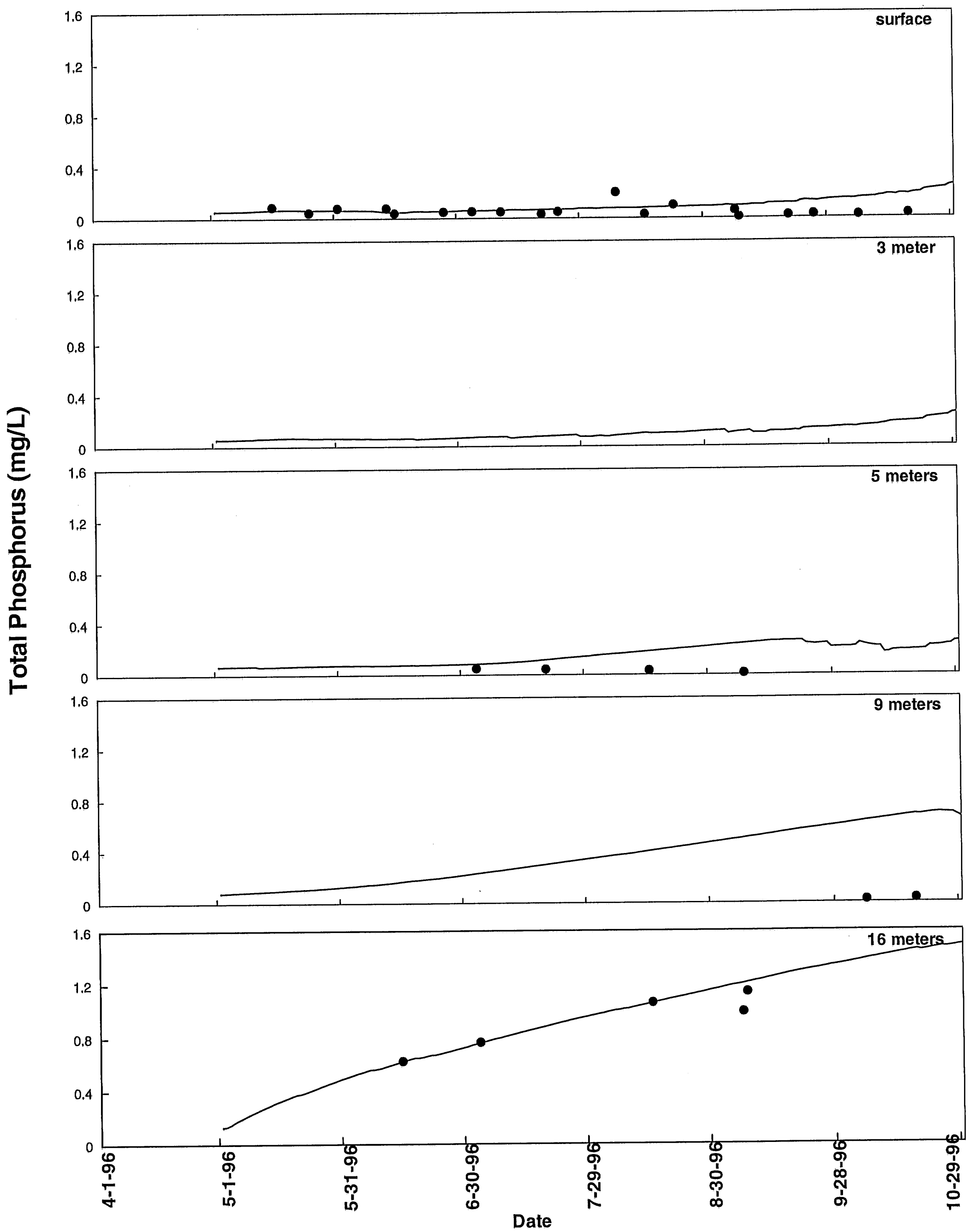


Figure F.7. Simulated (line) and observed (dots) total phosphorus at a) surface, b) 3 m, c) 5 m, d) 9 m, and e) 16 m below the surface for Lake McCarrons, April to October 1996, using 1995 calibration coefficients.

APPENDIX G. CHLOROPHYLL PROFILES WITH DEEPENED MIXED LAYER

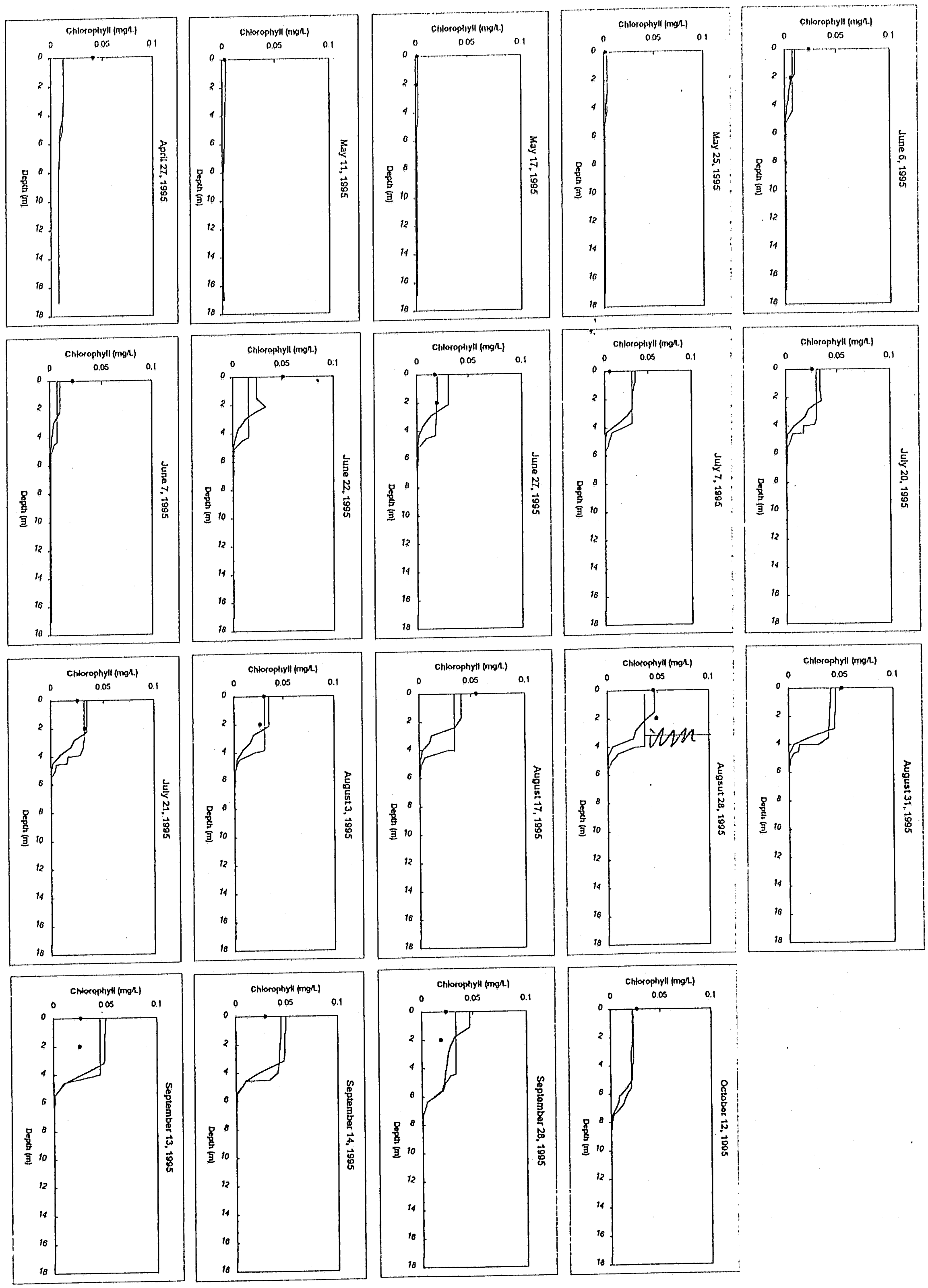


Figure G.1. Existing (solid line) and 4-m deepening (dashed line) chlorophyll *a* profiles for Lake McCarrons - 1995.

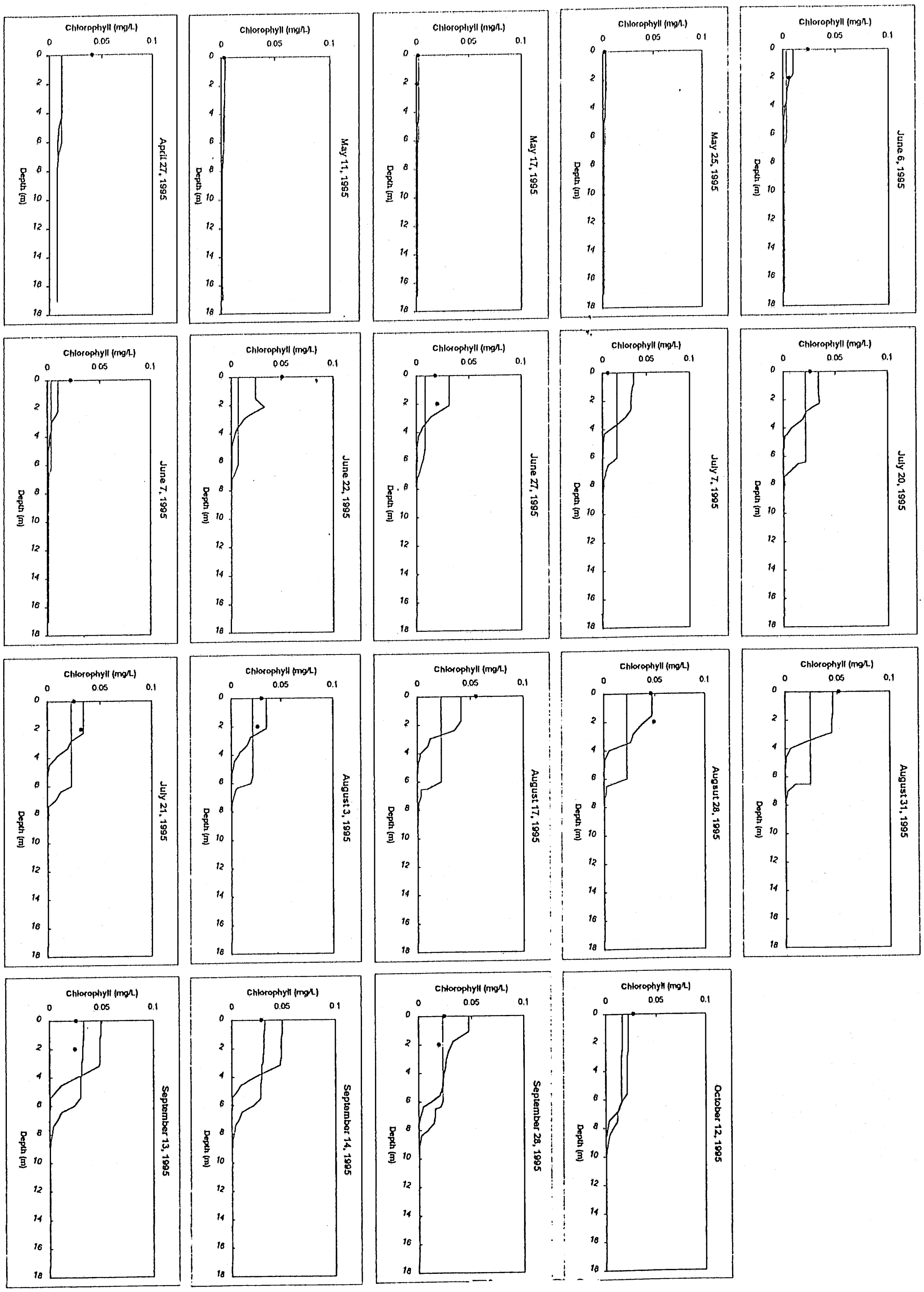


Figure G.2. Existing (solid line) and 6-m deepening (dashed line) chlorophyll *a* profiles for Lake McCarrons - 1995.

