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THERMAL ASPECTS OF TWO POCONO LAKES

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ABSTRACT

Thermal structures in lakes are studied by engineers and ecologists to gain insight to many biological and chemical lake processes. Since on-site sampling of temperature profiles cannot be performed on a daily basis at most lakes, and thermal profile forecasts are useful in preventing eutrophication and acidification of lakes, models are implemented to predict current and future temperature profiles. In this study, the U.S. Army Corps of Engineers' program CE-THERM-R1 is used to predict temperature profiles in Lake Lacawac and Lake Giles, which are part of the Pocono Comparative Lakes Program.

Lake Lacawac, a natural lake with an undisturbed watershed and moderate productivity, is classified as mesotrophic. Lake Giles' very clear water is acidic, resulting in low productivity, and an oligotrophic classification. Data collection and parameter evaluation for the lakes are included. Predicted temperature profiles for the lakes are compared to monthly measured profiles, and fall turnover in each lake is evaluated. Accurate temperature profiles are predicted for Lake Lacawac and Lake Giles, validating the CE-THERM-R1 modeling technique. Fall turnover, when isothermal conditions are evident in the water column, occurs two weeks later in Lake Giles than in Lake Lacawac, as expected by its greater depth and light penetration capability.

Wind function and light attenuation coefficients are sensitive parameters in the model study, and must be estimated or calibrated carefully. Inflow rates and outflow rates, estimated from local hydrology, have negligible effects on the two lake systems. Prediction of reliable and rational thermal profiles in Lake Lacawac and Lake Giles is essential, before modeling other lake processes can begin.

CHAPTER 1 INTRODUCTION

1.1 General Description

1.1.1 Lake Modeling

Accurate predictions of thermal aspects of lakes and reservoirs are useful to engineers and ecologists. Lake models are developed and implemented to predict thermal, biological, and chemical aspects of existing and proposed relatively slow moving bodies of water. A better understanding of the complex, interrelated behavior of lake ecosystems can be gained from a successful mathematical or computer model which eases data collection and computations. This thesis examines thermal processes in two different lakes, including the collection of necessary input data, model theory and calibration, and computer model predictions of thermal profiles.

1.1.2 Pocono Comparative Lakes Program

Educators, scientists, engineers, and students have been monitoring and studying three Pennsylvania Pocono lakes since 1988 as part of the Pocono Comparative

Lakes Program (PCLP). These lakes, Lacawac, Giles, and Waynewood are located in northeastern Pennsylvania's Pocono Mountain region, and encompass the range of eutrophication from an unproductive oligotrophic lake (Giles) to a highly nutrified and productive eutrophic lake (Waynewood). The long term research goal is to provide understanding of natural lake processes, as well as irregularities due to natural and man-made watershed characteristics. Sampling is conducted monthly at each lake, and more frequently in the summer. Data collected includes temperature, light penetration, and oxygen profiles, Secchi disk depth, pH, alkalinity, chlorophyll-a, and zooplankton. Chemical analyses of the lakes were performed four times in 1989 (Moeller and Williamson, 1991a).

1.1.3 Lake Classifications

Lakes are categorized into trophic categories, oligotrophic, mesotrophic and eutrophic. Oligotrophic lakes are low in nutrients and productivity. Clear blue water allows significant light penetration in oligotrophic lakes. Eutrophic lakes are at the other end of the trophic scale. Rich in nutrients, phosphorous and nitrogen, eutrophic lakes have abundant microscopic and rooted plant growth, including algae, which cause poor water quality, and a greenish color. Intermediate nitrogen and phosphorous levels and productivity indicate a mesotrophic lake classification. Evidence of lake eutrophication can be found in

deteriorating water quality, such as high concentrations of total phosphorous and chlorophyll-a, inability for light to penetrate to deeper layers, and decreasing dissolved oxygen in the hypolimnion (Thomann and Mueller, 1987).

1.1.4 Lake Processes

Lake processes differ with trophic state and with stratification conditions. Inputs to lakes contain light, oxygen, nutrients, and sediments. Light from solar radiation enters the water column surface and decreases exponentially with depth. Wind mixing, inflowing water, and photosynthesis supply oxygen to the surface layers, and what is not consumed by respiration and oxidization diffuses. Inflowing waters also carry nutrients and sediments. Eutrophication can be enhanced by nutrients from sources such as agriculture and development, located in a lake's watershed. Changing seasons and weather conditions affect a lake's thermal structure, which influences all other lake processes. In the spring, as air temperature increases, the lake surface warms. Eventually the lake becomes stratified into an upper, well mixed, oxygenated layer, called the epilimnion, and a cooler bottom layer, or hypolimnion, which loses oxygen to existing aquatic life, organic decay, and sediment demand (see Figure 1.1). During summer stratification, processes occurring in the epilimnion are influenced by temperature, light, winds, inflow rates, inflow oxygen and nutrients concentrations, and the

addition of oxygen at the water surface, enhancing plant life and growth. Sediments and dead plant material settle to the cooler, denser, darker hypolimnion and consume any remaining oxygen during decomposition. Stratification into the warmer epilimnion and cooler hypolimnion continues until mid-summer, when the lake slowly destratifies as the epilimnion cools. Fall winds and cooler temperatures cause a complete mixing of the water column, allowing oxygen to the bottom layers through an exchange of epilimnion and hypolimnion water. During the winter, the lake cools uniformly and isothermal water column conditions enable oxygen diffusion to all depths of the lake, yet the colder water temperatures and weather conditions inhibit plant development and photosynthesis. Warming of the surface layers begins again the next spring.

1.1.5 Applications of Predictions

Lake water quality properties are inherently interdependent, making simplified water quality models essential for engineers and scientists. Engineers utilize water quality models in the design and maintenance of reservoirs. Water supply reservoirs have water quality standards which must be satisfied, and efficient methods of compliance can be predicted by models. Designs of reservoir outlet structures can be simulated to ensure allowable outflow rates, temperatures, and dissolved oxygen. Long term reservoir management requirements to maintain

fishing, recreation and aesthetic features can be established using model forecasts. Biologists studying plant and animal life in lakes relate thermal conditions to the behavior of these organisms. Ecologists interested in lake ecosystems gain knowledge of and insight to temperature dependent lake processes, decay rates, and uptake rates from thermal profile modeling.

1.2 Scope

1.2.1 Lake and Reservoir Computer Models

Many types of computer methods are available to model lake and reservoir water quality. Programs utilize a zero, one, two, or three dimensional approach to model and forecast thermal, biological, and chemical parameters. An assortment of reservoir operational schemes can be represented by these models. CE-QUAL-R1 (U.S. Army Corps of Engineers, 1986), a one-dimensional reservoir water quality model is employed here to simulate thermal conditions in two PCLP lakes, Lake Lacawac and Lake Giles, from July through December, 1992. The U.S. Army Corps of Engineers Waterways Experiment Station in Vicksburg Mississippi developed CE-QUAL-R1 with the capacity to model 27 water quality and 11 sediment biological and chemical factors (U.S. Army Corps of Engineers, 1986; subsequent referrals to this reference will be designated as the "User's Manual").

CE-QUAL-R1 makes assumptions and simplifications in order to optimize computation time, and predict accurate concentration profiles, while requiring only necessary and readily obtainable input data. CE-QUAL-R1 contains a supporting program, CE-THERM-R1, which analyzes only temperature, total dissolved solids, and suspended solids components of a reservoir or lake. Accurate predictions of thermal profiles with CE-THERM-R1 provide validation of the lake model, before beginning extensive data collection for application to other water quality parameters.

1.2.2 Lake Thermal Profile Modeling

Modeling and predicting temperature profiles in lakes is a subset of water quality modeling. Two applications of thermal modeling are predicting temperature profiles at particular times, and estimating fall turnover and onset of spring stratification. This research and modeling first develops reliable temperature profiles for a Lake Lacawac and Lake Giles to validate the modeling technique, and model parameters selected. Matching predicted temperature profiles and PCLP field measured profiles for each lake during the model study gives an indication of the accuracy of the model. Daily predictions of temperature profiles in the proximity of fall turnover provide insight to the advent of isothermal

conditions in Lake Lacawac and Lake Giles. Comparisons of thermal structure, and model applicability for these lakes are discussed.

1.3 Literature Review

1.3.1 Surface Water Quality Models

Water quality models are constantly revised, updated, and amended to keep up with data requirements for modeling recently discovered or regulated contaminants in water systems, as well as state of the art computational techniques. Computer programs have been implemented to solve complicated mathematical equations defining interrelated lake ecosystem processes. Stefan et al. (1990) review many models which have been developed to predict reservoir and lake temperature and water quality, including CE-QUAL-R1 and CE-QUAL-W2, developed by the U.S. Army Corps of Engineers, MINLAKE and RESQUAL II, created at the University of Minnesota, and Upstate Freshwater Institute model, UFILS1. A discussion of attributes and shortcomings of the working computer water quality models follows.

- Zero Dimensional Models

Zero dimensional models consider a fully mixed reservoir or lake, with constant temperature and contaminant concentrations throughout the water body. The

solution to the conservation of mass, or the conservation of thermal energy equation, knowing initial conditions, inflow rates and loads, outflow rates, and decay rates, provides concentration or temperature in the lake during a given time step. The time step must be large enough (one year) to justify neglecting hydrodynamic processes and effects in the lake. These box models or input-output models are effective for predicting and preventing long term lake eutrophication. Lake networks and series have been successfully modeled using zero dimensional model theories, with outflow from the upstream lake serving as inflow to the next downstream lake (Stefan et al., 1990).

- One Dimensional Models

If vertical temperature and concentration profiles at daily or weekly time intervals are desired for a water body, a one dimensional water quality model should be used. The lake or reservoir is divided into layers, each having constant thermal, biological, and chemical properties, and the conservation of energy equation and concentration of mass equation is solved for each layer at each time step. Thermal energy and constituent concentrations can be transferred throughout layers by diffusion and entrainment, but to accommodate inflows and outflows, layer sizes must change. Initial conditions, boundary conditions, and assumptions required by one dimensional models are inflow rates, inflow temperatures, inflow concentrations, outflow rates and temperatures, wind effects on the lake surface, and water surface heat budget, while heat transfer through the lake bed is

neglected. CE-QUAL-R1, MINLAKE, and RESQUAL II are one dimensional, mixed layer models. Both CE-QUAL-R1 and MINLAKE have the ability to model thermal and many biological and chemical processes in lakes and reservoirs (Stefan et al., 1990). MINLAKE, which was designed to model Minnesota lakes (Riley and Stefan, 1987), is not supported, and documentation is no longer "in print". Explained in the User's Manual, CE-QUAL-R1 is intended to model reservoirs with specific outlet structure mechanisms, and has been successfully applied to DeGray Lake in Arkansas, and Merrill Creek Reservoir in New Jersey (Effler et al., 1986). CE-QUAL-R1, and its thermal profile counterpart, CE-THERM-R1, are available for public domain. UFILS1 is also a one dimensional mixed layer model, developed from CE-THERM-R1, which considers thermal processes in lakes only, and investigates heat absorption by sediment (Tsay et al., 1992).

- Two Dimensional Models

Two dimensional models predict temperature and water quality in reservoirs and lakes containing both vertical and horizontal gradients. Vertical gradients are caused by stratification, and horizontal gradients result from advection from significant inflow rates and outflow rates, and an elongated shaped water body. Two dimensional models also consider hydrodynamic effects on water quality parameters, and utilize similar boundary conditions as one dimensional models. Finite difference methods produce solutions to the conservation of mass equation

and conservation of energy equation, which include two dimensional advection and diffusion terms. CE-QUAL-W2 is a two dimensional, implicit model developed to simulate reservoirs and stratified estuaries. This model can predict concentrations of twenty water quality constituents, including point sources and distributed nonpoint contaminant sources, and model branched systems and looped systems (Stefan et al., 1990).

- Three Dimensional Models

Vertical multilayered grids represent lakes and reservoirs in three dimensional models. Very few three dimensional models exist because they are complicated, expensive, and cumbersome with time and space varying diffusion and turbulence coefficients. These models are used to simulate large water bodies with irregularities in shape and use, such as Lake Ontario, and the Chesapeake Bay (Stefan et al., 1990).

Selecting a water quality model for a particular lake or reservoir depends on the size of the water body, the desired model predictions (Stefan et al., 1990), and the ability to gather required input data. CE-THERM-R1 is chosen to model Lake Lacawac and Lake Giles because of its one dimensional solution, reasonable data requirements, availability, and comprehensive documentation.

1.3.2 Applications of One Dimensional Models

1.3.2.1 CE-THERM-R1 Application to Merrill Creek Reservoir

Merrill Creek Reservoir, sixty-eight meters deep, is located in Warren County, New Jersey, south east of Pennsylvania's Pocono region and serves as a flow augmentation device to the Delaware River during low flow periods. Prior to its construction, the reservoir was modeled by Effler et al. (1986) using CE-THERM-R1 to determine the extent of variations in thermal stratification due to natural meteorological changes. The model predicted accurate thermal profiles for nearby Round Valley Reservoir, providing model calibration and validation. Initial conditions and coefficients for Merrill Creek Reservoir were estimated using conditions in other local lakes and reservoirs as sources of information. A light attenuation coefficient of 0.4 m^{-1} was selected based on predicted phytoplankton pigment contributions to the water. Inflow and outflow were assumed equal, and equivalent to the flow rate in the existing stream channel. The model started with initial isothermal conditions on March 23, and ran at one day time intervals through November 20, for 13 years when the reservoir, if existing, would have been full. Meteorologic updates were obtained from the Allentown, Pennsylvania National Weather Service station, located 36 kilometers west of the proposed reservoir. The study focuses on epilimnion depth and temperature, maximum thermocline gradient, hypolimnion temperature, and water column stability

relationships with meteorological conditions. Sensitivity analyses performed on daily temperature and wind speed inputs found heat flux and turbulent kinetic energy in the reservoir most sensitive to variations in these meteorological inputs. Effler et al. (1986) conclude that deepening of the epilimnion, increasing density gradient, warming of the hypolimnion, and stability during summer stratification are affected by variable meteorological conditions, and, therefore, meteorological conditions must be accurately defined for the reservoir model. This is especially important because the thermal processes affected by weather conditions directly impact other water quality parameters.