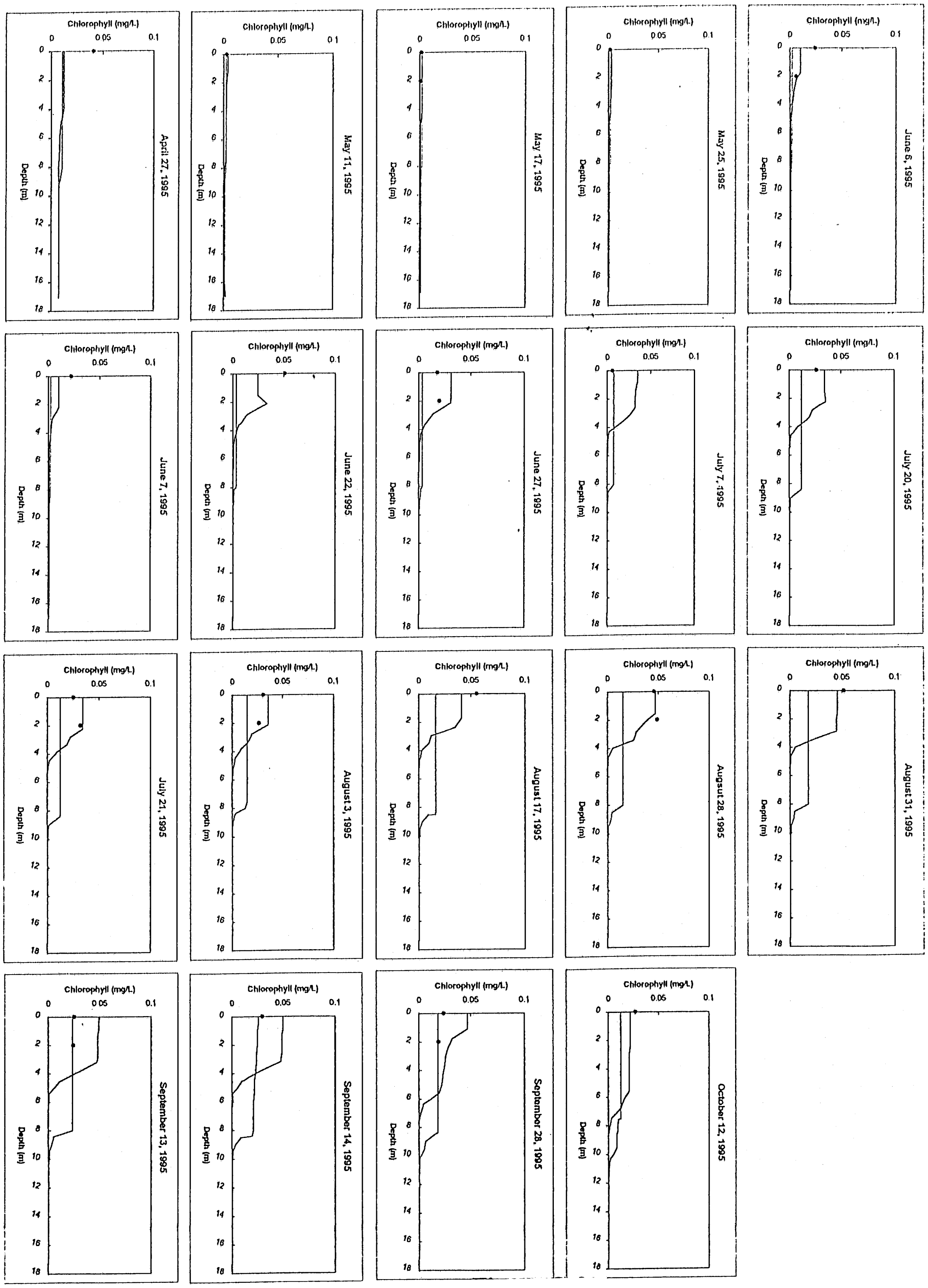


Figure G.3. Existing (solid line) and 8-m deepening (dashed line) chlorophyll *a* profiles for Lake McCarrons - 1995.

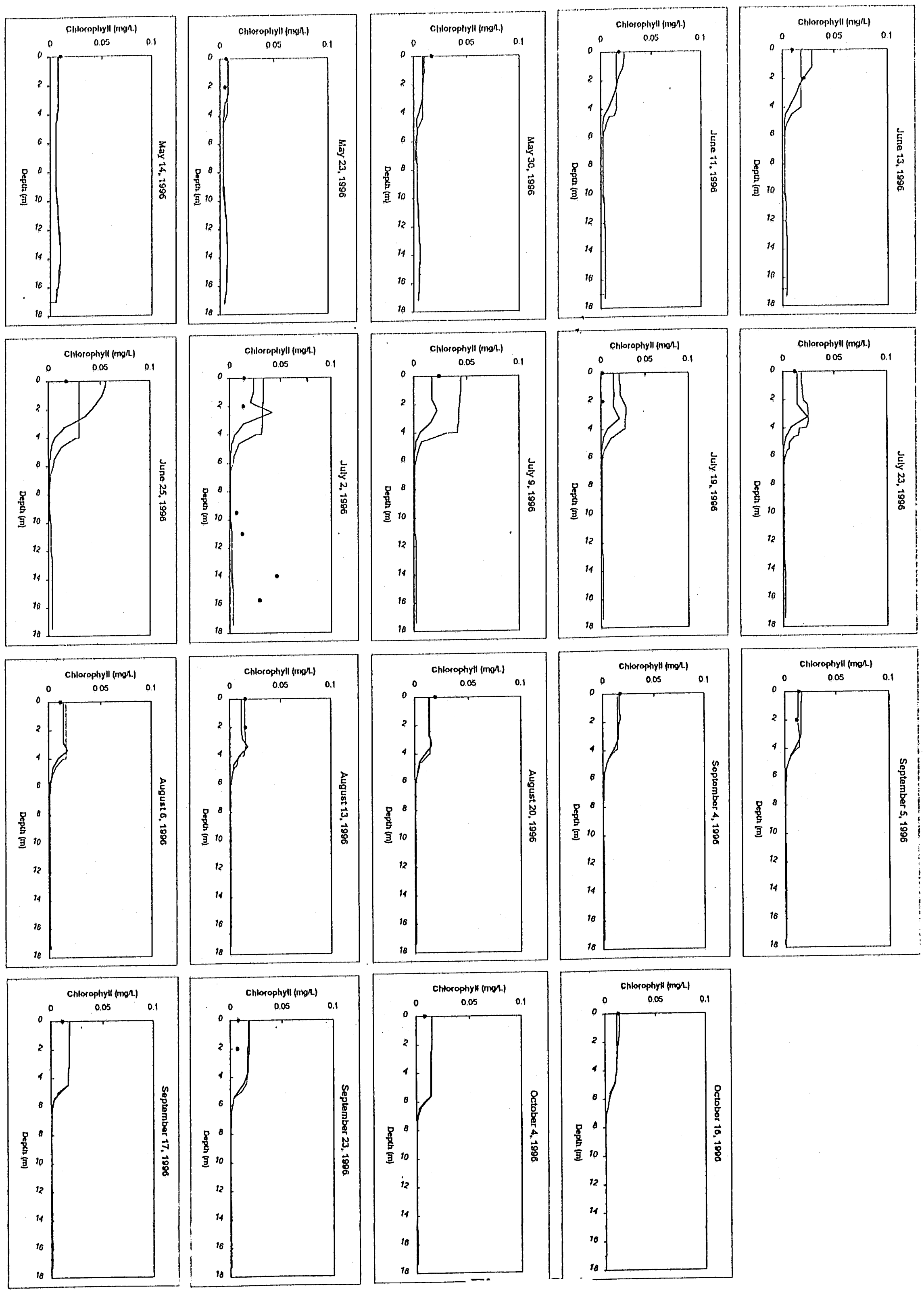


Figure G.4. Existing (solid line) and 4-m deepening (dashed line) chlorophyll *a* profiles for Lake McCarrons - 1996.

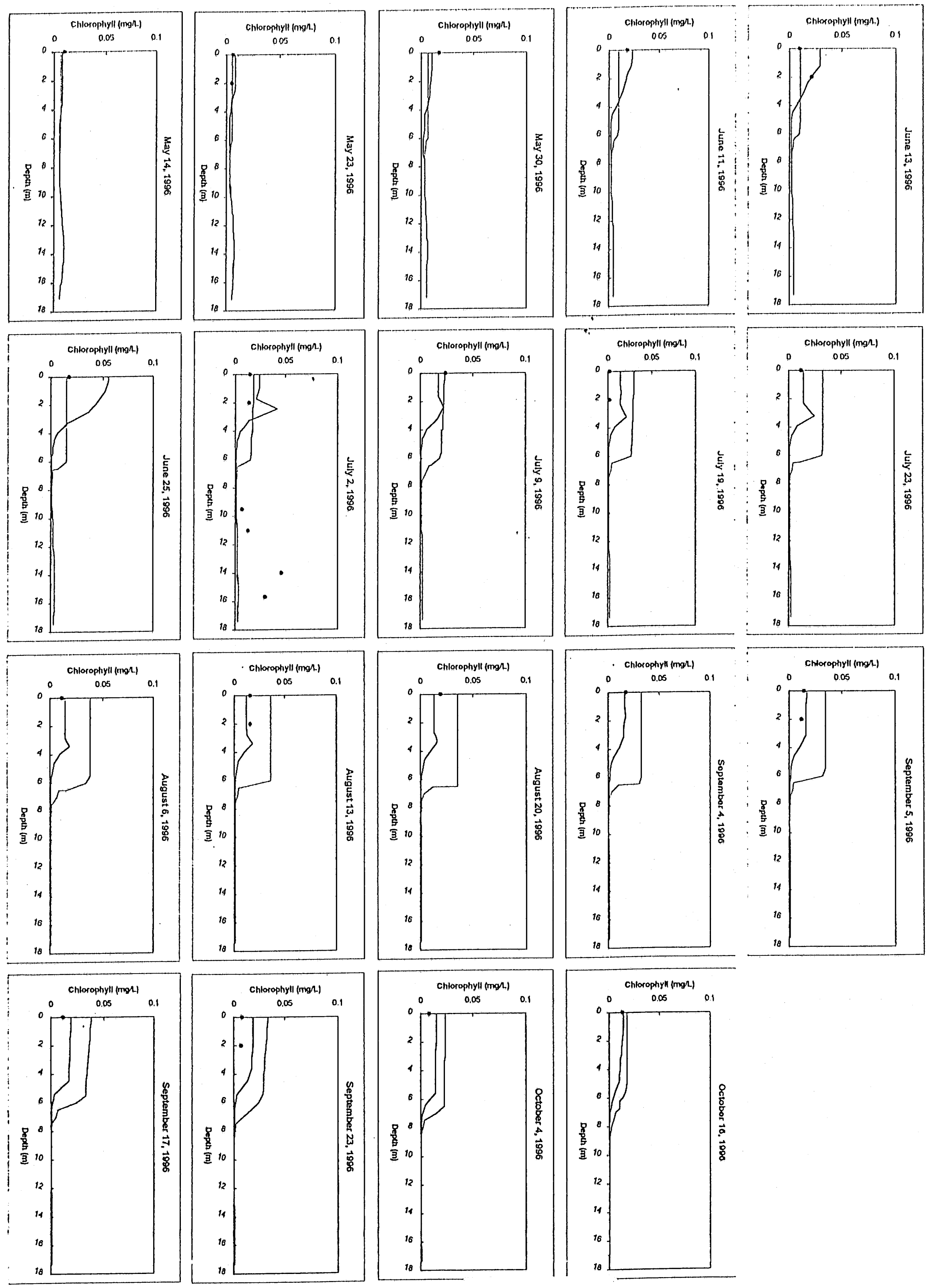


Figure G.5. Existing (solid line) and 6-m deepening (dashed line) chlorophyll *a* profiles for Lake McCarrons - 1996.

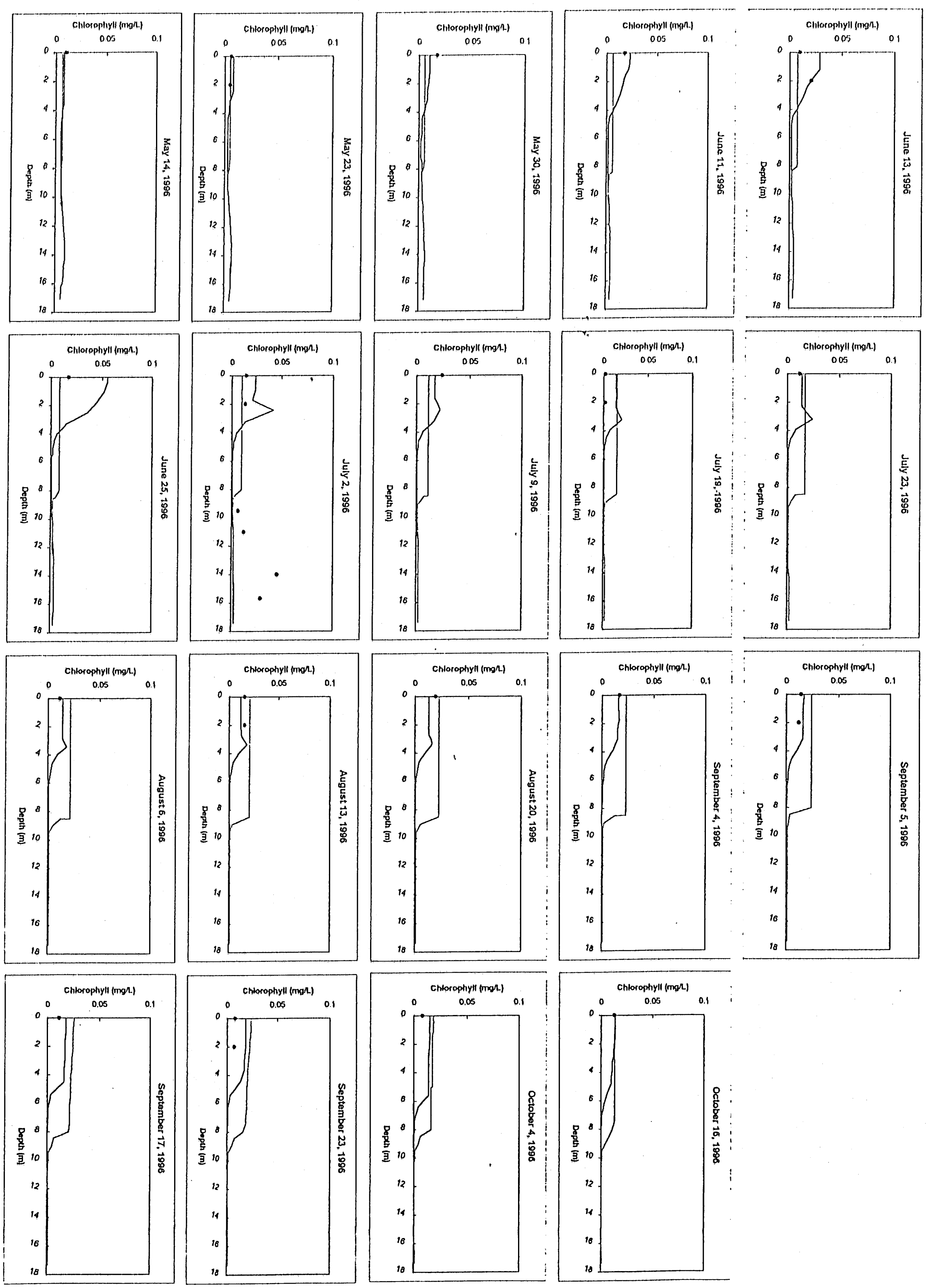
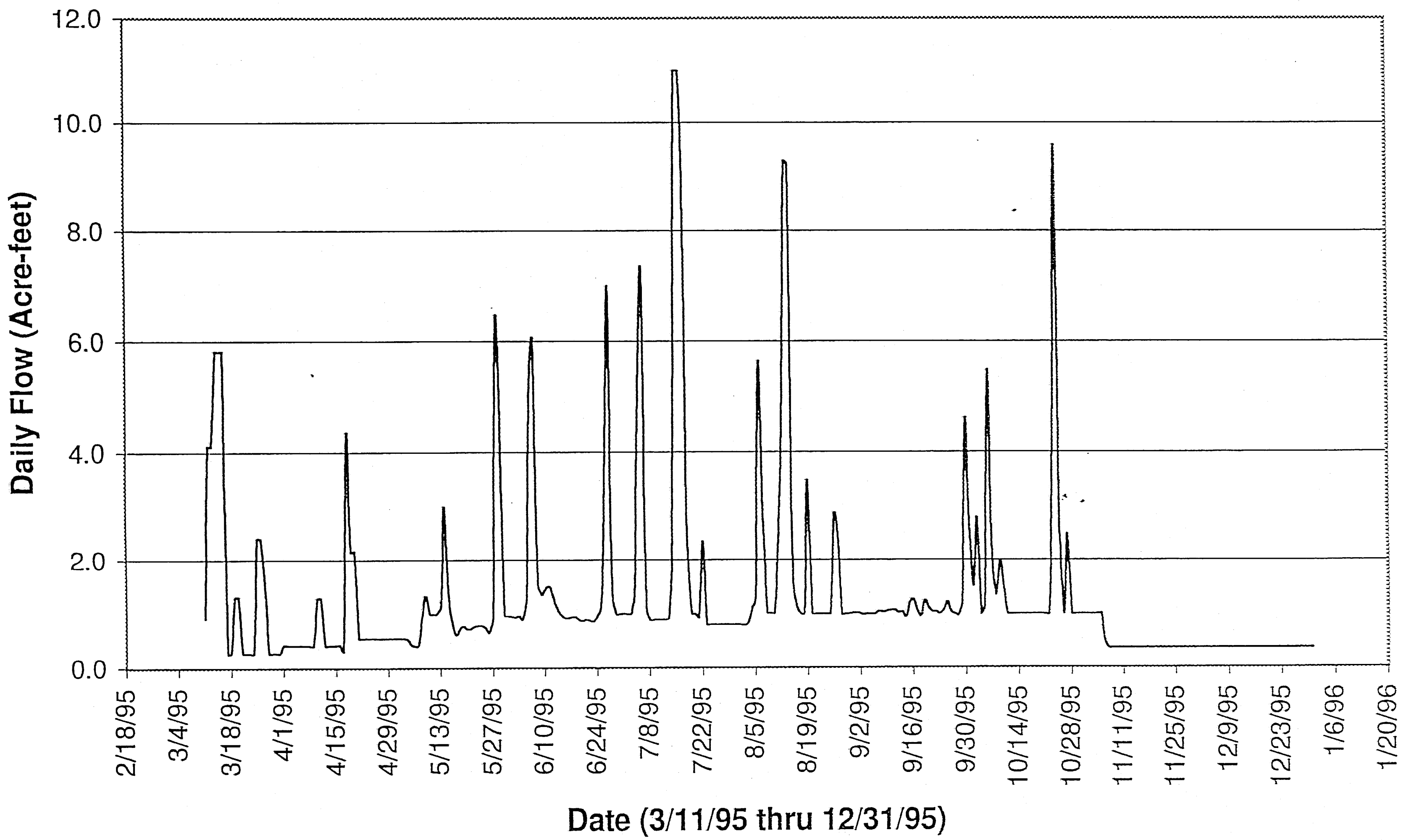
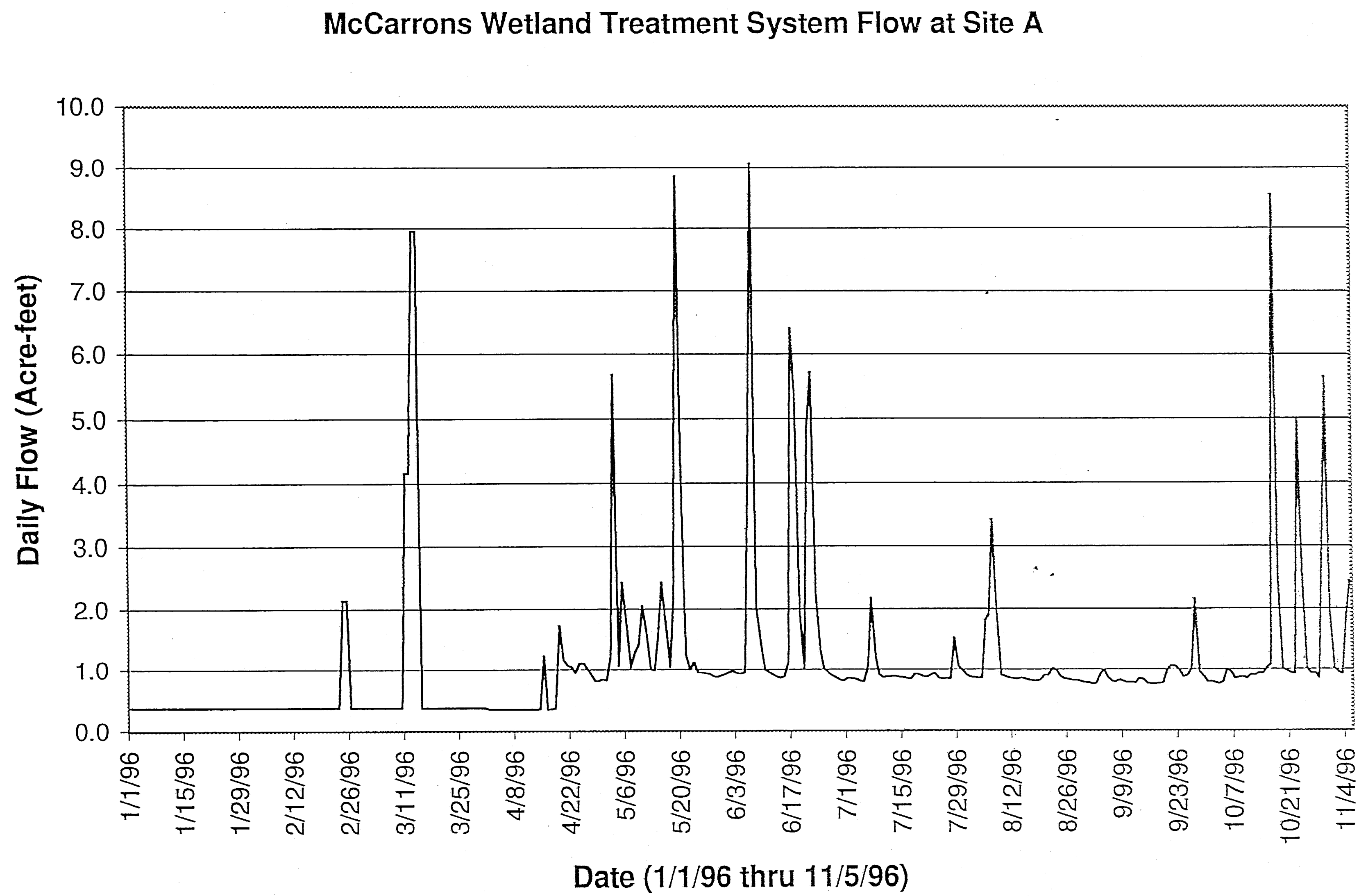


Figure G.6. Existing (solid line) and 8-m deepening (dashed line) chlorophyll *a* profiles for Lake McCarrons - 1996.

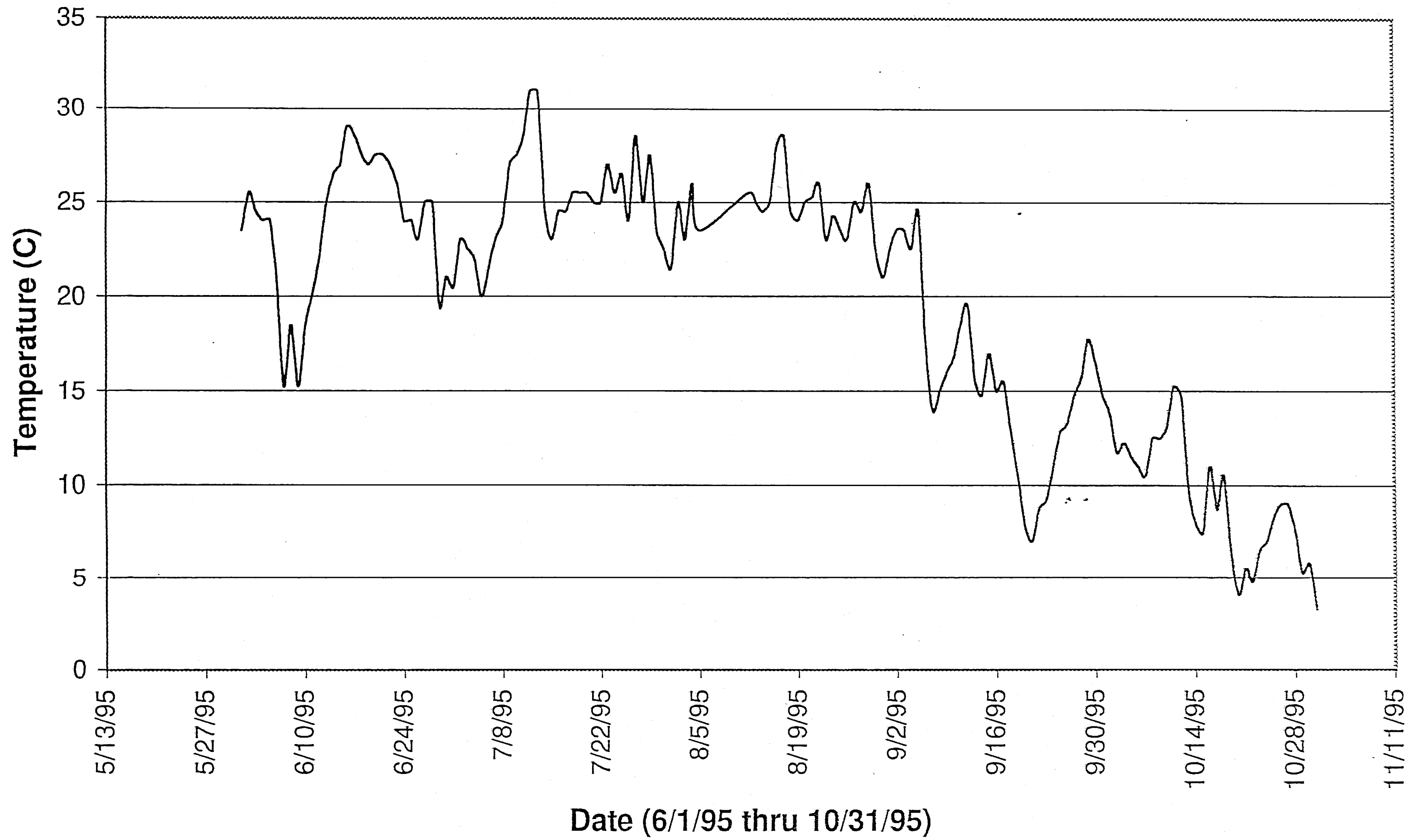
APPENDIX H. DAILY QUANTITY AND QUALITY OF FLOW FROM WETLAND TO LAKE MCCARRONS (1995-1996 MODEL INPUT DATA)