1.3.2.2 Thermal Profile Modeling with UFILS1

Wood's Lake, an acidic Adirondack lake, twelve meters deep, was modeled using UFILS1, a one dimensional, mixed layer, lake temperature model by Rice et al., (1987). The model run began on May 13, 1985, and ran with daily time steps until October 31, 1985. One meter thick layers were specified, and inflow rates and outflow rates were negligible, rationalized by the lake's detention time of 210 days. Daily weather data was obtained from a weather station at Wood's Lake for sixty percent of the study period, and the remainder was supplemented with correlated data from National Weather Service stations in Old Forge (18 kilometers away), and Syracuse (130 kilometers away), New York. Light

penetration profiles and temperature profiles were sampled weekly, at the deepest part of the lake, during the simulation period. The model was calibrated, and resulting thermal profiles showed slight deviations in the epilimnion temperature from measured profiles, smoother predicted profiles than actual, and slightly warmer than actual hypolimnion temperatures in the fall months. The predicted profiles appear smooth and more stable because they are daily averages, compared to instantaneous actual thermal profiles, where temperature can vary depending on the time of day measurements are taken. The warm hypolimnion temperature may result from neglecting heat transfer to sediments, most of which sink to the lower hypolimnion region of the lake, and difficulties in representing the irregular lake bottom topography. A sensitivity analysis showed that the light attenuation coefficient is a sensitive parameter, as expected for this clear lake. Light meter data is more accurate than estimates from Secchi disk depth in determining the light attenuation coefficient, and essential for estimating this coefficient for clear lakes.

Using monthly averages of meteorologic data presented little change in UFILS1 output, and the correlated weather data from National Weather Service stations did not adversely affect the thermal profiles. The Wood's Lake UFILS1 model was considered an acceptable prototype for modeling Adirondack lakes in the future (Rice et al., 1987).

Subsequent modifications to include sediment heat flux were made to UFILS1. The original and revised models were applied to Wood's Lake, Cranberry Pond, also a shallow, clear Adirondack lake, and two deeper and larger upstate New York lakes; Dart's Lake and Little Simon Pond. Sediment heat flux effects were not noticeable in the two deeper lakes. Including sediment heat flux in the smaller lake models contributed to less heat in the hypolimnion and a better match between predicted and existing profiles (Tsay et al., 1992).

CHAPTER 2 PHYSICAL AND HYDROLOGICAL ATTRIBUTES OF LAKES

2.1 Lake Lacawac

2.1.1 Highlights

Lake Lacawac, a Natural Landmark dedicated by the United States Department of the Interior, is situated in Wayne County, Pennsylvania, northwest of the upstream tail of Lake Wallenpaupack, a man-made, recreational reservoir. Preserved as part of the Lacawac Sanctuary, Lake Lacawac and its pristine watershed are protected from development. The lake has no well-defined inflow, and outflow water discharges to a small stream. Water quality studies of light penetration, dissolved oxygen, pH, phosphorous and nitrogen concentrations, and biomass classify Lake Lacawac as mesotrophic (Moeller and Williamson, 1991a), as do its yellow to brown water color and silty bottom. Light attenuation coefficients describe light penetration into the lake water, and can be estimated with the Secchi disk depth, which is the depth to which a disk, divided into alternating black and white quarters, lowered into the water can no longer be seen. Site latitude, longitude, and elevation are found on the U.S.G.S. Lakeville, Pennsylvania Quadrangle. A bathymetric map of Lake Lacawac, dated October, 1992 (Figure 2.1) provides information to obtain a relationship between lake depth

measured from the bottom, and lake area at that depth. A similar regression analysis was performed for a lake width to depth relationship, where the width of the lake is taken from shore to shore approximately two hundred meters from the outflow. Coefficients, c_1, c_2, c_3, and c_4 were formulated for use in the following equations:

$$AREA = c_1 Z^{c_2} \tag{1}$$

$$WIDTH = c_3 Z^{c_4} \tag{2}$$

Physical features, details, and coefficients described in this section are in Table 2.1.

2.1.2 Meteorological Data and Lake Lacawac Weather Station

A weather station was installed on Lake Lacawac's dock in June of 1992 (see Figure 2.1 for the dock location). Incoming radiation, air temperature, surface water temperature, relative humidity, rainfall, wind speed, and wind direction are recorded at the Lacawac weather station (LWS) at ten minute intervals. The data is down-loaded from a storage unit to a portable personal computer on a monthly basis, and maintained on a data base at Lehigh University. Daily averages of this

data are useful for the lake modeling undertaken in this study, and for determining hydrologic conditions and rates.

Other weather data necessary to fully analyze local hydrology and run CE-THERM-R1 entail cloud cover, dew point temperature, barometric pressure, and evaporation. Cloud cover, or percentage of sky cover during daylight hours, and barometric pressure are obtained from data recorded and published by a National Weather Service station (NWS) at Wilkes-Barre Scranton Airport in Avoca, Pennsylvania (U.S. Department of Commerce, 1992), approximately twenty-two miles west of Lake Lacawac. Dew point temperature is the temperature at which water vapor in air condenses, forming precipitation, under given humidity conditions. The dew point is estimated empirically using the following equation.

$$T_a - T_d = (14.55+0.144T_a)(1-RH) + [(2.5+.007T_a)(1-RH)]^3 + (15.9+0.117T_a)(1-RH)^{14} \quad (3)$$

where T_a is Lacawac weather station dry bulb temperature (°C), T_d is dew point temperature (°C), and RH is Lacawac weather station relative humidity (decimal fraction). Equation (3) is valid for temperatures between -40 degrees Celsius and 50 degrees Celsius, and estimates dew point temperature within 0.3 degrees Celsius (Singh, 1992).

2.1.3 Lake Lacawac Watershed Hydrology

Inflow to Lake Lacawac is comprised of overland flow and ground water seepage. Monthly average inflows and outflows for July through December are estimated from rainfall and evaporation data. Precipitation is recorded at LWS, and monthly pan evaporation from Francis E. Walter Dam, July through October 1989 to 1991 (U.S. Department of Commerce, 1989-1991), is available to estimate lake evaporation and watershed evapotranspiration. A coefficient of 0.75 (Rahn, 1973) is used to convert pan evaporation to lake evaporation, and a coefficient of 0.70 (Ponce, 1989) is used to convert pan evaporation to evapotranspiration. Rainfall over the watershed area minus evapotranspiration from the land area within the watershed constitutes inflow to Lake Lacawac (Sitkowski, No Date). Everything flowing into the lake, with the exception of evaporation from the lake surface, eventually discharges through Lake Lacawac's outflow channel. In August of 1992, lake evaporation and evapotranspiration were greater than precipitation, consequently inflow and outflow of zero were assumed for the month of August. Monthly hydrologic data are listed in Table 2.2, and estimated inflow rates and outflow rates are summarized in Table 2.3.

2.2 Lake Giles

2.2.1 Highlights

Lake Giles, located approximately eight miles east of Lake Wallenpaupack, has a clear blue color, acidic conditions, general lack of plant life, and rocky bottom clearly classifying it as oligotrophic. Owned by Blooming Grove Hunting and Fishing Club, Lake Giles is used for recreational purposes, and has a few surrounding cabins and homes. Lake Giles' inflow comes from natural runoff, and outflow discharges through a small, unregulated stream. Site latitude, longitude, and elevation are found on the Rowland and Pecks Pond, Pennsylvania U.S.G.S. Quadrangles. Similar regression analyses were performed on Lake Giles topography, as was previously mentioned for Lake Lacawac bathymetry, to determine coefficients in Equations (1) and (2) for area and width ratings. The Lake Giles bathymetry plan, dated October, 1992 is shown in Figure 2.2. Physical features, details, and coefficients are listed in Table 2.1.

2.2.2 Lake Giles Watershed Hydrology

Lake Giles' inflow and outflow mechanisms are similar to those for Lake Lacawac. Overland flow, ground water seepage inflows, and stream discharges

for Lake Giles are estimated using LWS precipitation, Francis E. Walter Dam pan evaporation, and the same pan-to-lake evaporation coefficient and pan evaporation to evapotranspiration conversion, as defined for Lake Lacawac. Inflow rates and outflow rates are larger for Lake Giles than Lake Lacawac, as outlined in Table 2.3, because Lake Giles has a notably larger watershed area and lake surface area.

2.2.3 Lake Waynewood

Lake Waynewood is a eutrophic lake, similar in size to Lake Lacawac. Agriculture and recent development (farms and a golf course) in its 72,840,854 m^2 watershed contaminate inflows, causing elevated levels of productivity and frequent algal blooms (Schultz, 1990; Moeller and Williamson, 1991a). Lake Waynewood thermal predictions are not included in this study.

CHAPTER 3 MODELING WITH CE-QUAL-R1

3.1 General Description

3.1.1 Capabilities and Limitations

CE-QUAL-R1 was developed to numerically model lake and reservoir water quality parameters in the vertical dimension. Some of the water quality characteristics analyzed are temperature, suspended solids, total dissolved solids, dissolved oxygen, alkalinity, pH, coliforms, detritus, zooplankton, fish, three algal groups, and many other biological, chemical, and physical functions. The User's Manual describes how the program considers interactions between these parameters and meteorological conditions affecting radiation at the lake surface, inflow rates, inflow concentrations and temperatures, outflow rates, outflow temperatures, and outlet structures. Diffusion, entrainment, mixing, and heat transfer between layers are defined or computed for each time step (one day is recommended in the User's Manual). Properties of biological and chemical parameters needed for model input and execution include production rates, mortality rates, decay rates, and saturation concentrations. In addition to temperature and concentration profiles, CE-QUAL-R1 has the ability to model reservoir withdrawal ports schemes, watershed development impacts on water

quality, anoxic conditions, and potential algal bloom episodes. The model does not consider ice and snow conditions. Model predictions of temperature, biological, and chemical profiles are not valid during frozen lake surface conditions.

3.1.2 Program Structure

CE-QUAL-R1 produces thermal and concentration profiles for the deepest part of the modeled lake or reservoir. Latitudinal and longitudinal variations in the lake are not considered by this one-dimensional approach, and inflow concentrations are evenly dispersed in layers with similar temperature and density characteristics. The modeled lake is divided into horizontal, variable width, mixed layers. Each layer has constant thermal, biological, and chemical concentrations. There is no vertical flow between layers, but to compensate for large inflows or outflows, the layers can change thickness. Water density varies with temperature, total dissolved solids concentration, and suspended solids concentration. CE-QUAL-R1 uses density when determining the depths and thicknesses of inflows, thicknesses of outflows, and mixing coefficients. Essential simplifications are made in the evaluation of hundreds of possible reservoir ecosystem species and relationships in both aerobic and anaerobic environments. Zooplankton, fish, organics, sediments, and three algal groups are considered,

assuming that individual species do not compete, and the exact number of a species cannot be predicted. These assumptions and simplifications are necessary to effectively use conservation of mass to determine the concentrations of constituents in each layer.

3.1.3 Conservation of Mass/Energy

CE-QUAL-R1 determines layer concentrations of every considered component using the conservation of mass formulation, as found in the User's Manual. This equation for layer i is:

$$\frac{\partial}{\partial t}(V_i C_i) = (Q_{in} C_{in} - Q_{out} C_i) + \frac{\partial}{\partial z}(D_i A_i \frac{\partial C}{\partial z})\Delta z_i + SOURCES - SINKS \quad (4)$$

where V_i is layer volume, C_i is constituent or thermal energy concentration, Q_{in} and Q_{out} are the layer inflow and outflow respectively, C_{in} is inflowing concentration, D_i is the combined diffusion coefficient for wind mixing, penetrative convective mixing, and molecular diffusion, A_i is the layer surface area, Δz_i is layer thickness, t is time, and z is layer elevation from the lake bottom. The left hand side of Equation (4) represents the rate of change of mass in the layer. Inflow rates from streams, and outflow rates from outlet structures, ports,

and weirs transfer mass into or out of a layer as defined by the first term on the right hand side of Equation (4). The second term is a diffusion term, which incorporates wind mixing, penetrative convective mixing, and molecular diffusion effects. Numerical dispersion also contributes to mixing since mass which enters a new layer is immediately dispersed in the layer. Sources and sinks of mass or energy include internal, ecologically stimulated fluctuations of chemical or biological masses, and energy fluxes at the water surface.