McCarrons Wetland Treatment System Flow at Site A

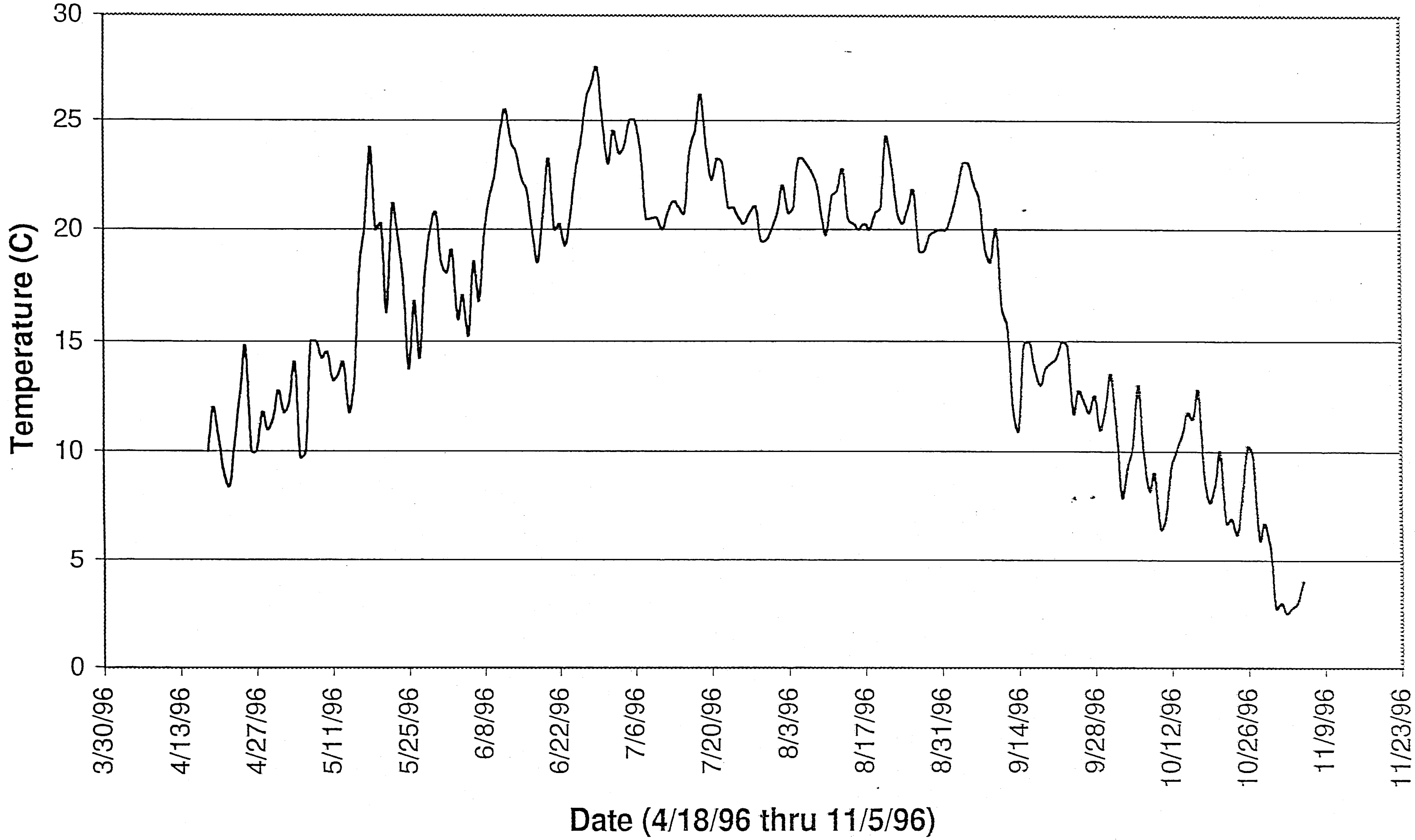



McCarrons Wetland Treatment System Flow at Site A
Daily Flow (Acre-feet)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1/1/96
1/15/96
1/29/96
2/12/96
2/26/96
3/11/96
3/25/96
4/8/96
4/22/96
5/6/96
5/20/96
6/3/96
6/17/96
7/1/96
7/15/96
7/29/96
8/12/96
8/26/96
9/9/96
9/23/96
10/7/96
10/21/96
11/4/96
Date (1/1/96 thru 11/5/96)

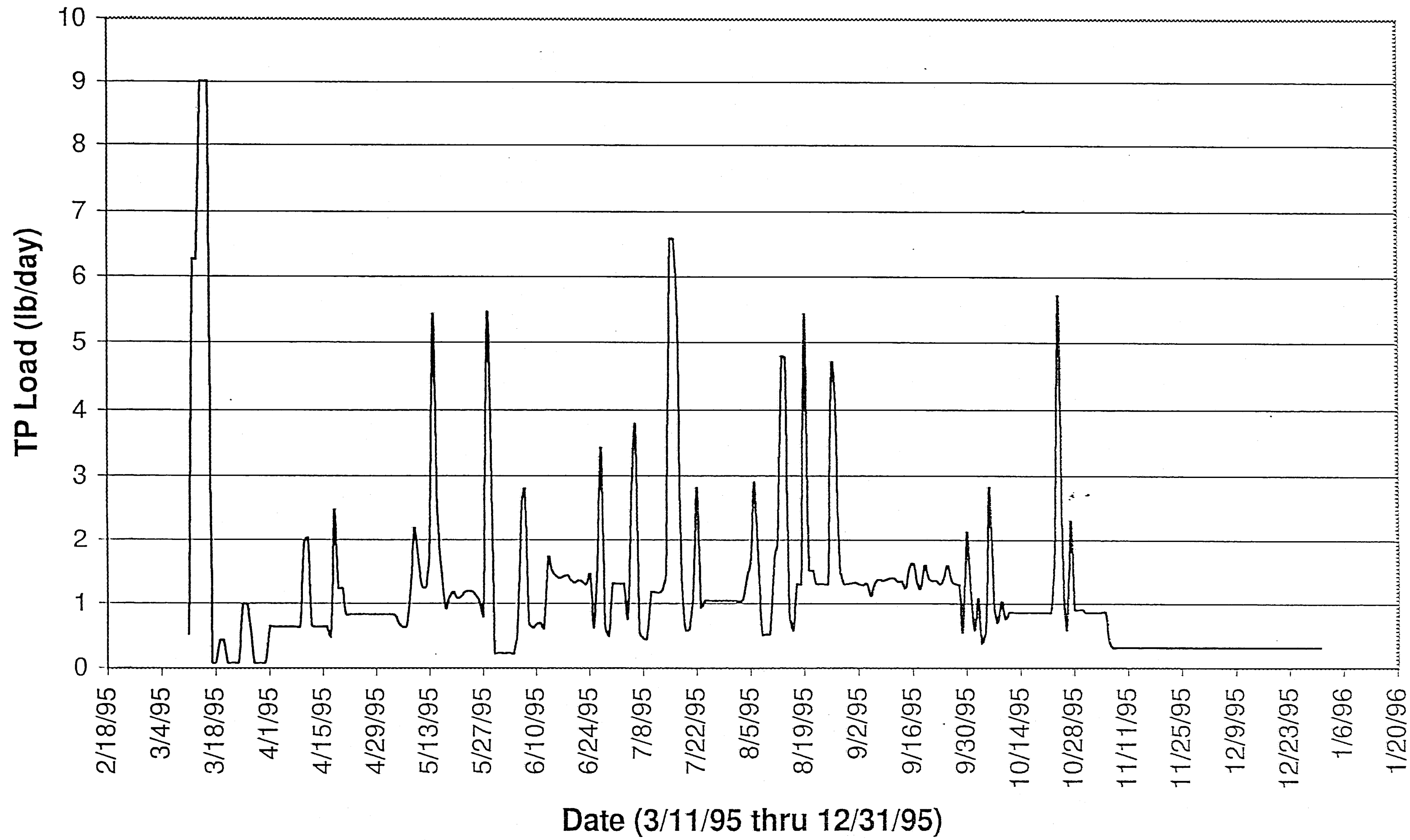
McCarrons Wetland Treatment System Daily Temperature at Site A



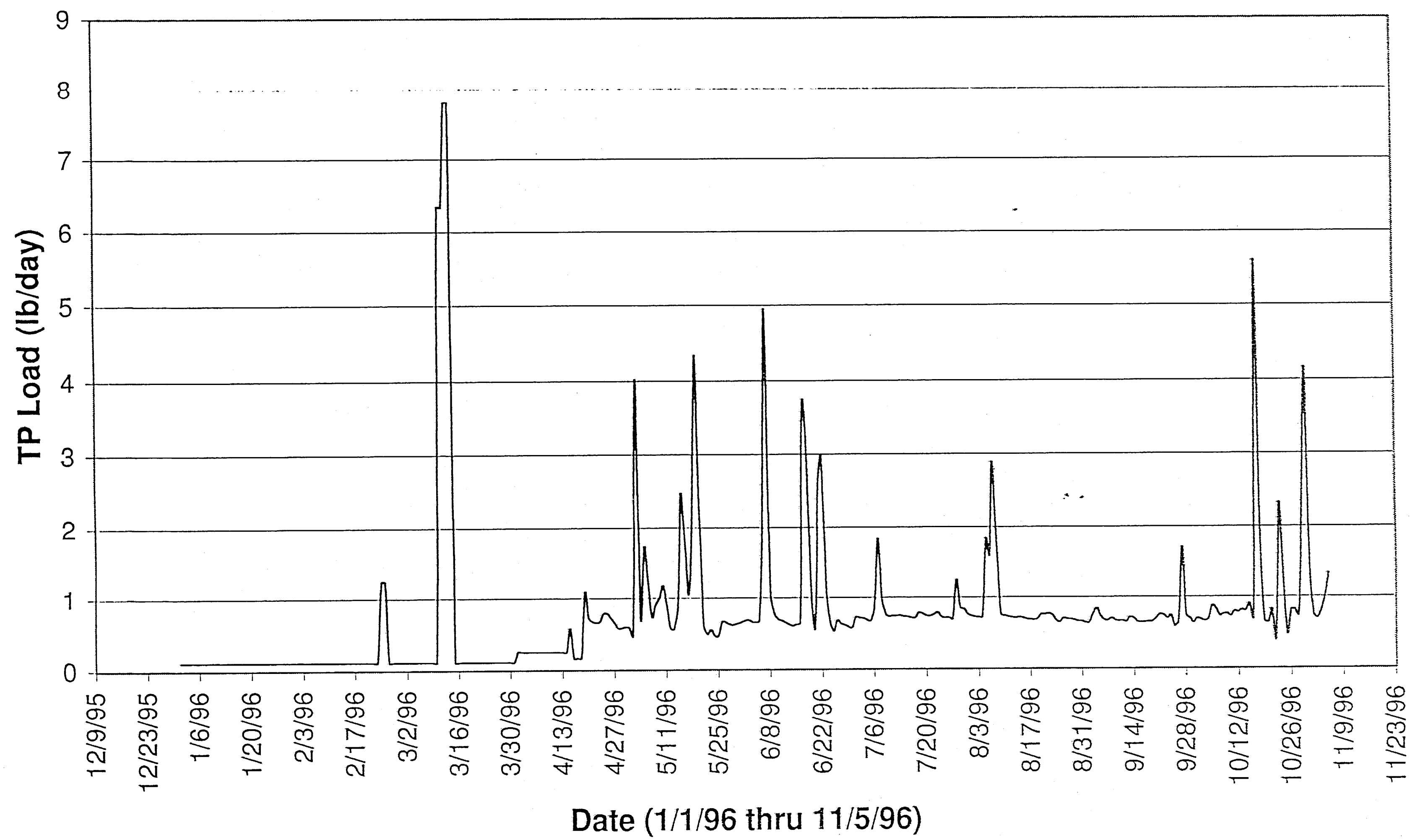
McCarrons Wetland Treatment System Daily Temperature at Site A

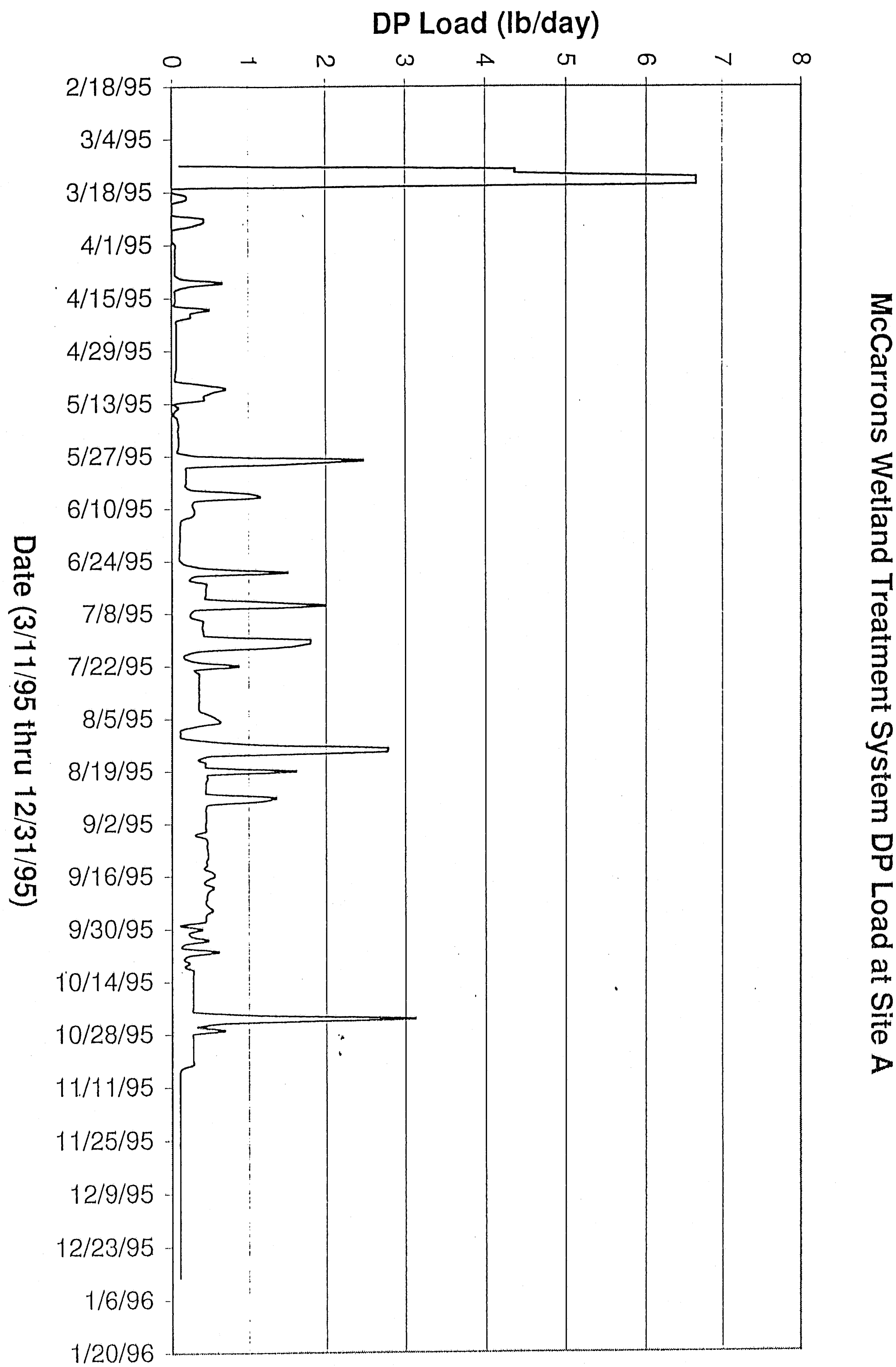


McCarrons Wetland Treatment System TP Load at Site A



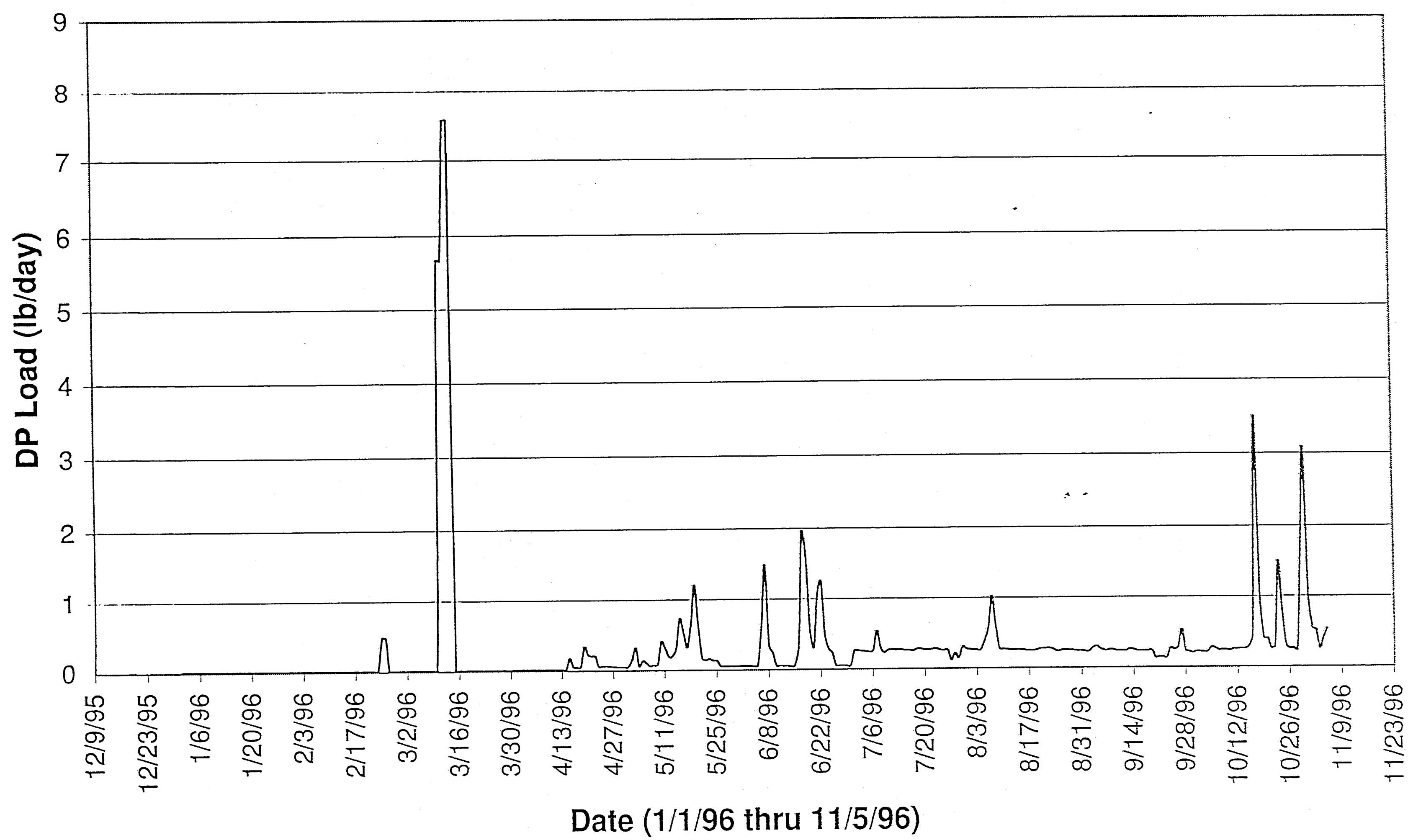
McCarrons Wetland Treatment System TP Load at Site A



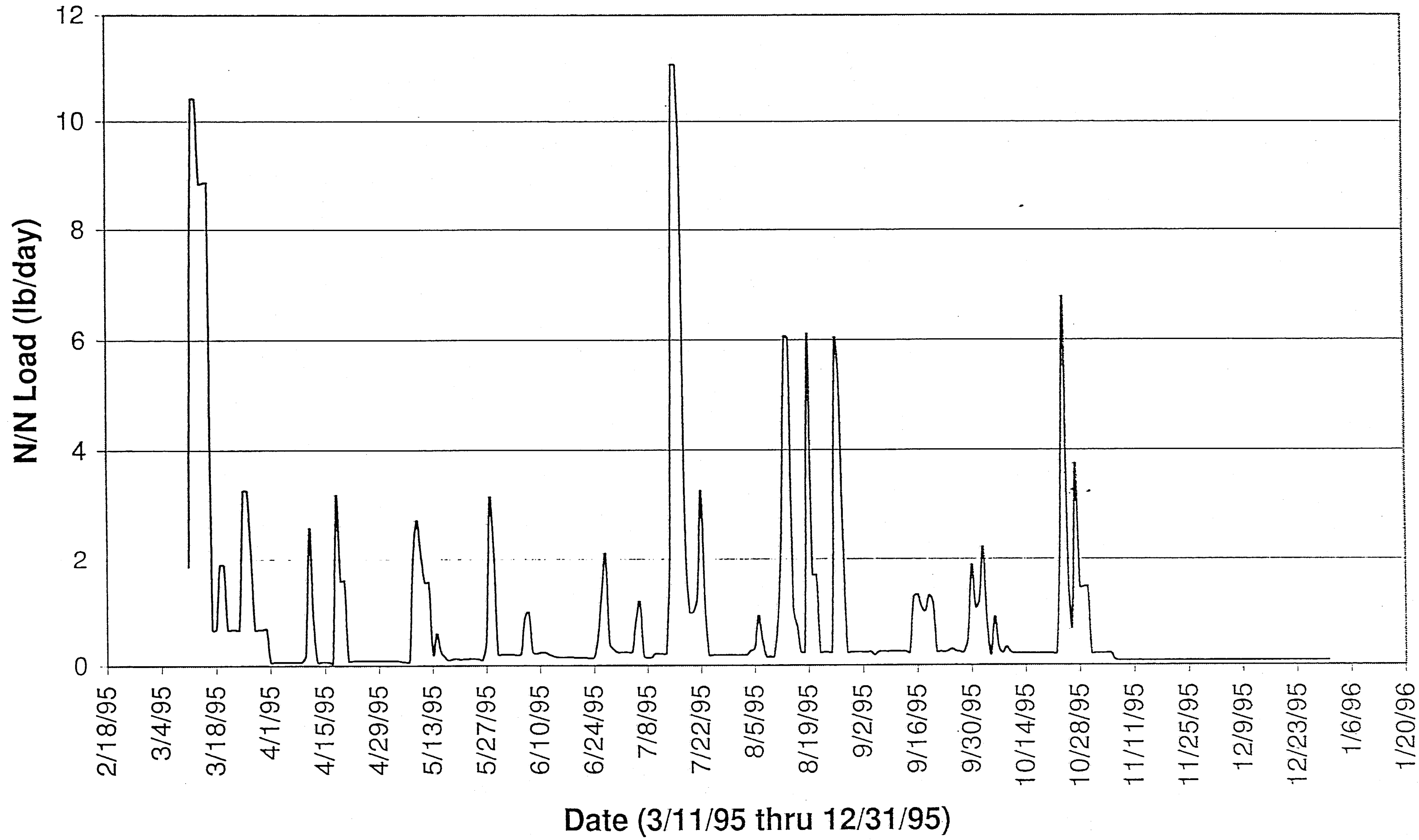


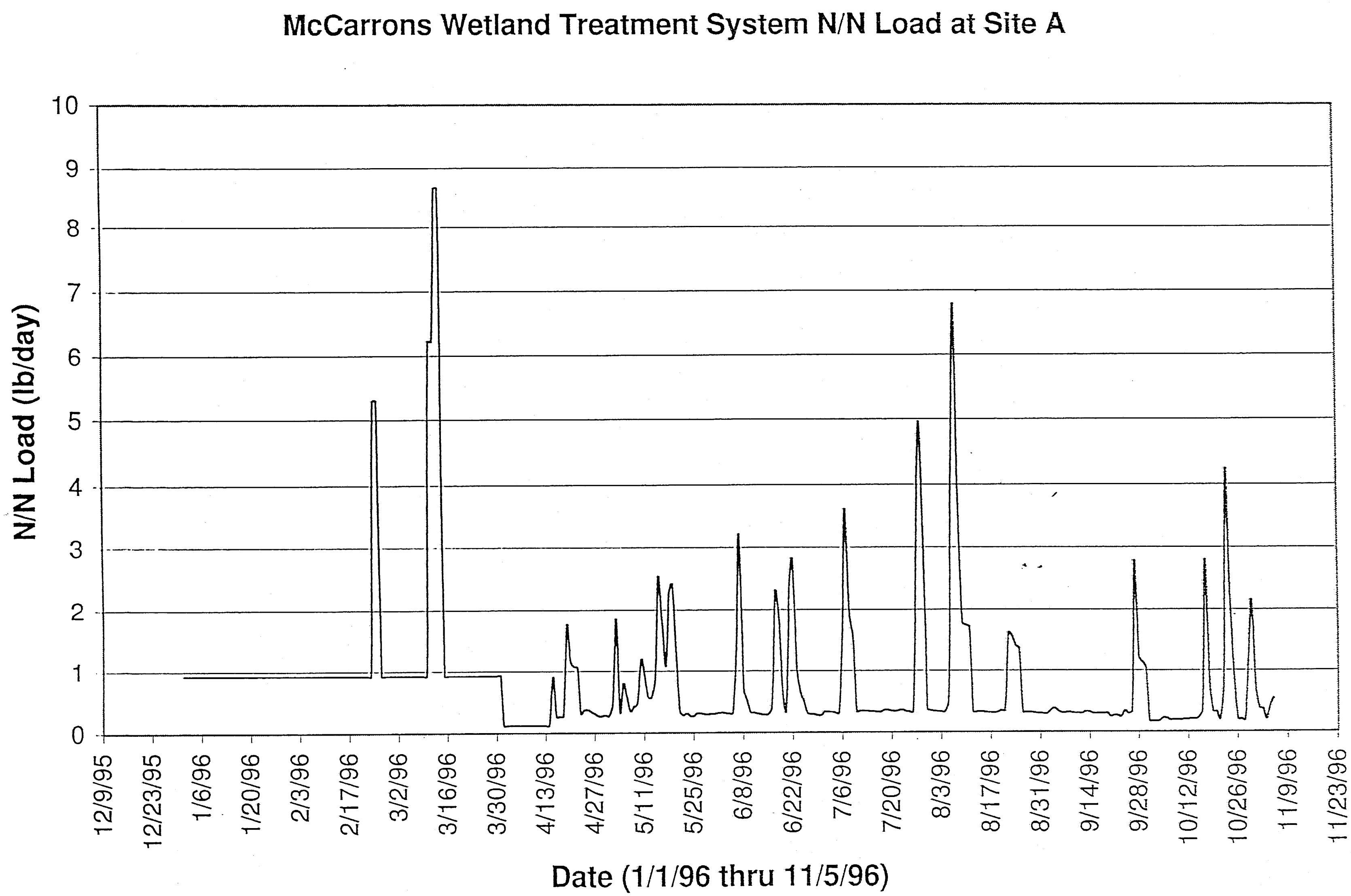
McCarrons Wetland Treatment System DP Load at Site A
DP Load (lb/day)
0
1
2
3
4
5
6
7
8
Date (3/11/95 thru 12/31/95)
2/18/95
3/4/95
3/18/95
4/1/95
4/15/95
4/29/95
5/13/95
5/27/95
6/10/95
6/24/95
7/8/95
7/22/95
8/5/95
8/19/95
9/2/95
9/16/95
9/30/95
10/14/95
10/28/95
11/11/95
11/25/95
12/9/95
12/23/95
1/6/96
1/20/96