Temperature is concentration of thermal energy and can be represented by the conservation of energy equation as follows.

$$\rho_i C_p \frac{\partial}{\partial t}(T_i V_i) = \frac{\partial}{\partial z}(\rho_i C_p D_i A_i \frac{\partial T}{\partial z})\Delta z_i + \frac{\partial}{\partial z}(\Phi_i A_i)\Delta z_i + \rho_i C_p (Q_{in} T_{in} - T_i Q_{out}) \quad (5)$$

where ρ_i is water density, C_p is water specific heat, T_i is water temperature or thermal energy in layer i, V_i is the volume of layer i, D_i is the diffusion coefficient, A_i is the area of layer i, Δz_i is the thickness of layer i, Φ_i is the net solar radiation flux at the water surface or between adjacent layers, Q_{in} and Q_{out} are layer inflow and outflow, and T_{in} is the inflowing water temperature. The accumulation of heat or thermal energy in a layer is defined by the left hand side of Equation (5). The three terms on the right hand side of Equation (5) represent wind, penetrative convection, and molecular diffusion mixing; absorption of solar

radiation by a layer; and advection and entrainment due to inflows and outflows to or from layer i. For the surface layer of the lake, Equation (5) must also include other heat fluxes that only occur at the surface: short wave radiation, incoming long wave radiation, back radiation, latent heat loss, and sensible heat flux. Details of the energy equation fluxes are in the following section.

3.2 Detailed Structure and Data Acquisition - CE-THERM-R1

3.2.1 CE-THERM-R1

Thermal profiles can be predicted independently using CE-THERM-R1. This subprogram utilizes thirty-one of CE-QUAL-R1's fifty-three subroutines. Applications of the model to Lake Lacawac and Lake Giles require the use of eighteen of these subroutines. The following sections highlight important aspects, formulae, and expressions used in CE-THERM-R1, as referenced in the User's Manual, to solve for temperature in Equation (5) for application to Lake Lacawac and Lake Giles.

3.2.2 Heat Budget

Daily averages of meteorological data are used in the computations of the heat budget at the water surface as defined in the User's Manual. Heat budget inputs are short wave solar radiation and long wave atmospheric radiation. Heat budget losses include back radiation and evaporative heat loss. Conductive heat transfer at the water surface can be a heat budget source or sink term, depending on air and water temperatures.

- Short Wave Solar Radiation

Before contributing to the heat budget at the earth's surface, short wave solar radiation is intercepted by cloud cover, attenuated by dust and water particles in the atmosphere, and reflected by the water surface (Orlob, 1981). Several solar radiation factors contribute to net short wave solar radiation, Q_{ns}, at the lake surface as illustrated in Equation (6).

$$Q_{ns} = F_r F_c F_s \left(\frac{Q_o}{R^2} \sin\alpha\right) \qquad (6)$$

where F_r is the reflection factor, F_c is the cloudiness factor, F_s is atmospheric transmission of solar radiation, and Q_o is solar radiation intensity at the edge of the atmosphere. R is the relative distance between the earth and the sun, and α is solar altitude. Atmospheric transmission is empirically based on coefficients

for mean atmospheric transmission, absorption and scattering effects, and dust attenuation, d, as well as albedo. Albedo is the percentage of short wave radiation reflected by the water surface, and is related to solar angle and surface characteristics (Henderson-Sellers, 1984). The reflection factor is also related to albedo. The cloudiness factor is a function of daily cloud cover. Solar radiation at the edge of the atmosphere is approximately 0.33 Kcal/m^2/second. Detailed equations for the terms in Equation (6) appear in Appendix A.

- Long Wave Atmospheric Radiation

Long wave radiation emitted by the atmosphere is influenced by cloud cover, air temperature and relative humidity. Three percent of long wave radiation is reflected by the water surface. Refer to Appendix A for the long wave radiation equation.

- Back Radiation

Long wave radiation is emitted back to the atmosphere by the lake. This back radiation is calculated based on the Stefan-Boltzmann law, where heat flux is dependent on the water surface temperature (raised to the fourth power), water emissivity, and the Stefan-Boltzmann constant. The back radiation equation is in Appendix A.

- Latent Heat of Evaporation

Evaporative heat loss occurs at the lake surface when the saturated vapor pressure at the surface water temperature is greater than the vapor pressure of the air, causing water to evaporate into the air. If the saturated vapor pressure at the surface water temperature is less than the air vapor pressure, then water vapor in the air condenses at the surface and enters the lake, but the model ignores heat or energy transfer in this case. Heat loss at the water surface due to evaporation is a function of water density, latent heat of vaporization, wind speed, wind coefficients a and b, and the saturated vapor pressure at the water surface temperature and vapor pressure at the air temperature difference. See Appendix A for the evaporation equation.

- Conduction or Sensible Heat

Heat transfer occurs across the lake surface due to the temperature difference between the air and water. This conductive heat transfer is also related to Bowen's Ratio, and barometric pressure. When the water surface temperature is greater than the air temperature, heat is conducted from the lake surface into the atmosphere. Heat is added to the lake surface when air temperature is greater than the water temperature. The equation for conductive heat transfer is in Appendix A.

To apply the radiation fluxes to solve the conservation of energy equation, long wave radiation, back radiation, evaporation, and conductive heat loss are combined as Q*.

$$Q^* = Q_{na} - Q_b - Q_e - Q_c \tag{7}$$

Because some of these radiation terms are temperature dependent, the net total heat flux at the surface layer for each time step is calculated using the surface layer temperature from the previous time step. Shortwave solar radiation is absorbed exponentially by the lake, and its heat flux is considered separately as described below.

3.2.3 Internal Absorption of Solar Radiation

Solar radiation is absorbed exponentially into the lake contributing to the thermal energy concentration in each layer. A fixed percentage, β, of net solar radiation, Q_{ns}, is absorbed by the top 0.6 meter of water, and the balance is exponentially absorbed by the remaining layers in the water column. The flux of solar radiation Φ(z) at depth z, in layers below the top 0.6 meter is

$$\phi(z) = (1-\beta)\, Q_{ns} e^{-\eta(z-0.6m)} \tag{8}$$

where β is the percent fraction of solar radiation absorbed in 0.6 meter surface layer, and η an extinction coefficient equal to $\eta_{\text{clear water}} + \eta_{\text{particulate self-shading}}$. The net

flux of solar radiation energy available to heat a layer equals the flux entering over the upper surface area of the layer minus the flux leaving the lower surface.

3.2.4 Inflows

CE-THERM-R1 determines the elevation and thickness of the inflow zone, and distributes the inflowing water and concentrations among appropriate lake layers. To determine into which layers inflow is placed, the density of the inflow water is compared with the density of each layer in the lake from the prior time step. The center of the inflow zone is in line with the lake layer with the closest density. If the inflow density is less than the density of any layer, then it enters the lake surface layer, and if the inflow is denser than all layers, it is added to the base lake layer. The thickness of the inflow zone is determined in two parts to account for possible entrance into stratified regions. The equation for one-half of the inflow zone is solved iteratively until convergence on an inflow zone thickness is reached, with the lake surface and bottom serving as limits (see Appendix B for details).

3.2.5 Outflows

CE-THERM-R1 has capabilities to simulate weir outlets, single and multiple port

outlets, and a combination of the two. Either continuous discharge or specified operating schedules for reservoirs are the possible outflow rate schemes. Modeling natural outflow from Lake Lacawac and Lake Giles is simulated by flow over a weir (overland or stream outflow), and flow through a small port (ground water seepage). Weir discharge is similar to surface water outflow to a stream, and a thin port placed near the middle depth of the lake allows outflow rates equivalent to estimated seepage rates. See Appendix B for details of determining which layers are affected by outflows.

3.2.6 Layers

Once inflows and outflows are computed for a time step, the water budget for each layer of the lake is determined to resize layer thicknesses and volumes, if necessary. A net positive inflow to a layer causes an increase in thickness, and a net outflow causes a decrease in layer thickness. When a layer is resized, geometry, thermal energy, and other concentrations are recalculated. If a layer becomes thicker than a maximum specified in the model, then it is divided in half, and if it loses enough water volume to become thinner than the minimum, it is combined with the upper adjacent layer. At all times, the sum of the layer thicknesses is the lake depth.

3.2.7 Mixing

The depth of the lake's well mixed epilimnion is computed by CE-THERM-R1 using an integral energy method, which compares wind generated turbulent kinetic energy with the work required to move a layer of water from directly below the epilimnion to the epilimnion center. Wind work and penetrative convective mixing contribute to turbulent kinetic energy, TKE. Wind shear, TKE_w, is calculated by

$$TKE_w = \int_{A_s} C W_* \tau \Delta t \, dA \qquad (9)$$

where A_s is lake water surface area, C is a sheltering coefficient equal to the portion of lake surface exposed to the full effects of wind, W_* is water shear velocity, τ is the shear stress at the water surface, and Δt is the time step. Equations pertaining to calculation of these variables are in Appendix B.

When the lake is cooling, TKE_c is generated by penetrative convective energy. During the fall, as the air and water temperatures are cooling, the epilimnion temperature decreases and density increases, allowing mixing with metalimnion layers and deepening of the upper mixed layer. TKE_c is especially evident near the time of fall turnover. The energy created by penetrative convective mixing is correlated with the net heat flux at the water surface as follows.

$$TKE_c = -C_c Q_n A_s Z_{mix} g \alpha \frac{\Delta t}{c_p} \quad (10)$$

where C_c is the penetrative convection coefficient, assumed to be 0.3, as recommended in the User's Manual, Q_n is the net heat flux at water surface (>0 values only, when the water surface is losing heat), Z_{mix} is the epilimnion depth, α is the water thermal expansion coefficient per °C, and c_p is water specific heat. Dissipation is considered when combining TKE_w and TKE_c into total TKE using a Richardson number parameter, which is described in Appendix B.

Finally, entrainment, or work, W_L, required to lift a layer of water from below the epilimnion to the center of mass of the epilimnion is calculated with Equation (11).

$$W_L = \Delta\rho \, \Delta V \, g \, (Z_{mix} - Z_g) \quad (11)$$

where $\Delta\rho$ is the density difference between the layer beneath the epilimnion and the epilimnion water, ΔV is the layer volume to be moved to the epilimnion, Z_{mix} is the epilimnion depth, and Z_g is the depth to the epilimnion center of mass. Layers below the epilimnion are entrained or mixed into the epilimnion, deepening the upper mixed region, as long as TKE is greater than W_L, or until the lake destratifies, becoming isothermal. When a layer is entrained, its thermal concentration is mixed into the epilimnion region, and epilimnion depth and center of mass are revised.

3.2.8 Diffusion Coefficients

Vertical mixing in the water column is caused by many processes, including inflowing water, outflowing water, wind waves, wind and internal currents, turbulence, and convection. A single eddy diffusion coefficient, DC(I), groups the resulting impacts on diffusive mixing between adjacent layers. The eddy diffusion coefficient is needed to compute diffusive flux across a layer surface area, which is used in the conservation of energy equation (Equation (5)) to represent the transport of thermal energy between layers when a temperature gradient is present. Equations used to calculate the diffusion coefficient are presented in Appendix B.

3.2.9 Temperature Profile Calculation

CE-THERM-R1 solves the conservation of thermal energy equation for the thermal concentration in each lake layer during each time step. The terms of the conservation of energy equation have been defined in the previous sections. A forward-step finite difference scheme involving a modified gaussian elimination technique is implemented to determine the temperature profiles. The starting date temperature profiles, total dissolved solids profiles, and suspended solids profiles, and the desired time step must be specified in the data file, serving as

a starting point for the model computations. The stability of the water column is checked after each temperature profile is computed, and before the profile for the subsequent time step is determined. Each layer density, from lake bottom to top, is analyzed to ensure that there is no layer with a denser layer above it. If an instability is found, the two layer densities and thermal properties are volume-weighted averaged. This check is repeated to confirm complete water column thermal stability. A similar solution technique for the conservation of mass equation is implemented simultaneously to determine suspended solids and total dissolved solids concentration profiles at each time step.

3.3 Calibration

3.3.1 Model Initialization

Daily averages of meteorologic data were collected from July 1, 1992 through December 31, 1992. Initial temperature, total dissolved solids, and suspended solids profiles on July 16, 1992 for Lake Lacawac, and July 14, 1992 for Lake Giles serve as the starting point for the model solution procedure. Total dissolved solids profiles were estimated from 1989 conductance measurements (Moeller and Williamson, 1991a and 1991b), and suspended solids were approximated from compiled chlorophyll-a and dry mass data (Hargreaves, Personal

Communication). The inflow temperatures, corresponding to flow rates determined from hydrologic evaluations described in Sections 2.1 and 2.2 , were estimated by averaging dew point and ground water temperatures. Monthly outflow rates, also estimated with hydrological data, are subjectively divided into ninety percent weir flow, simulating stream channel discharge, and ten percent port flow, representing ground water seepage flow. These outflow rates were continuous, and updated monthly in the model formulation. Initially, Lake Lacawac is divided into thirteen one-meter thick layers, and Lake Giles is divided into twenty-four one-meter thick layers. Maximum layer thickness is two meters, and minimum layer thickness is one-half meter for both lakes. Since inflows and outflows to both lakes are relatively small, layer resizing is not necessary for Lake Lacawac and Lake Giles models. The model computation interval is set at twenty-four hours. Several remaining parameters must be determined or adjusted in the model calibration, as explained in the following sections.

3.3.2 Calibration Procedure

To calibrate the model, the following steps are taken:

1. Water Budget

Wind coefficients a and b, and dust attenuation coefficient, d, are adjusted to match model evaporation with actual evaporation estimates.

2. Thermal Structure

   Light attenuation coefficients are fine-tuned to match starting model temperature profiles and initial measured profiles.

3. Thermocline Slope

   Wind and advection diffusion calibration coefficients are modified to provide a model thermocline slope and epilimnion depth similar to the measured data.

This calibration procedure is elaborated in sections below.