McCarrons Wetland Treatment System DP Load at Site A

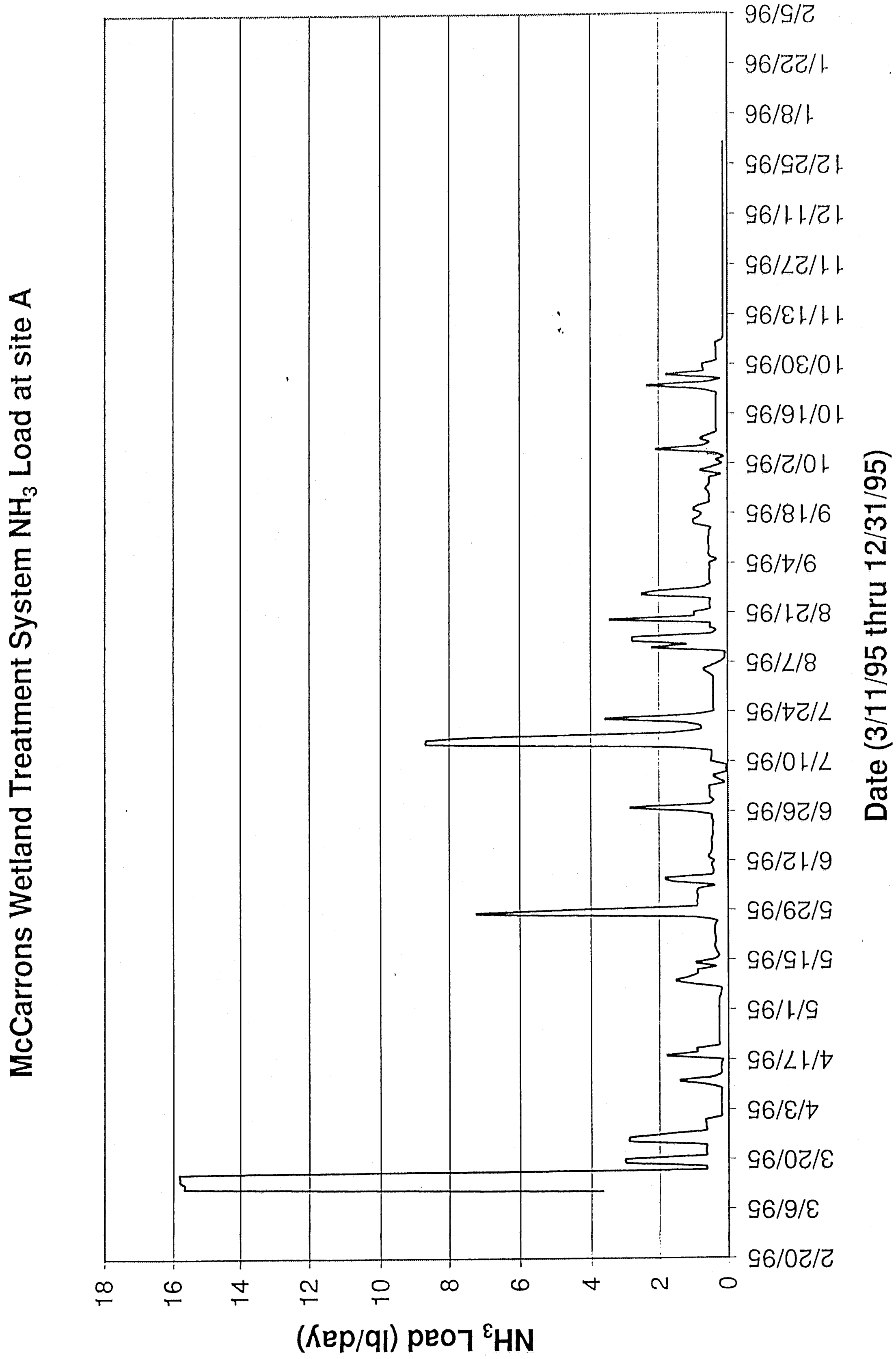


McCarrons Wetland Treatment System N/N Load at Site A

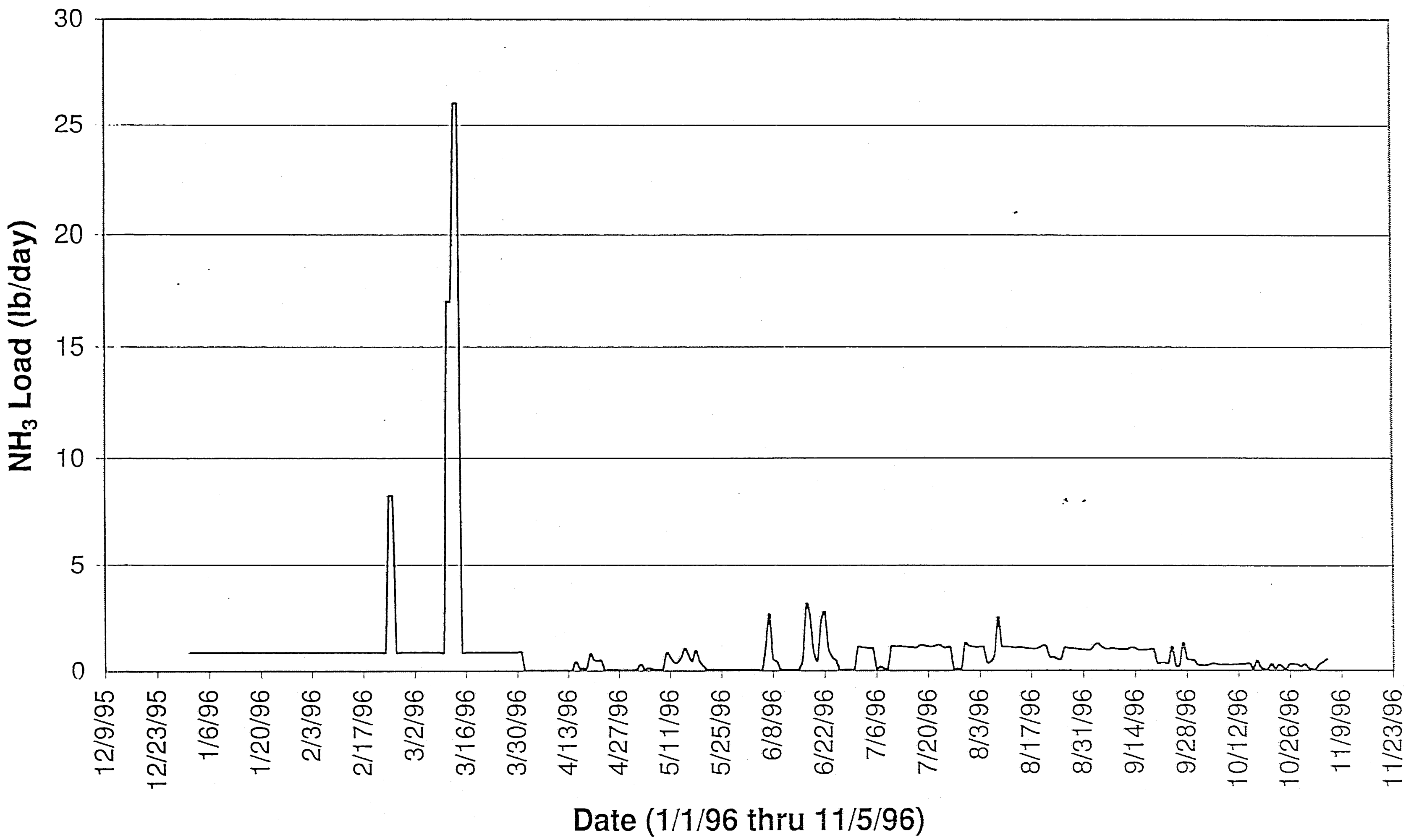


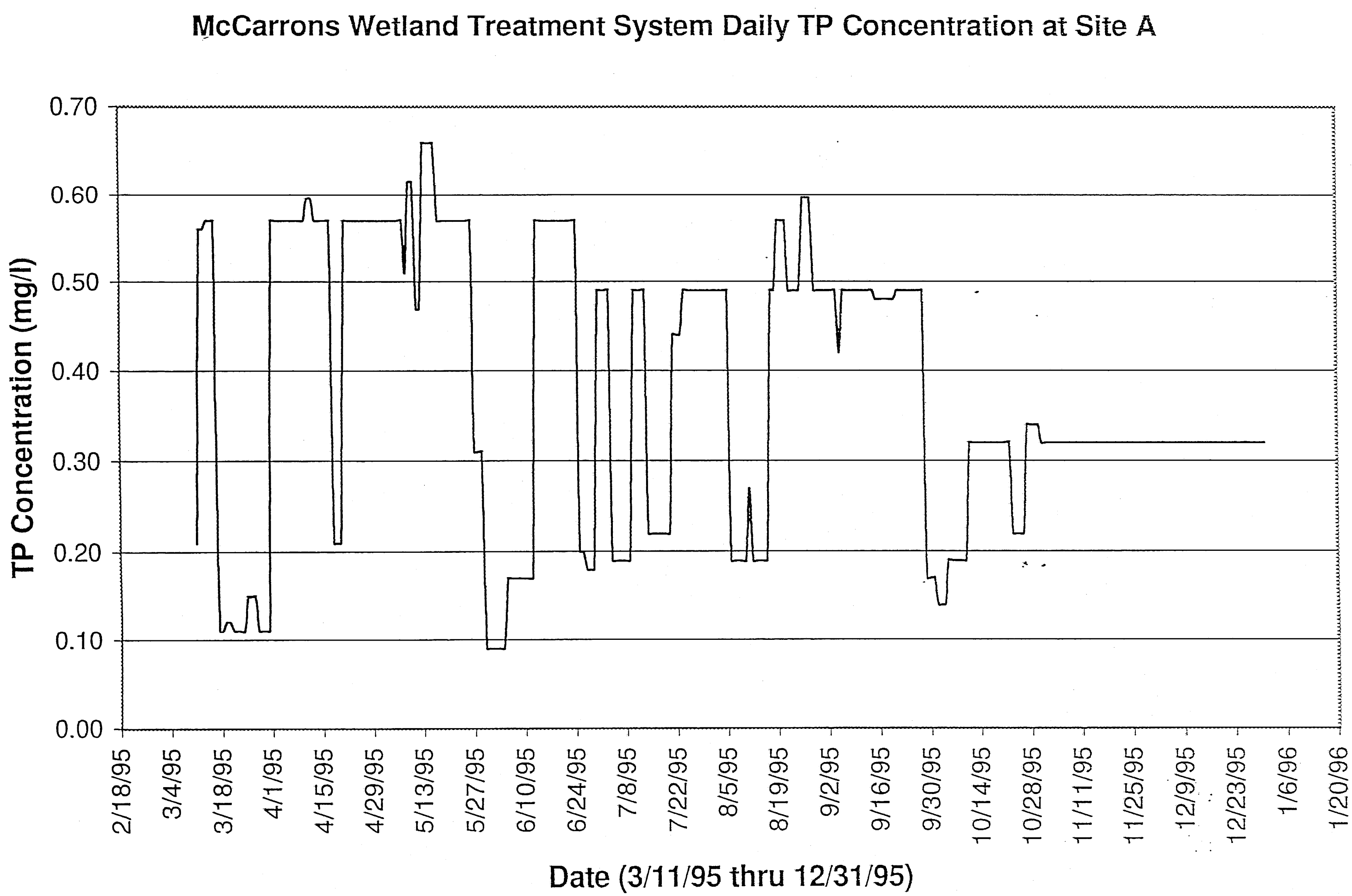


McCarrons Wetland Treatment System N/N Load at Site A
N/N Load (lb/day)
0
1
2
3
4
5
6
7
8
9
10
12/9/95
12/23/95
1/6/96
1/20/96
2/3/96
2/17/96
3/2/96
3/16/96
3/30/96
4/13/96
4/27/96
5/11/96
5/25/96
6/8/96
6/22/96
7/6/96
7/20/96
8/3/96
8/17/96
8/31/96
9/14/96
9/28/96
10/12/96
10/26/96
11/9/96
11/23/96
Date (1/1/96 thru 11/5/96)

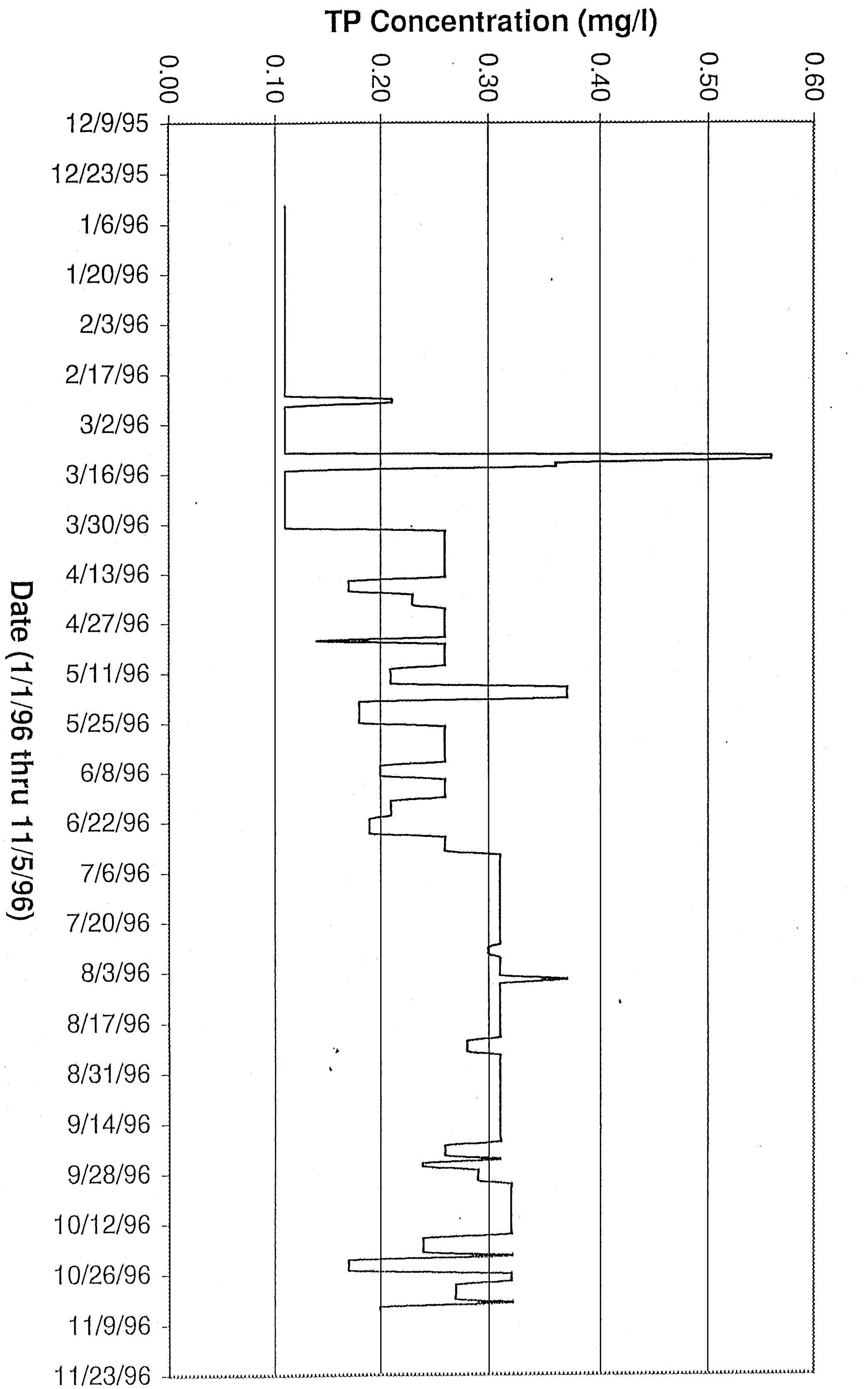

McCarrons Wetland Treatment System NH_3 Load at site A
NH_3 Load (lb/day)
0
2
4
6
8
10
12
14
16
18
Date (3/11/95 thru 12/31/95)
2/20/95
3/6/95
3/20/95
4/3/95
4/17/95
5/1/95
5/15/95
5/29/95
6/12/95
6/26/95
7/10/95
7/24/95
8/7/95
8/21/95
9/4/95
9/18/95
10/2/95
10/16/95
10/30/95
11/13/95
11/27/95
12/11/95
12/25/95
1/8/96
1/22/96
2/5/96

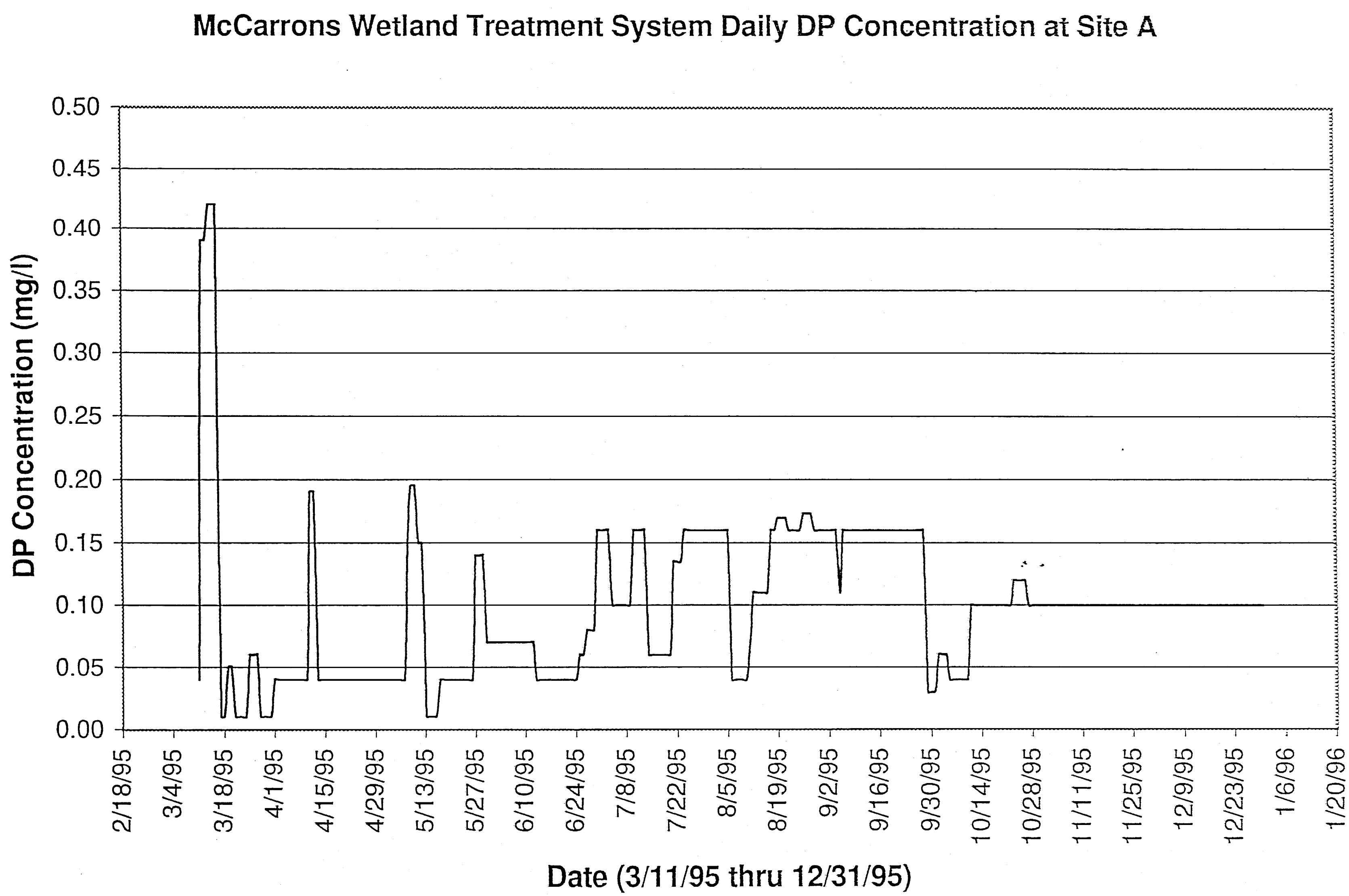
McCarrons Wetland Treatment System NH_3 Load at Site A

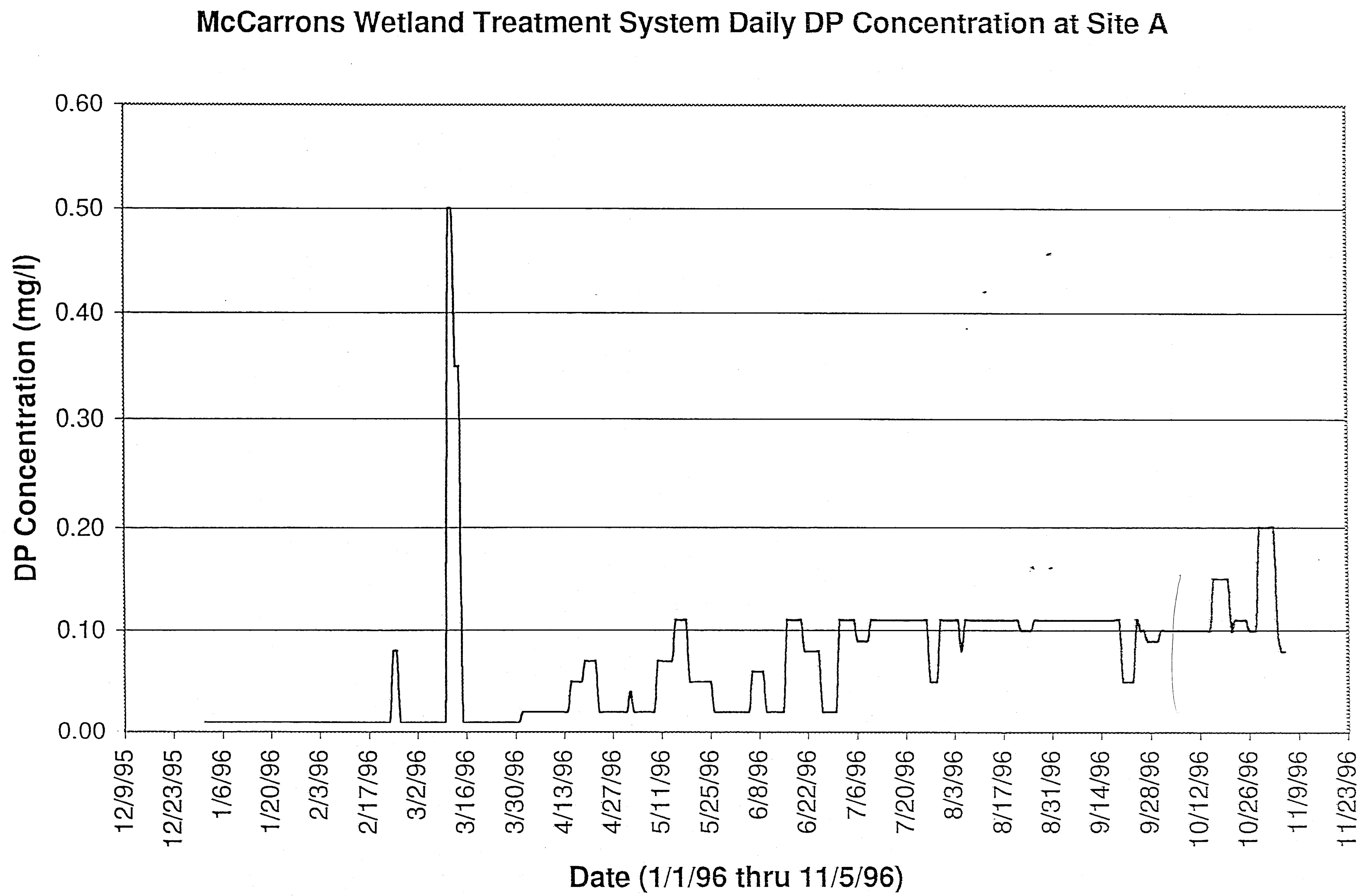


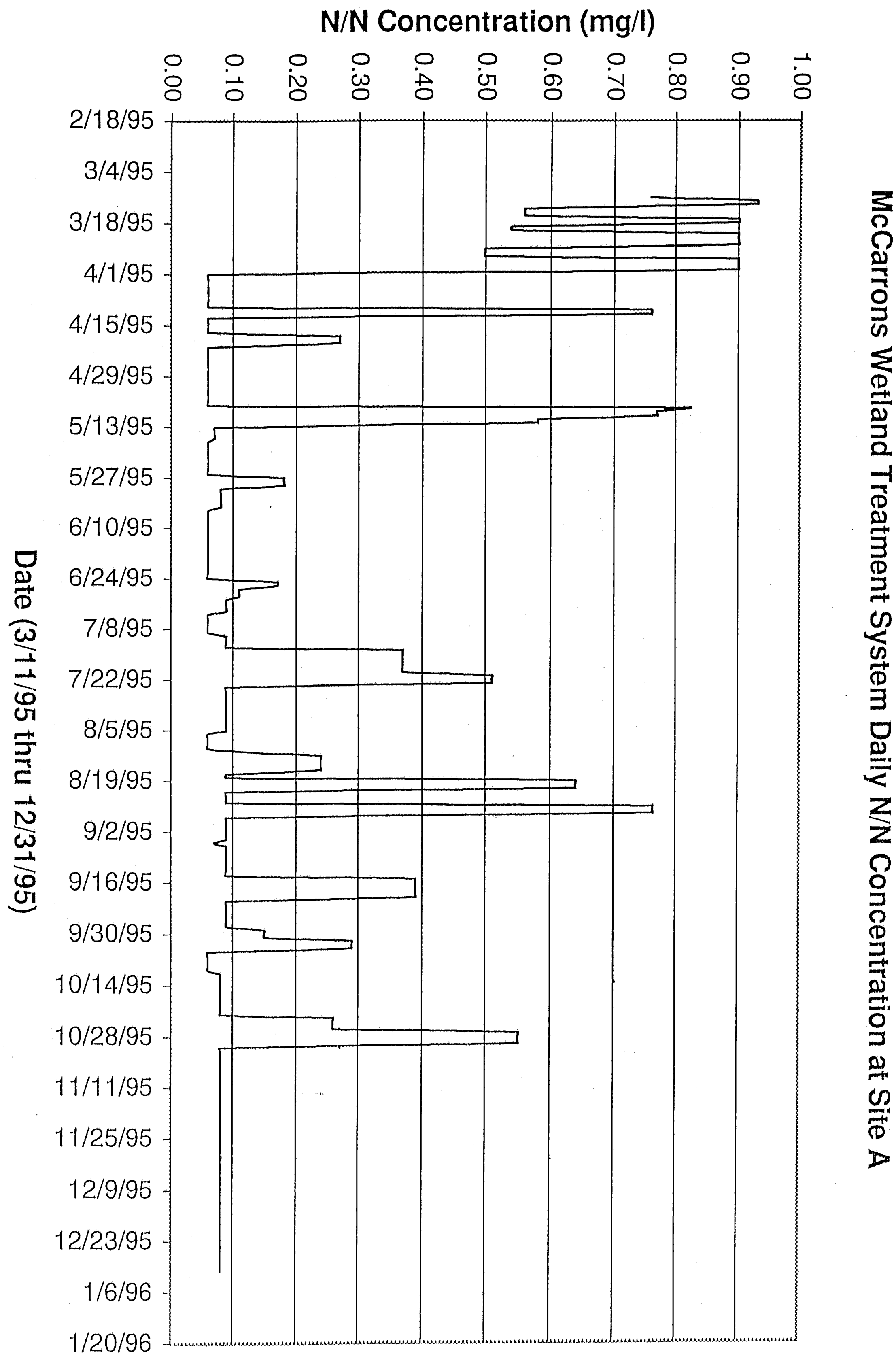

McCarrons Wetland Treatment System Daily TP Concentration at Site A
TP Concentration (mg/l)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2/18/95
3/4/95
3/18/95
4/1/95
4/15/95
4/29/95
5/13/95
5/27/95
6/10/95
6/24/95
7/8/95
7/22/95
8/5/95
8/19/95
9/2/95
9/16/95
9/30/95
10/14/95
10/28/95
11/11/95
11/25/95
12/9/95
12/23/95
1/6/96
1/20/96
Date (3/11/95 thru 12/31/95)