3.3.2.1 Water Budget and Evaporation

The water budget for a lake system has stream inflow, overland inflow, ground water inflow, and precipitation inflow, while evaporation from the lake surface, evapotranspiration from the watershed, seepage, and stream or outlet structure discharges comprise outflow. Two parameters to verify the water budget are lake water surface elevation and evaporation. The PCLP sampling team does not record the exact lake levels, therefore the model water budget was calibrated for

evaporation. Lake evaporation was estimated from monthly pan evaporation data recorded at Francis E. Walter Dam, from July through October, 1989 to 1991. July and August data were used to calibrate the model since initialization data is for mid-July for each lake model. Predictions for the following months provide model verification. Initially, the diffusion calibration coefficients were set to zero, defaulting to an eddy diffusion coefficient of fifteen times molecular diffusion. Wind function variables a and b, and dust attenuation coefficient, d, were adjusted to obtain an appropriate evaporation rate, while maintaining lake water levels above the weir crest (at the approximate outflow channel elevation) for the study period.

The following water budget calibration was performed for Lake Lacawac.

- Wind Function Coefficients

Coefficients a and b were adjusted simultaneously, using recommended values from previous lake and reservoir studies cited in the User's Manual, to closely match model and estimated evaporation as well as epilimnion temperatures. To accomplish this for Lake Lacawac, values of 2.5×10^{-9} m/mb-sec, and 0.5×10^{-9} 1/mb are selected for a and b, respectively.

- Dust Attenuation Coefficient

To lower the lake surface heat, a dust attenuation coefficient of 0.44

(dimensionless) is used. Although this is above the User's Manual recommended value of 0.06, which was adopted from 1948 field studies (Klein, 1948), more recent studies suggest an increase in atmospheric turbidity during a 1967 to 1972 EPA study period, reporting highest values greater than 0.3 in the eastern United States mountain regions, during the summer months (Robinson and Valente, 1982). Presuming the trend continued due to air pollution and volcanic dust released into the atmosphere, higher dust attenuation conceivably could have resulted in 1992 in the Pocono Mountain region.

In the model for Lake Lacawac, a total of 0.04 meters of evaporation was calculated between July 16 and July 30, 1992, and 0.08 meters evaporation was predicted during August. Estimations of monthly evaporation are in Chapter Two. Assuming similar wind and atmospheric turbidity conditions at Lake Giles, the same wind coefficients and turbidity values were applied to that lake model. Simulated evaporation for Lake Giles was 0.04 meters between July 18 and July 28, and 0.08 meters in August. Estimated lake evaporation from pan evaporation is the same for Lake Giles and Lake Lacawac, 0.055 meters during the second half of July, and 0.10 meters during the month of August as described in Chapter Two.

3.3.2.2 Thermal Structure and Thermocline Slope

Epilimnion temperature, hypolimnion temperature, thermocline gradient, and epilimnion depth are thermal properties for which the model should be calibrated. The thermal structure greatly depends on solar radiation and the lake's heat budget. Light extinction coefficients, which control the amount of solar radiation absorbed by various layer in the lake, were fine-tuned to match epilimnion and hypolimnion temperatures. The User's Manual provides relationships between Secchi disk depth and the extinction coefficient for clear water, as well as the percent of solar radiation absorbed in the 0.6 meter surface layer, but there are only vague guidelines for the selection of the self-shading extinction coefficient. Since only one value for each extinction coefficient is used for the entire model period, slight adjustments of each light parameter may be necessary for calibration.

For Lake Lacawac, the following thermal structure calibration was performed.

- Light Extinction Coefficients

The clear water extinction coefficient, $\eta_{clear\ water}$, was set to 0.49 m^{-1}, slightly higher than the value of 0.3 m^{-1} calculated using the User's Manual recommendations for estimates using Secchi disk depth. With this number, the percent of light absorbed in the 0.6 meter surface layer, β, was estimated to be 0.4, and

adjustment of this coefficient was not necessary to improve the calibration. A self-shading coefficient, $\eta_{\text{particulate self-shading}}$, of 0.4 $m^{-1} \cdot$ mg/l was selected to adequately match the modeled and actual hypolimnion temperatures.

- Diffusion Calibration Coefficients

Diffusion coefficient fine-tuning is required to properly predict epilimnion depth and thermocline slope once the water budget parameters and light attenuation coefficients are determined. The diffusion coefficient equation is defined in Appendix B. To calibrate the thermocline structure, the two diffusion calibration coefficients were independently, incrementally increased (within recommended ranges as noted in the User's Manual) until an acceptable thermocline was produced with the model. Final values of 2.0×10^{-5} (dimensionless) for the wind diffusion calibration coefficient, and 2.0×10^{-6} (dimensionless) for the advective diffusion calibration coefficient were determined to predict accurate thermoclines. Other diffusive mixing coefficients, sheltering coefficient, and penetrative convection coefficient, were not changed in the calibration.

Calibration of the Lake Giles thermal structure proceeded similarly. Again, calibration was performed for July and August profiles, and September through December predictions verify the model. Model guidelines do not extend to include coefficients for typical oligotrophic lake light regimes. Therefore, a clear water extinction coefficient, $\eta_{\text{clear water}}$, of 0.20 m^{-1} was extrapolated. Percent light

absorbed in the top 0.6 meters, β, was set to 0.17, and 0.15 was a suitable value for the self-shading coefficient, $\eta_{\text{particulate self-shading}}$. These values predict similar July and August temperature profiles, in comparison with measured temperature data. Dimensionless wind diffusion and advected diffusion calibration coefficients of 2.0×10^{-5}, and 6.0×10^{-6}, respectively produce satisfactory thermoclines in Lake Giles for July and August.

CHAPTER 4 RESULTS

4.1 Temperature Profiles

4.1.1 Lake Lacawac

Comparisons of model predicted and measured temperature profiles for the entire study period, as displayed in Figures 4.1 and 4.2, show slower cooling trends in the model epilimnion and hypolimnion temperatures than measured, and generally smoother and more stable predicted profiles than actual. Since the model is calibrated for July 30, and August 26, 1992, as described in Chapter Three, the predicted profiles should closely match the actual profiles on those dates. The July 30 predicted and measured profiles are nearly identical as seen in Figure 4.3(a). Although the surface temperatures match for August 26, the rest of the predicted profile is considerably warmer than the existing profile. Apparent in Figure 4.3(b), the model prediction is a daily average, with a stable, well mixed epilimnion, in contrast to the relatively unstable and unmixed measured epilimnion, representative of conditions at the time of sampling. The thermocline slopes are similar, and predicted and measured temperatures are within one degree Celsius at the lake bottom. Figure 4.3(c) shows that a moderately warmer predicted profile is evident September 24 as well. The

epilimnion temperature deviates 1.3 degrees Celsius, and the predicted hypolimnion temperature is 1.1 degree Celsius higher than the actual on this day. The model predicted epilimnion depth is one meter deeper than the measured epilimnion, and the modeled and measured thermocline slopes are parallel. By October 15, deepening of the epilimnion, and the onset of thermal destratification are evident, as illustrated in Figure 4.3(d). The predicted epilimnion, 14.2 degrees Celsius, is eight meters deep, and the measured, an average 13 degrees Celsius, is seven meters deep. The predicted hypolimnion temperature is approximately 1.6 degrees Celsius warmer than measured. Isothermal conditions are apparent November 20, 1992. The model and measured temperature profiles, in Figure 4.3(e), are only 0.5 degrees Celsius different, with the modeled temperature less than the actual lake temperature. The model prediction for Lake Lacawac on December 30, 1992, pictured in Figure 4.3(f), is not valid due to an ice layer which formed on the lake in mid-December (Hargreaves, Personal Communication). The measured profile temperature ranges between two and three degrees Celsius, as the ice had broken up by this time (before freezing completely in January, 1993). CE-THERM-R1 does not have the capability to model and predict lake temperatures during frozen conditions.

4.1.2 Lake Giles

In general, the Lake Giles model accurately predicts epilimnion thermal conditions throughout the study as seen in Figures 4.4 and 4.5. The model predicts that the hypolimnion cools at a slightly slower rate than is actually occurring, while the predicted epilimnion temperatures are usually somewhat warmer than measured. Lake Giles was calibrated with temperature profiles measured on July 28, and August 25, 1992. The model profile is 1.1 degrees Celsius warmer than measured on the first calibration date. The actual epilimnion depth is one meter deeper than predicted on July 28, and the thermocline and hypolimnion are nearly identical, as presented in Figure 4.6(a). The August 25 measured profile, Figure 4.6(b), shows an unstable epilimnion layer, similar to the measured August 25 Lake Lacawac profile. On this date the model predicted a stable, well mixed epilimnion for Lake Giles as well. The model predicted temperatures average 1.4 degrees Celsius warmer than the measured throughout the epilimnion. Again on September 23, the epilimnion temperature predicted by CE-QUAL-R1 is warmer than the measured epilimnion. Figure 4.6(c) shows that modeled and predicted epilimnion depths agree, and the metalimnion and hypolimnion are very similar in slope and temperature. The variation in epilimnion temperature continued to grow as seen in Figure 4.6(d) for October 14, to a 2.1 degree Celsius overprediction. The predicted hypolimnion temperature was 1.9 degrees Celsius warmer than actual conditions. The

modeled and measured profiles show isothermal conditions in Lake Giles on November 19, the last sampling date in 1992, as illustrated in Figure 4.6(e). The modeled profile sustained a constant 9.2 degree Celsius temperature, 1.7 degrees Celsius higher than measured.

4.2 Fall Turnover Date

4.2.1 Lake Lacawac

To predict the date of fall turnover when Lake Lacawac became isothermal, profiles at forty-eight hour intervals, between October 15 and November 20, were generated and analyzed, some of which are presented in Figure 4.7. A noticeable cooling and deepening of the epilimnion was occurring in Lake Lacawac, while the hypolimnion temperature remained constant. On October 25, Lake Lacawac isothermal conditions were evident. A complete mixing of the water column occurred, resulting in warming of the lower layers and cooling of the surface layers. The lake cooled, remaining isothermal, after October 25. Weather data for October 25, 1992 reported extremely high winds, averaging 15.5 kilometers per hour, more than three times higher than the monthly average of 5.1 kilometers per hour, showing that the turnover was most likely caused by wind mixing.

4.2.2 Lake Giles

Temperature profiles generated at forty-eight hour intervals were examined for Lake Giles between mid-October and mid-November to determine destratification. Figure 4.8 shows that the epilimnion was slowly cooling and deepening until November 10, when the epilimnion temperature had cooled to within 0.1 degree Celsius of the hypolimnion temperature. At this time Lake Giles was isothermal, and began cooling uniformly. November 10 was a fairly windy day, with winds averaging 7.9 kilometers per hour, and air temperature had been cooling for several days prior, possibly causing the lake to attain homogeneous thermal conditions.

4.3 Evaporation

Approximately 0.265 meters of water evaporated from lakes in the Pocono region between mid-July and October 31, 1992, as estimated by conversion of available Francis E. Walter Dam pan evaporation data to lake evaporation. CE-THERM-R1 predicted a total of 0.27 meters of evaporation from Lake Lacawac during this period, and of 0.31 meters from Lake Giles. The oligotrophic characteristics of

Lake Giles, such as water clarity, ability to absorb heat in the surface layer, and retention of heat in the lower layers contribute to its slightly higher evaporation.

4.4 Sensitivity Analysis

4.4.1 Framework

Coefficients, parameters, and driving forces controlling the lake system model were calculated and estimated with various degrees of certainty. In the sensitivity analysis the least reliable factors were varied in additional Lake Lacawac model runs. Parameters are estimated to have good, fair or poor reliability. Parameters with good reliability, such as lake bathymetry and site location are not considered in this sensitivity analysis. If some data was available to aid in selection of a parameter value, then it is considered fairly reliable, such as light extinction coefficients which can be estimated with Secchi disk depth. If no supporting data is available for a parameter, such as diffusion coefficients, its reliability is considered as poor. Parameters with fair and poor reliability are listed in Table 4.1.

The resulting water budget and thermal profiles are compared to the original calibrated simulation to evaluate model sensitivity to each of these factors.

Parameters are categorized into high, medium and low sensitivity classifications, as described in Table 4.1. A small (one to ten percent) change in a parameter with high sensitivity results in a noticeable change in the predicted profiles (greater than 0.5 degree Celsius) or total evaporation (of at least 0.1 meter). Changes in a low sensitivity parameter have little (less than 0.1 degree Celsius) or no effect on the model results. These parameters are discussed below.

4.4.2 Inflows and Outflows

- Inflow and outflow rates

Inflow and outflow rates influence the lake modeling process by adding and removing advected thermal energy as shown in Equation (5). Estimated monthly averages from local rainfall data, and regional evaporation and evapotranspiration data are generalizations of continually fluctuating conditions. Daily and seasonal meteorological conditions affect overland flow rates, infiltration rates, and evaporation and evapotranspiration rates. The estimated monthly inflow and outflow rates for Lake Lacawac are small, and the model is insensitive to variations in these rates. In fact, simulating inflow and outflow of zero for the study period results in no change in evaporation, and thermocline temperature differences of 0.1 to 0.2 degree Celsius.

- Inflow Temperature

Negligible temperature changes result in the metalimnion and hypolimnion from setting inflow temperatures equal to dew point temperature, and using temperatures closer to the constant ground water temperature, 12.8 degrees Celsius. The slight thermal variations in the middle of the lake can be attributed to changes at typical inflow and outflow zone locations.

- Outflow Arrangement

The outflow structure arrangement, consisting of a weir to simulate stream outflow, and a port to simulate seepage, also are insensitive, due to the small lake outflow rates. Modifying the weir length and discharge coefficient do not affect the thermal profiles, and changes in the port elevation cause an occasional tenth of a degree Celsius change near its elevation. Also, changes in the partitioning of weir and seepage rates, from ten percent seepage and ninety percent stream outflow, to twenty-five percent seepage and seventy-five percent stream outflow, do not alter the resulting thermal profiles.

4.4.3 Wind Coefficients and Dust Attenuation Coefficient

Wind coefficients a and b, and the dust attenuation coefficient, d, have poor reliability, because evaporation is not measured at Lake Lacawac, and recent

measurements of local dust attenuation are not available (see Table 4.1). Variations in wind coefficients directly impact evaporation, sensible heat and epilimnion or surface temperature, and sensitivity analyses reveal that the model is sensitive to these parameter values. A ten percent increase in a and b causes a six percent increase in evaporation, and an approximately one degree Celsius decrease in epilimnion temperature. The model run cannot be completed with a fifty percent increase in the wind coefficients because the lake water evaporates, and the water surface falls to a level below the weir elevation. A ten percent decrease in a and b causes a six percent decrease in evaporation and a slightly warmer (less than one degree Celsius) epilimnion.

The dust attenuation coefficient also controls evaporation and surface temperature. With the User's Manual recommended value of 0.06 the epilimnion temperature increases two degrees Celsius before aborting the run when the lake level falls below the weir elevation. If the weir elevation is lowered to twelve meters, the resulting evaporation is 0.41 meters, and the thermal profiles are 0.5 to two degrees warmer in each layer. The epilimnion depth is not affected by wind coefficients and dust attenuation variations.

4.4.4 Diffusion Coefficients

Wind and penetrative advection diffusion coefficients were calibrated to match metalimnion temperatures. Adjustments of these coefficients only slightly affect the thermocline slope, as well as the epilimnion temperature. Slight changes in evaporation also result due to this heating or cooling of the surface water. Modifications of the sheltering coefficient, which contributes to diffusive wind mixing, and the penetrative convection coefficient, which influences penetrative mixing, provide negligible temperature profile differences.

4.4.5 Light Coefficients

The three light attenuation coefficients, extinction due to clear water, $\eta_{\text{clear water}}$, self-shading coefficient, $\eta_{\text{particulate self-shading}}$, and percent light absorbed in the top 0.6 meters, β, gauge absorption of solar radiation by the lake. Since the heat budget is directly related to absorption of solar radiation, lowering the clear water extinction coefficient or the self-shading extinction coefficient allows more heat into the lower layers of the lake, and, therefore, increases temperatures. The values determined from Secchi disk depth and in the model calibration are within an acceptable range, and provide accurate thermal profiles.

- Clear Water Extinction Coefficient

A ten percent decrease in the clear water extinction coefficient, $\eta_{clear\ water}$, causes less than one degree Celsius increase in hypolimnion temperature, while a fifty percent decrease causes a five to six degree Celsius increase. Increasing this parameter ten percent produces 0.5 to one degree Celsius cooler surface temperatures and 0.1 to 0.5 degree Celsius warmer hypolimnion temperatures, matching existing profiles closely, but this value of 0.54 is artificially high for Lake Lacawac mesotrophic conditions and Secchi disk depth. Evaporation from the lake determined using the model is not affected by changes in this coefficient.

- Self-Shading Extinction Coefficient

The extinction due to particulate matter coefficient, $\eta_{particulate\ self\text{-}shading}$, affects thermocline and hypolimnion temperatures primarily, although the model has a medium sensitivity level to this parameter. Increasing this self-shading coefficient by fifty percent decreases lower layer temperatures less than one degree Celsius, while a fifty percent reduction warms the lower layers slightly. Surface temperature and evaporation are negligibly affected by self-shading extinction coefficient changes.

- Percent Absorbed in Top 0.6 Meters

The fraction of light absorbed by the 0.6 meter surface layer, β, influences the difference between epilimnion and metalimnion temperatures. For instance, a fifty percent increase in surface absorption of solar radiation causes a less steep thermocline, and a generally cooler (by a few tenths of a degree Celsius) thermal profile, whereas a fifty percent decrease results in an approximately one meter deeper epilimnion and one meter shallower hypolimnion, as well as a slightly warmer metalimnion. Again, the model evaporation is not sensitive to variations in this fraction.

4.4.6 Settling Velocity

A particulate matter settling velocity of one meter per day selected for the model is based on User's Manual recommendations, but there is no data available to confirm this. Summer stratified temperature profiles are sensitive to changes in the settling velocity. A fifty percent slower settling velocity produces a one degree Celsius cooler metalimnion, and 0.2 to 0.3 degree Celsius cooler temperatures in the hypolimnion, while a ten percent decrease results in a slightly cooler metalimnion region. Increasing the settling velocity ten percent has the opposite effect, increasing metalimnion and hypolimnion temperatures slightly.

4.4.7 Total Dissolved Solids and Suspended Solids

The initial total dissolved solids (TDS) profile used in the model are estimated from a 1989 chemical analysis of Lake Lacawac (Moeller and Williamson, 1991a), and inflow concentrations of TDS are estimated from monthly averages in the lake during 1989. Suspended solids (SS) profiles are determined from estimates of dry mass from chlorophyll-a from sampling during the study period (Hargreaves, Personal Communication), and inflow concentrations are assumed to be zero. TDS and SS concentrations add very slightly to water density, and, therefore, modifications of these concentrations do not affect Lake Lacawac model predicted thermal profiles.

CHAPTER 5 DISCUSSION AND CONCLUSIONS

5.1 Accuracies of Model Predictions

5.1.1 Lake Lacawac

Once all required data is estimated and obtained through model calibration, temperature profiles are generated using CE-THERM-R1 and output for six dates in 1992, to compare with profiles measured on the same dates. The predicted profiles closely resemble the actual profiles, particularly in thermal structure and thermocline slope. The most evident deviations are in epilimnion temperature, with the model predicting slightly higher than actual temperatures in four of the six cases. Possible causes for the high epilimnion temperature predictions could be low winds measured by the Lacawac weather station, located at the edge of the lake, and not necessarily indicative of wind speeds and effects at the center of the lake. Complications in estimating the atmospheric dust attenuation coefficient for the Pocono Mountain region, and uncertainties of light attenuation coefficients in water may also contribute to the difficult task of balancing the water budget, while simultaneously calibrating the temperature profiles. The model prediction for December 30 is obviously invalid due to prior lake freezing, and the model's inability to simulate and forecast thermal properties within the

lake during periods with freezing conditions.

Fall turnover is predicted to occur on October 25, 1992 for Lake Lacawac. Although actual temperature profiles are not available on or near that date, windy and cold weather conditions on October 25 exhibit evidence that a complete, wind induced mixing in the lake could have happened.

Modeled and actual estimations of evaporation for Lake Lacawac are very close, especially for July and August, since the wind coefficients were calibrated using evaporation for these months. Modeled and estimated evaporation for September and October concur, verifying the choice of wind function coefficients a and b. The estimation of monthly lake evaporation from pan evaporation data at Francis E. Walter Dam, using a pan to lake coefficient of 0.75 (Rahn, 1973), is a generalization, and the verification of the model should not be completely based on this. However, the agreement between predicted and actual thermal profiles for Lake Lacawac provides supplementary model validation.

5.1.2 Lake Giles

The five temperature profiles predicted using CE-THERM-R1 for Lake Giles closely resemble their actual measured counterparts. Greater discrepancies in

epilimnion temperature in Lake Giles predictions are noticeable, in comparison to the Lake Lacawac model output.

Fall turnover did not occur as dramatically in Lake Giles as it did in Lake Lacawac in 1992. Lake Giles is twenty-four meters deep, eleven meters deeper than Lake Lacawac. The possibility of wind generated energy penetrating and completely mixing this deeper lake is less than Lacawac, and the lake becomes isothermal when its epilimnion cools to the hypolimnion temperature. Warmer thermal conditions in Lake Giles, due to its oligotrophic status, allow more heat to be retained in the lake for a longer period of time, and therefore the predicted fall turnover occurs sixteen days later than Lake Lacawac's turnover.

Evaporation predictions for Lake Giles result in 0.31 meters, versus 0.265 meters as estimated from pan evaporation data for the four month period when actual data was available. Using Lake Lacawac wind speed, recorded at the dock is an underestimate of Lake Lacawac wind speed at the lake center, and may further underestimate the wind speed at the center of much larger Lake Giles. Also applying air temperature, dew point temperature weather data recorded at Lake Lacawac directly to the Lake Giles model, which has different surface thermal properties, may help explain these discrepancies.

5.2 Applicability for Predicting Water Quality Parameters

Guidelines for the impacts that thermal conditions in lakes have on specific water quality parameters of interest must be outlined before attempting to use this model for further predictions in Lake Lacawac and Lake Giles via CE-QUAL-R1. Desired water quality constituent concentrations and degrees of accuracy will determine acceptable temperature inconsistencies between model predictions and actual conditions. From an engineering standpoint, and considering the number of assumptions made in the process of formulating data for the input for both Lake Lacawac and Lake Giles, the profiles predicted by CE-THERM-R1 appear reasonable. Different assumptions and simplifications, as well as more exhaustive data collection and site specific hydrologic analyses may provide improved results. Areas where refinement of data collection, analysis, or processing may be useful and efficient for generating favorable thermal profiles are explained in greater detail in the next section.

5.3 Possible Future Modifications

This research begins to examine the complex structure of Lake Lacawac and Lake Giles ecosystems to model thermal properties and gain understanding of lake processes. Before CE-THERM-R1 can be verified as a useful and accurate model,

the following modifications should be made.

- Move the Lake Lacawac weather station to the middle of the lake.
- Determine a correlation between Lake Lacawac and Lake Giles weather conditions.
- Accumulate one full year of weather data, and run the model between spring thaw and winter freezing.
- Obtain more reliable estimates of evaporation from each lake and evapotranspiration from each watershed.
- Examine the relationship between the light extinction coefficients, and relate light data sampled at each lake to these parameters.
- Regularly sample total dissolved solids concentration profiles and suspended solids concentration profiles to provide additional calibration standards.
- Correlate solar radiation computed by CE- THERM-R1, and available in the output file, and that recorded at the Lake Lacawac weather station.
- Apply the model to Lake Waynewood to compare thermal processes along the full range of eutrophication.

Implementation of these recommendations may enable CE-THERM-R1 to predict more reliable thermal profiles in Lake Lacawac and Lake Giles, thus providing a

suitable basis for successful modeling of other lake water quality components with CE-QUAL-R1.

5.4 Final Conclusions

Lake Lacawac and Lake Giles have similar thermal structures. Both are well stratified in the summer, and Lake Lacawac destratifies at a quicker rate and becomes isothermal sixteen days earlier in the fall than Lake Giles. The lakes have similar surface temperatures, yet because Lake Giles is clearer and almost twice as deep as Lake Lacawac, the temperature of its lower layers remains warmer in the fall months, as measured and predicted, due to its greater ability to retain heat. The similarities in predicted monthly epilimnion temperatures may be a result of using the same meteorological data in both lake models, but differences in lake geometry, light attenuation coefficients, and diffusion coefficients enable the lakes to behave individually in their lower layers. The predicted profiles are smooth and stable, resulting from the model use of daily averages of inflows, outflows, and meteorological conditions when computing the temperature in each layer, in contrast to measured profiles which sample lake conditions at a particular time of day.

Sensitivity analyses reveal that inflow rates, outflow rates, and outlet structure are insignificant in both the Lake Lacawac and Lake Giles models. Wind function coefficients and diffusion calibration coefficients must be adequately determined in the model calibration. Further sampling and studies of total dissolved solids, suspended solids, and settling velocity would enable more accurate model calibration. Current dust attenuation coefficient measurements are necessary to correctly evaluate the heat budget at the water surface. Finally, light attenuation coefficients and sediment heat flux contribute greatly to thermal lake processes, and as recommended by Rice et al. (1987) should be determined as accurately as possible. Based on the assumptions made in the collection and estimation of input data and parameters for Lake Lacawac and Lake Giles models, the temperature profiles predicted using CE-THERM-R1 are satisfactory.