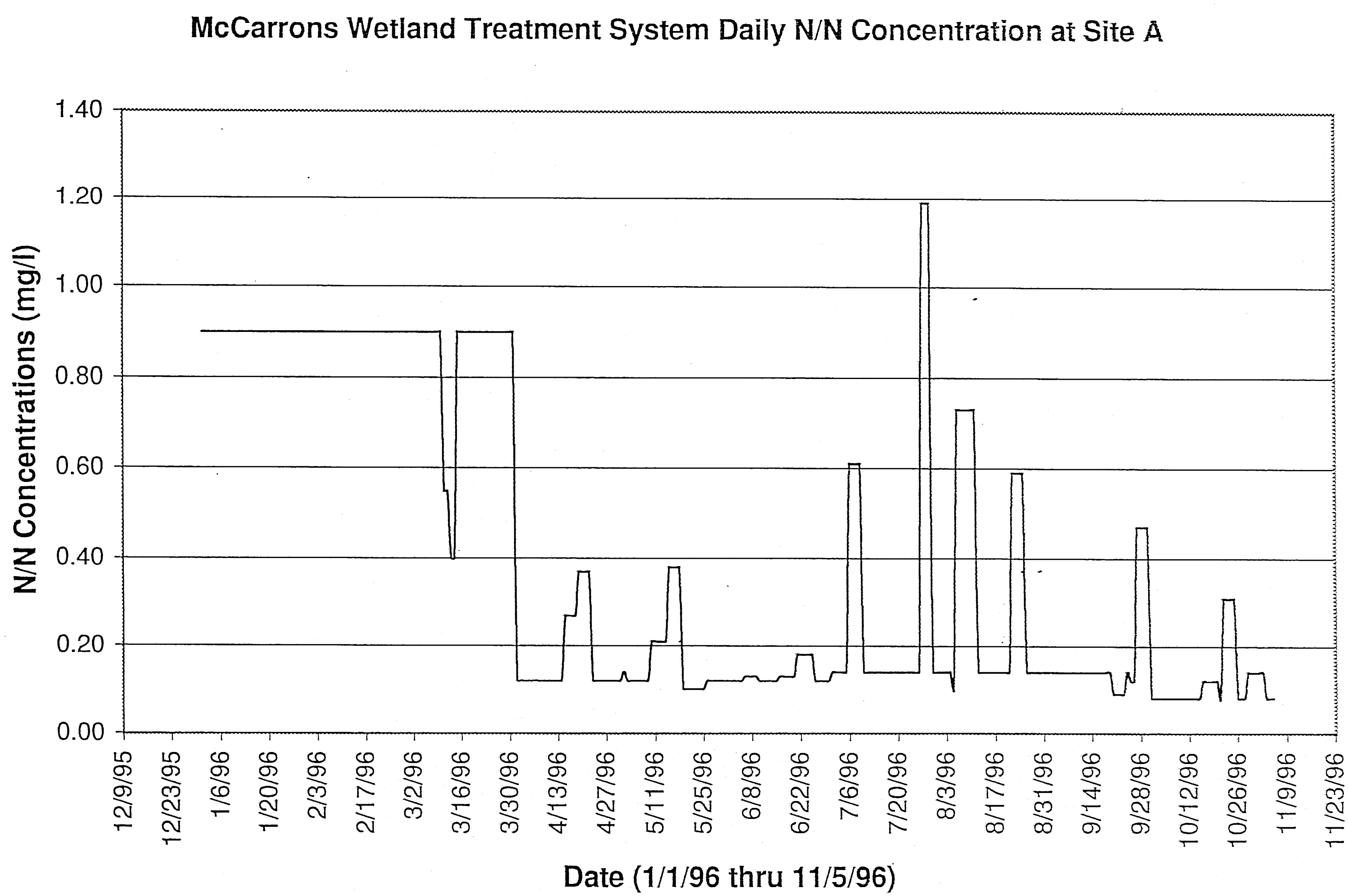
McCarrons Wetland Treatment System Daily TP Concentration at Site A



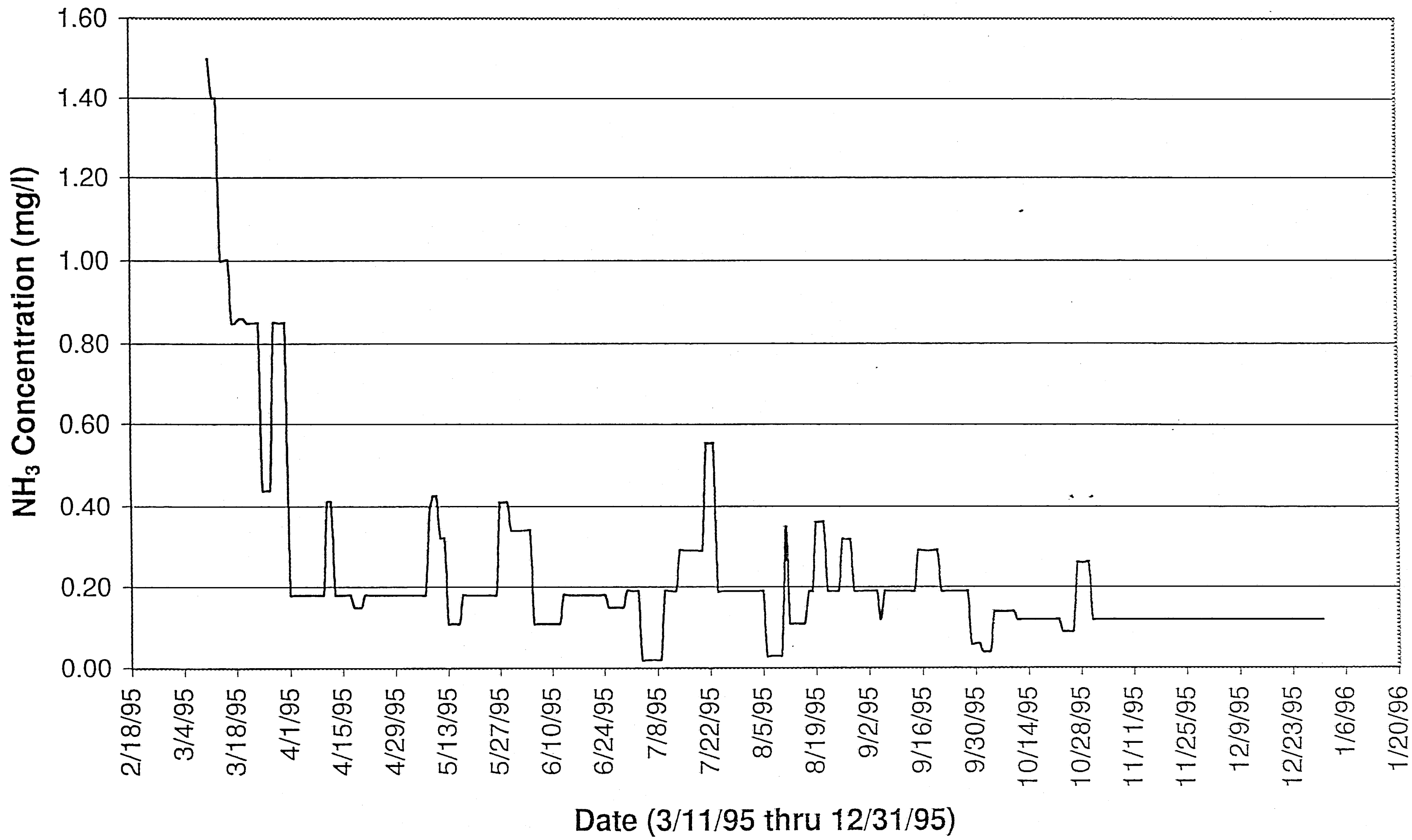

McCarrons Wetland Treatment System Daily DP Concentration at Site A
DP Concentration (mg/l)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
2/18/95
3/4/95
3/18/95
4/1/95
4/15/95
4/29/95
5/13/95
5/27/95
6/10/95
6/24/95
7/8/95
7/22/95
8/5/95
8/19/95
9/2/95
9/16/95
9/30/95
10/14/95
10/28/95
11/11/95
11/25/95
12/9/95
12/23/95
1/6/96
1/20/96
Date (3/11/95 thru 12/31/95)

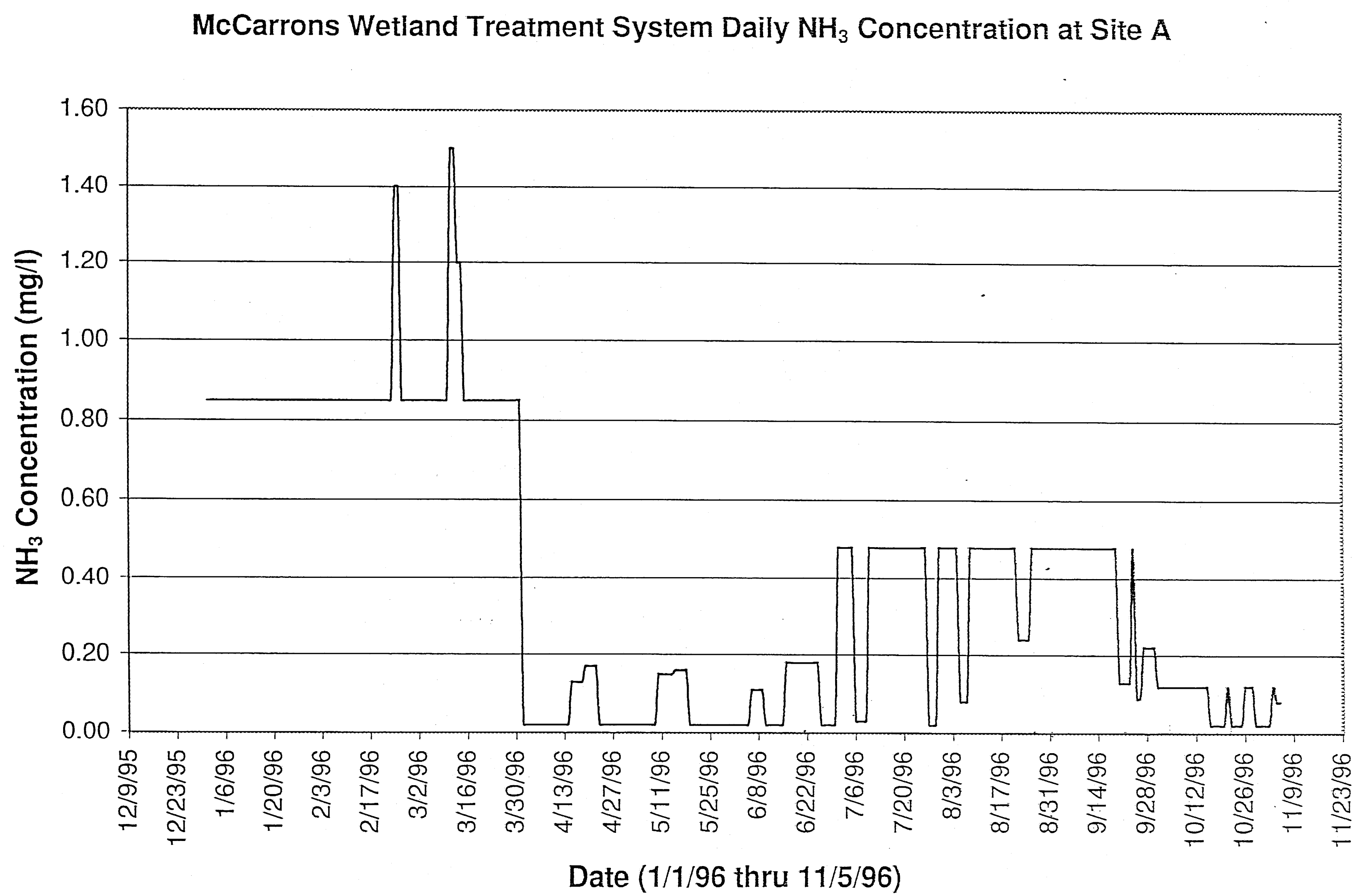

McCarrons Wetland Treatment System Daily DP Concentration at Site A
DP Concentration (mg/l)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
12/9/95
12/23/95
1/6/96
1/20/96
2/3/96
2/17/96
3/2/96
3/16/96
3/30/96
4/13/96
4/27/96
5/11/96
5/25/96
6/8/96
6/22/96
7/6/96
7/20/96
8/3/96
8/17/96
8/31/96
9/14/96
9/28/96
10/12/96
10/26/96
11/9/96
11/23/96
Date (1/1/96 thru 11/5/96)


McCarrons Wetland Treatment System Daily N/N Concentration at Site A
N/N Concentration (mg/l)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
Date (3/11/95 thru 12/31/95)
2/18/95
3/4/95
3/18/95
4/1/95
4/15/95
4/29/95
5/13/95
5/27/95
6/10/95
6/24/95
7/8/95
7/22/95
8/5/95
8/19/95
9/2/95
9/16/95
9/30/95
10/14/95
10/28/95
11/11/95
11/25/95
12/9/95
12/23/95
1/6/96
1/20/96


McCarrons Wetland Treatment System Daily N/N Concentration at Site A
N/N Concentrations (mg/l)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
12/9/95
12/23/95
1/6/96
1/20/96
2/3/96
2/17/96
3/2/96
3/16/96
3/30/96
4/13/96
4/27/96
5/11/96
5/25/96
6/8/96
6/22/96
7/6/96
7/20/96
8/3/96
8/17/96
8/31/96
9/14/96
9/28/96
10/12/96
10/26/96
11/9/96
11/23/96
Date (1/1/96 thru 11/5/96)

McCarrons Wetland Treatment System Daily NH_3 Concentration at Site A




McCarrons Wetland Treatment System Daily NH3 Concentration at Site A
NH3 Concentration (mg/l)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
12/9/95
12/23/95
1/6/96
1/20/96
2/3/96
2/17/96
3/2/96
3/16/96
3/30/96
4/13/96
4/27/96
5/11/96
5/25/96
6/8/96
6/22/96
7/6/96
7/20/96
8/3/96
8/17/96
8/31/96
9/14/96
9/28/96
10/12/96
10/26/96
11/9/96
11/23/96
Date (1/1/96 thru 11/5/96)