TABLES

Table 2.1 Lake Lacawac and Lake Giles Physical Features

FEATURE	LAKE LACAWAC	LAKE GILES
SURFACE AREA	214,000 m^2	481,000 m^2
DRAINAGE AREA	700,074 m^2	1,826,209 m^2
D.A./S.A. RATIO	3.3	3.8
MAXIMUM DEPTH	13 m	24 m
VOLUME	1,120,000 m^3	4,860,000 m^3
LAKE LENGTH	580 meters	1040 meters
DETENTION TIME	3.3 years	5.6 years
AREA COEFFS, c_1, c_2	4131.64, 1.514	21476.9, 0.9079
WIDTH COEFFS, c_3, c_4	81.308, 0.176	263.148, .2962
LATITUDE	41.38	41.38
LONGITUDE	75.29	75.09
SECCHI DEPTH	5 m	16 m

(Schultz, 1990; Moeller and Williamson, 1991a; Moeller and Williamson, 1991b)

Table 2.2 Pocono Region Hydrology

MONTH 1992	RAINFALL meters	PAN EVAP. meters	LAKE EVAP. meters	EVAP-TRNP meters
JULY	0.109	0.149	0.111	0.104
AUGUST	0.062	0.128	0.096	0.090
SEPTEMBER	0.084	0.086	0.064	0.060
OCTOBER	0.048	0.063	0.047	0.044
NOVEMBER	0.089	not available	not available	not available
DECEMBER	0.064	not available	not available	not available

Table 2.3 Lake Lacawac and Lake Giles Hydrological Features

MONTH	LAKE LACAWAC		LAKE GILES	
1992	INFLOW (m^3/s)	OUTFLOW (m^3/s)	INFLOW (m^3/s)	OUTFLOW (m^3/s)
JULY	0.0096	0.0024	0.0220	0.0059
AUGUST	0	0	0	0
SEPTEMBER	0.0114	0.0071	0.0278	0.0183
OCTOBER	0.0044	0.0013	0.0102	0.0033
NOVEMBER	0.0240	0.0240	0.0626	0.0626
DECEMBER	0.0166	0.0166	0.0434	0.0434

Table 4.1 Model Parameters

PARAMETER	LAKE LACAWAC	LAKE GILES	RELIABILITY	SENSITIVITY LEVEL
WEIR LENGTH	5 meters	3 meters	poor	low
WEIR ELEV.	12.80 meters	23.85 meters	poor	low
WEIR C_D	3.0	3.0	poor	low
PORT ELEV.	6 meters	12 meters	poor	low
WIND COEFFS. a b	2.5×10^{-9} 0.5×10^{-9}	2.5×10^{-9} 0.5×10^{-9}	poor	high
DUST ATTENUATION	0.44	0.44	poor	high
SHELTERING COEFFICIENT	1.0	1.0	fair	low
PENETRATIVE CONV. FRACT.	0.3	0.3	fair	low
DIFFUSION COEFF.-WIND	2.0×10^{-5}	2.0×10^{-5}	poor	high
DIFFUSION COEFF.-ADVECT.	2.0×10^{-6}	6.0×10^{-6}	poor	high
SETTLING VEL.	1.0 m/day	1.0 m/day	poor	high
CLEAR WATER EXTINCTION	0.49	0.20	fair	high
% ABSORBED IN TOP 0.6 m	0.40	0.17	fair	high
SELF-SHADING EXTINCTION	0.40	0.15	poor	medium
TOTAL DISS. SOLIDS	(Profiles)	(Profiles)	fair	medium
SUSPENDED SOLIDS	(Profiles)	(Profiles)	poor	medium

FIGURES

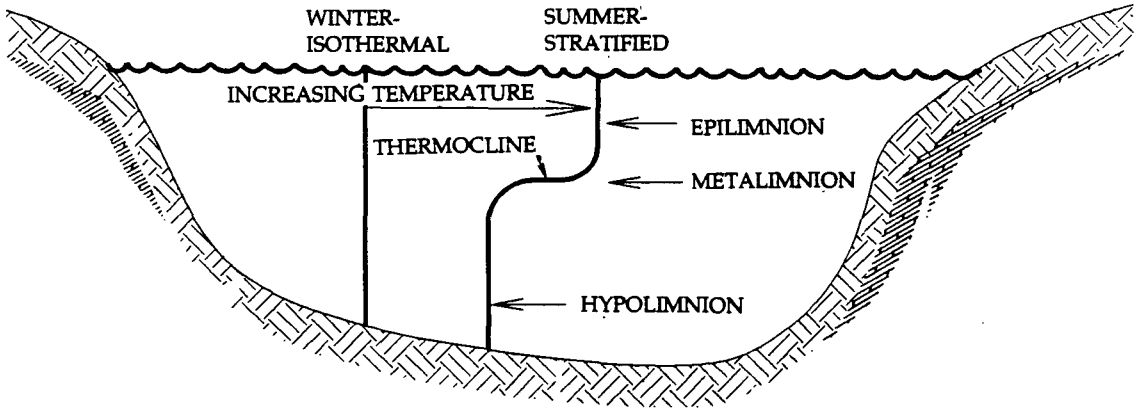

Figure 1.1 Typical Winter and Summer Pocono Lake Temperature Profiles

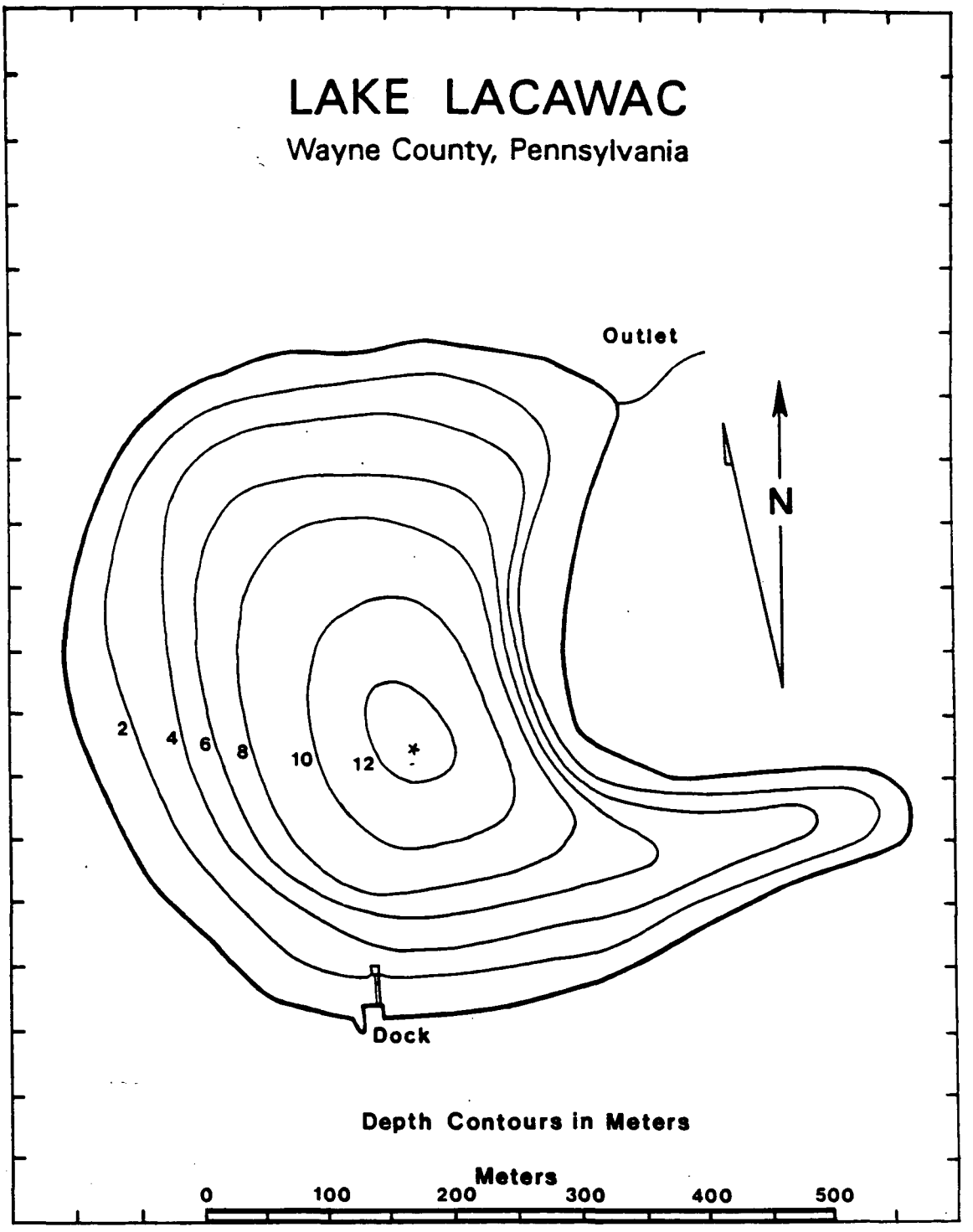

Figure 2.1 Lake Lacawac Bathymetry Map (Robert Moeller, Personal Communication)

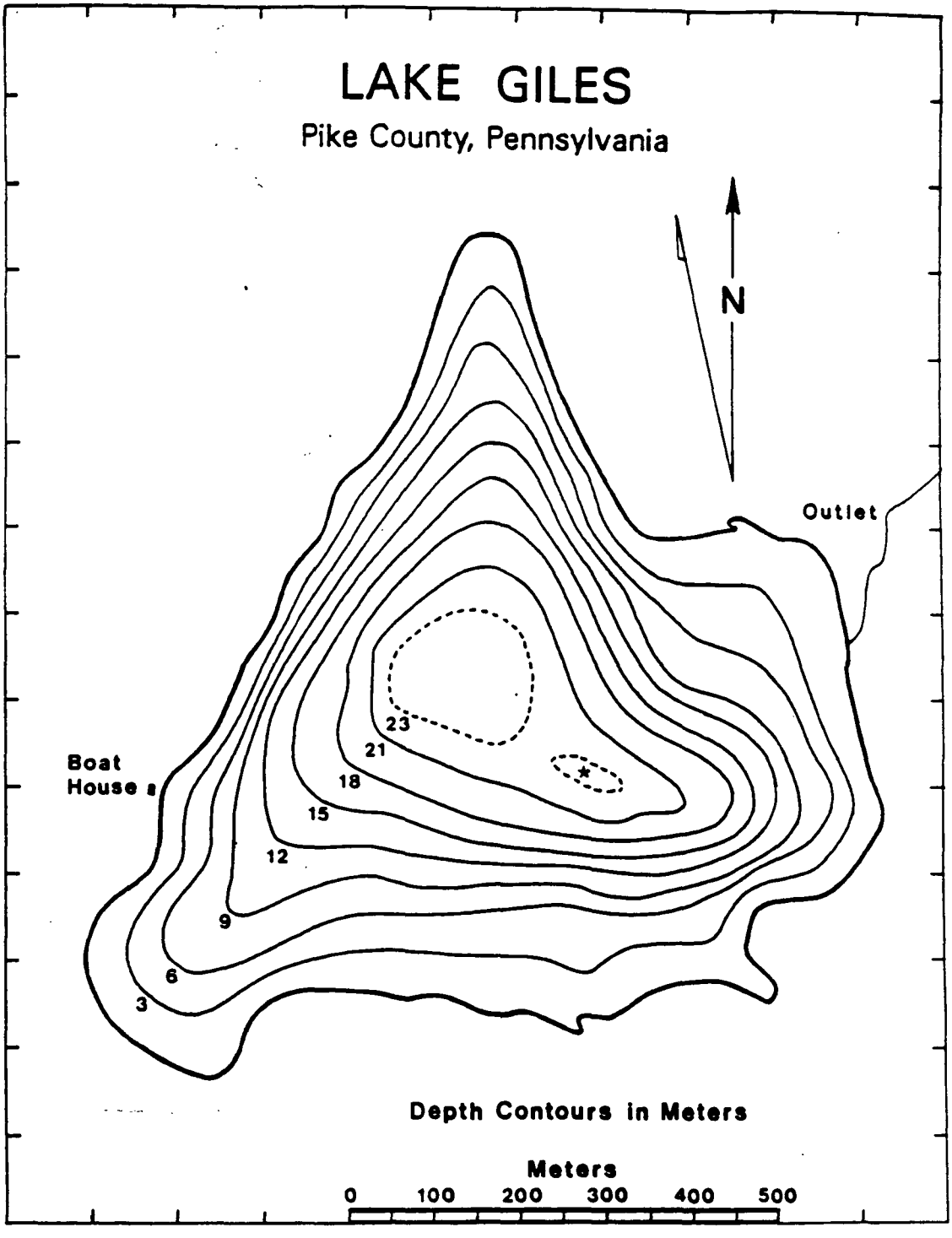

Figure 2.2 Lake Giles Bathymetry Map (Robert Moeller, Personal Communication)

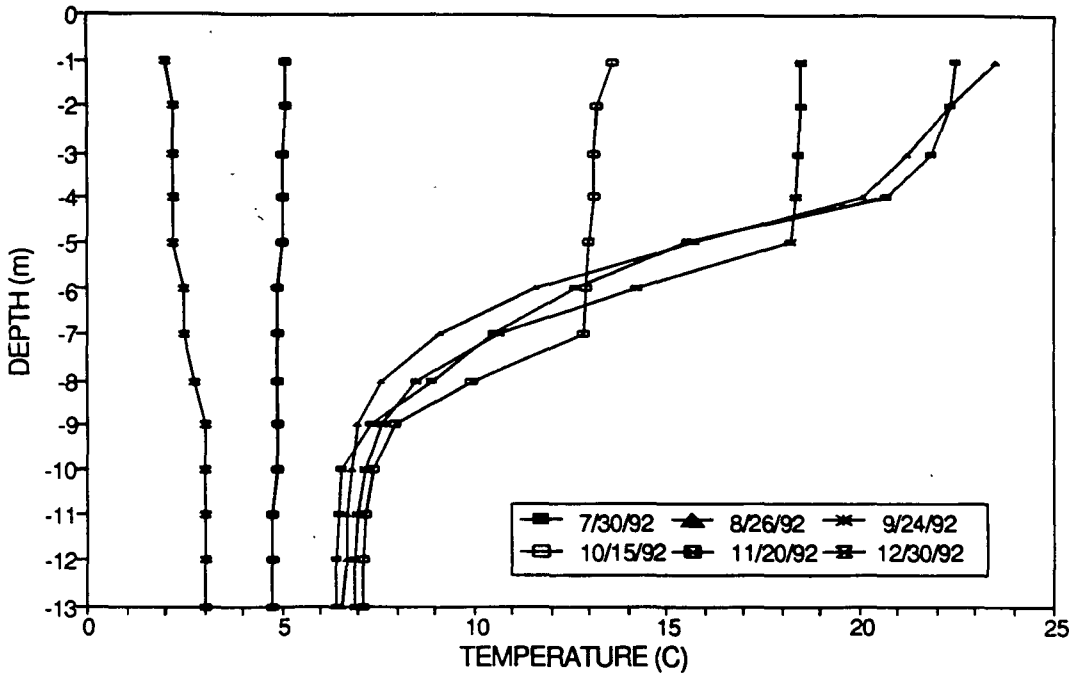

Figure 4.1 Lake Lacawac PCLP Measured Temperature Profiles

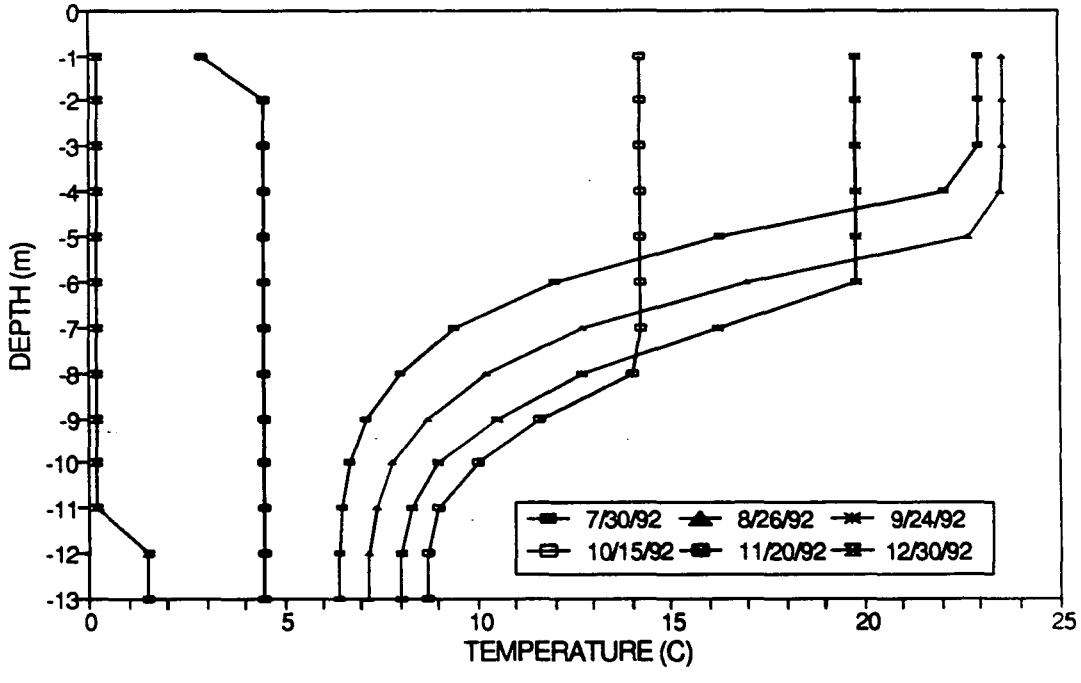

Figure 4.2 Lake Lacawac CE-THERM-R1 Predicted Temperature Profiles

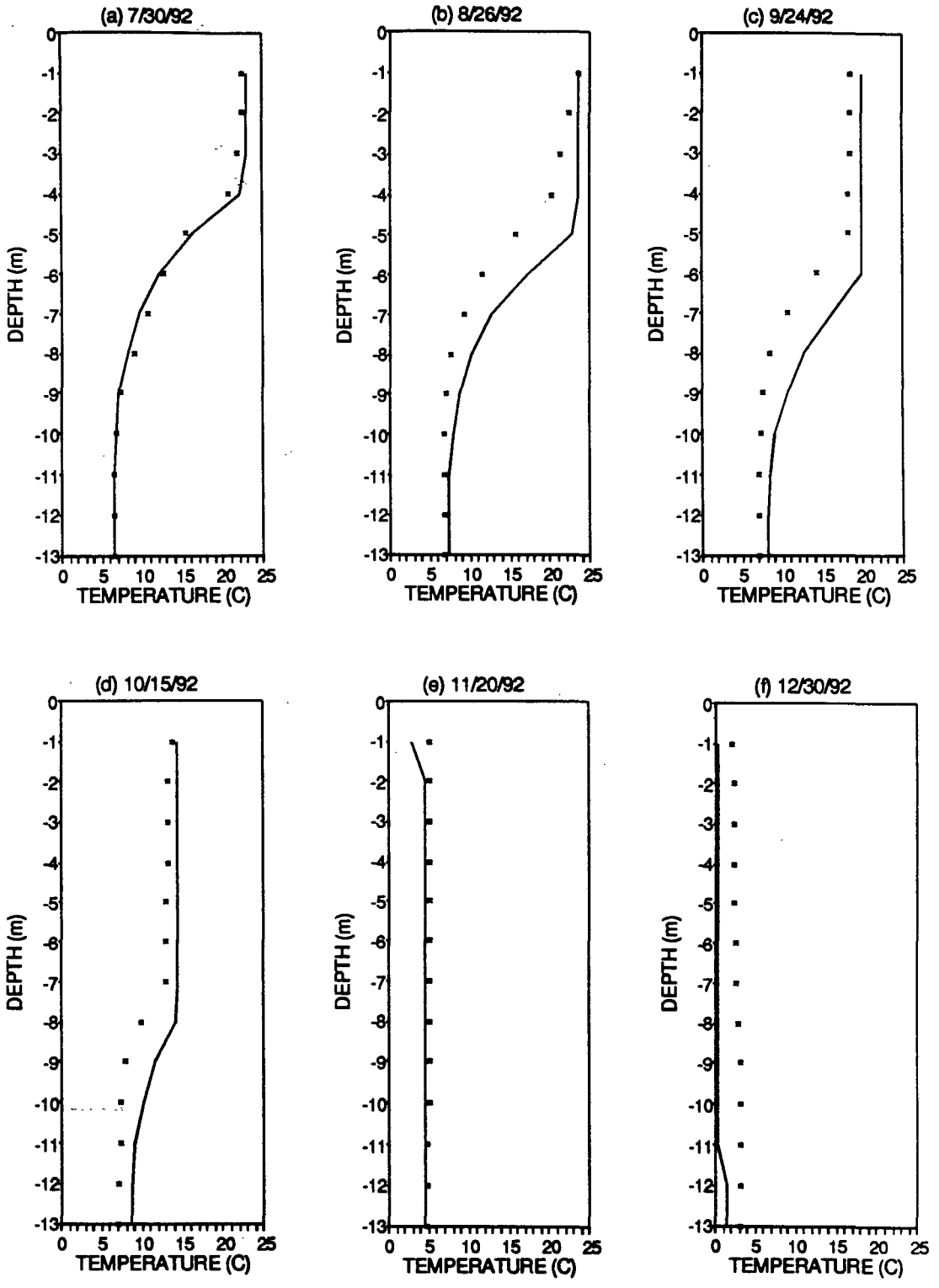

Figure 4.3 Lake Lacawac Monthly Measured and Modeled Temperature Profiles (dots represent measured data, lines denote model predictions)

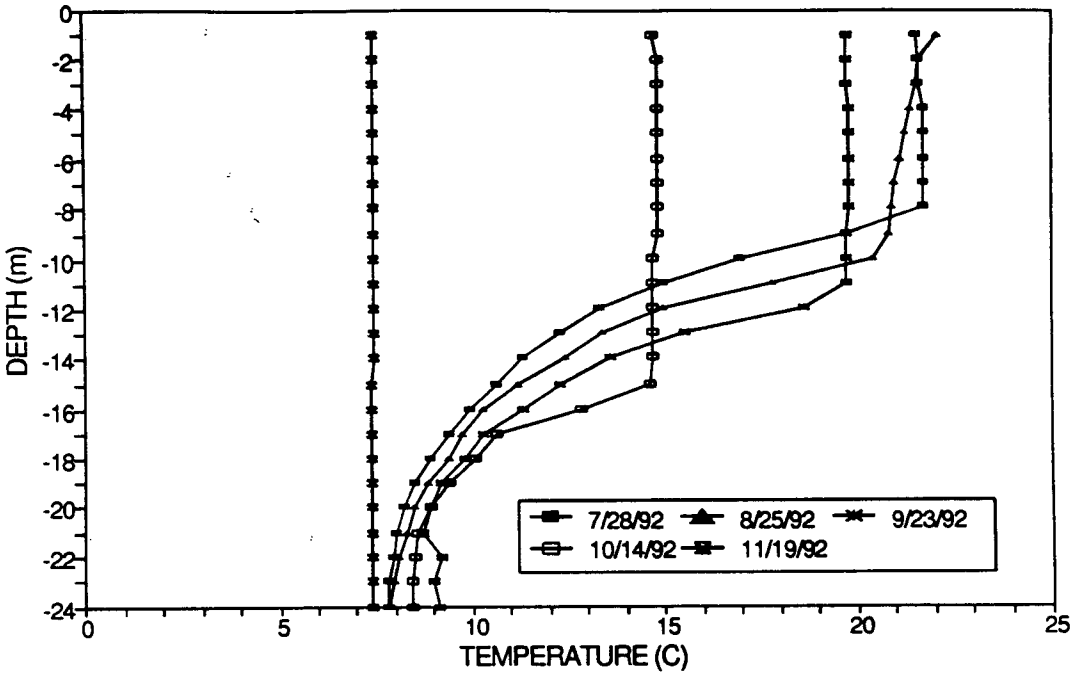

Figure 4.4 Lake Giles PCLP Measured Temperature Profiles

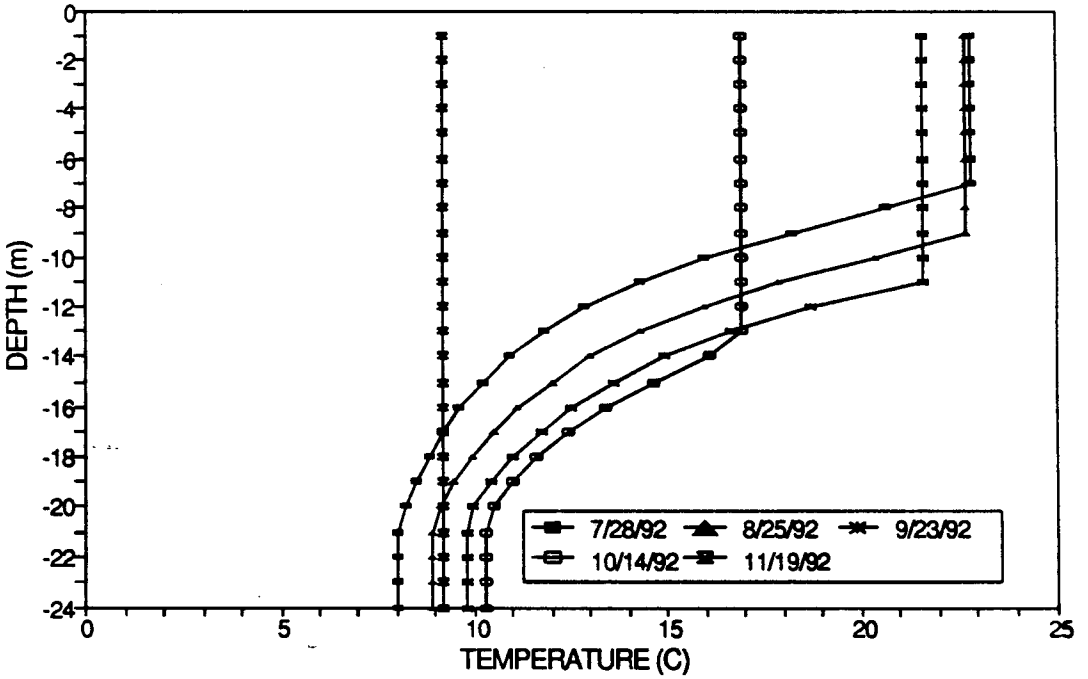

Figure 4.5 Lake Giles CE-THERM-R1 Predicted Temperature Profiles

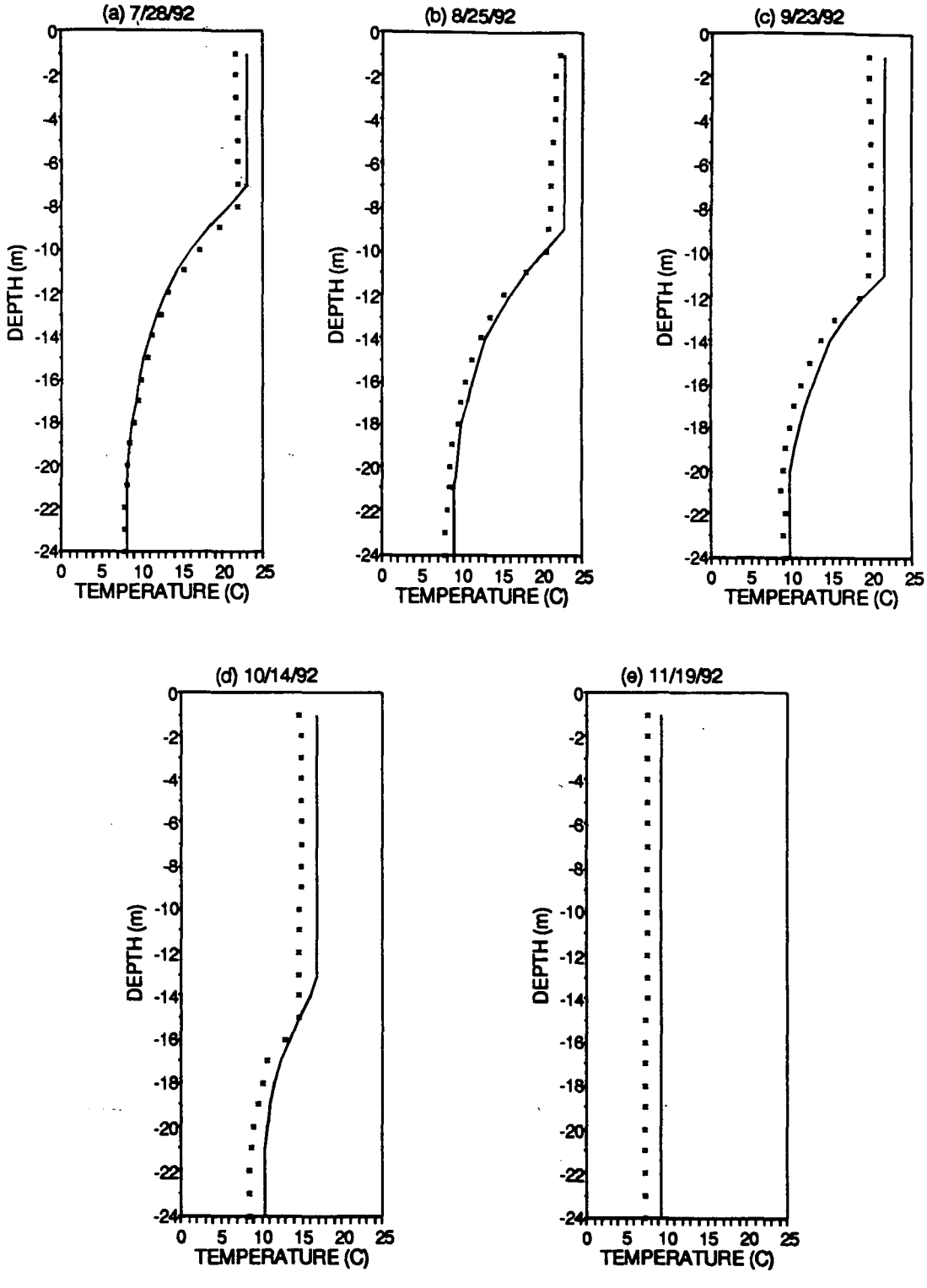

Figure 4.6 Lake Giles Monthly Measured and Modeled Temperature Profiles (dots represent measured data, lines denote model predictions)

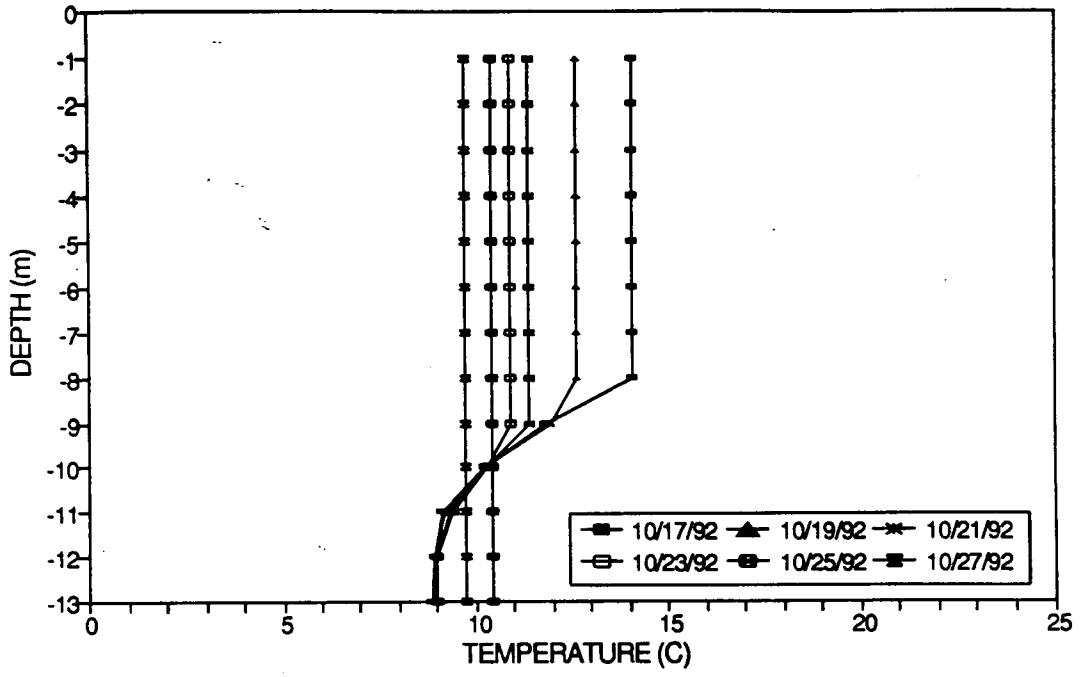

Figure 4.7 Temperature Profiles for Lake Lacawac Fall Turnover Prediction

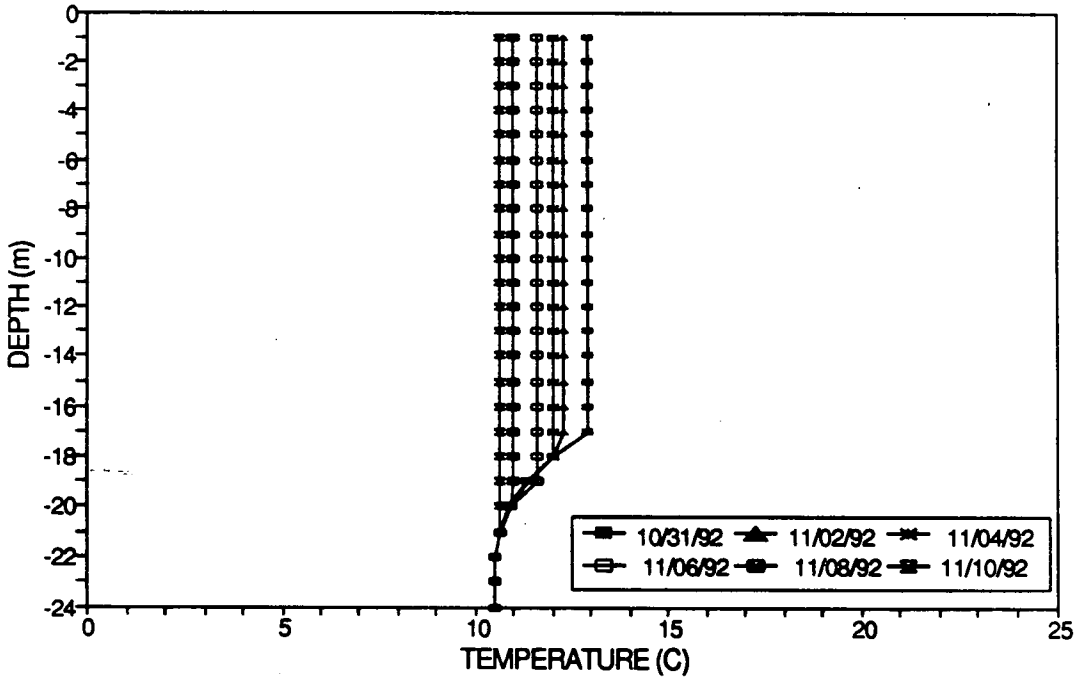

Figure 4.8 Temperature Profiles for Lake Giles Fall Turnover Prediction

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APPENDIX A

APPENDIX A HEAT BUDGET EQUATIONS

I. Short Wave Solar Radiation

Short wave solar radiation, Q_{ns}, is computed by

$$Q_{ns} = F_r F_c F_s \left(\frac{Q_o}{R^2} \sin\alpha\right) \tag{A.1}$$

where each term is defined as follows:

(a) R is the relative earth to sun distance given by

$$R = 1.0 + 0.17 \cos\left[\frac{2\pi}{365}(186 - JULIAN\,DAY)\right] \tag{A.2}$$

(b) Q_o, solar radiation at the edge of the atmosphere, is approximately 0.33 Kcal/m^2/second.

(c) F_s is atmospheric transmission of solar radiation given by

$$F_s = \frac{a'' + 0.5(1 - a' - d)}{1 - 0.5(ALBEDO)(1 - a' + d)} \tag{A.3}$$

where d is the dust attenuation coefficient, a'' is the mean atmospheric

transmission coefficient considering absorption and scattering given by

$$a'' = \exp(-[0.465 + 0.0408(0.00614e^{0.0489T_d})](0.179 + 0.421e^{-0.721\theta_{am}})\theta_{am}) \quad (A.4)$$

where T_d is dew point temperature, and the optical air mass, θ_{am} is

$$\theta_{am} = \frac{\exp(-ALT/2532)}{\sin\alpha + 0.15\left(\frac{180\alpha}{\pi}\right)^{-1.253}} \quad (A.5)$$

where ALT is the lake surface elevation above mean sea level, and α is solar altitude given by

$$\sin\alpha = \sin\phi\sin\delta + \cos\delta\cos\omega \quad (A.6)$$

where ϕ is the site latitude (radians), δ represents solar declination by

$$\delta = 0.4092 \cos\left[\frac{2\Pi}{365}(172 - JULIAN\ DAY)\right] \quad (A.7)$$

and ϖ is the solar hour angle given by

$$\omega = \frac{\Pi}{12}(t - t_L - 12) \quad (A.8)$$

where t is the simulation hour (during sunlight hours only), and t_L is the percent of 15° distance that the local meridian is west of its standard time zone meridian.

The mean atmospheric coefficient, a′ is defined by

$$a' = \exp(-[0.465 + 0.0408(0.00614e^{0.0489T_d})](0.129 + 0.171e^{-0.888\theta_{am}})\theta_{am}) \quad (A.9)$$

(d) The reflection factor, F_r, is

$$F_r = 1 - ALBEDO = 1 - A(53.7\alpha)^B \quad (A.10)$$

where A and B are empirical functions of cloudiness.

(e) F_c, the cloudiness factor, is expressed empirically as

$$F_c = (1 - 0.65C^2) \quad (A.11)$$

where C is the percent cloudiness during daylight hours.

II. Long Wave Atmospheric Radiation

Long wave radiation, Q_{na}, is computed by

$$Q_{na} = 1.23 \times 10^{-16} \times (T_a + 273)^6 \times (1 + 0.17C^2) \quad (A.12)$$

where T_a is dry bulb temperature, and C is the percent cloud cover.

III. Back Radiation

Back radiation, Q_b, emitted from the lake is calculated by

$$Q_b = 0.97\sigma(T+273)^4 \tag{A.13}$$

where σ is the Stefan-Boltzmann constant, and T is lake surface water temperature.

IV. Evaporative Heat Loss

Evaporative heat loss, Q_e, is

$$Q_e = \rho L(a+bW)(e_s-e_a) \tag{A.14}$$

where L is latent heat of vaporization, ρ is water density, a and b are empirical wind coefficients, e_s is saturated vapor pressure at the water surface temperature, and e_a is vapor pressure at the air temperature, or saturation vapor pressure at the dew point temperature. For $e_s \prec e_a$, Q_e is zero.

V. Conductive Heat Transfer

Heat transfer occurs across the lake surface, Q_c, is

$$Q_c = \rho L(a + bW)(C_B + 10^{-3}P)(T - T_a) \qquad \text{(A.15)}$$

where C_B is Bowen's Ratio, P is barometric pressure, T is lake water surface temperature, and T_a is the air temperature.

APPENDIX B

APPENDIX B SUPPLEMENTARY CE-THERM-R1 EQUATIONS

I. Inflow and Outflow Zone Thicknesses

The thickness of one-half (either the upper half or the lower half) of the inflow zone, d, is given by

$$d = 1.35\left(\frac{QL}{A}\frac{1}{\sqrt{g\frac{\Delta p}{\rho_o}}}\right)^{2/3} \qquad \text{(B.1)}$$

where Q is the inflow, L is the length of lake, A is the lower surface area of the layer considered, g is gravitational acceleration, Δp is the absolute value of the density difference between the inflow layer and the upper or lower limit of the inflow zone, and ρ_o = inflow layer density.

The weir outflow zone, or the depth below weir crest to withdrawal zone limit, Z_o, is computed by solving

$$\frac{Q}{L} - \left(C - \frac{DH_w}{Z_o + H_w}\right)\sqrt{\frac{\Delta\rho_o}{\rho_w} g (Z_o + H_w)^3} = 0 \qquad \text{(B.2)}$$

where C and D are dimensionless coefficients defined as follows

for $Z_o \geq H_w$ C = 0.54, D = 0.0

for $Z_o < H_w$ C = 0.78, D = 0.7

H_w is the depth of water surface above weir crest, Q is the weir discharge, L is weir length, $\Delta\rho_o$ is the density difference between water at weir crest and water at lower limit of withdrawal zone, and ρ_w is the density of water at the weir crest.

The thickness of the port withdrawal zone, Z, (the distances from the port to the upper and lower zone limits) is found by

$$Q - Z^2 \sqrt{\frac{\Delta\rho'}{\rho} g Z} = 0 \qquad \text{(B.3)}$$

where Q is port discharge, $\Delta\rho'$ is the density difference between water at the weir crest and water at upper or lower limit of the port withdrawal zone, and ρ is the density of water at the port location.

II. Turbulent Kinetic Energy

Turbulent kinetic energy created by wind shear, TKE_w, is calculated by

$$TKE_w = \int_{A_s} C W_* \tau \Delta t \, dA \qquad \text{(B.4)}$$

where A_s is the lake water surface area, C is a sheltering coefficient, Δt is the time

step, W_* is water shear velocity given by

$$W_* = \sqrt{\frac{\tau}{\rho_w}} \tag{B.5}$$

Shear stress at the water surface, τ, is

$$\tau = \rho_a C_d W^2 \tag{B.6}$$

where is ρ_a is air density, C_d is the coefficient of drag, as follows

$$C_d = 0.0005\ W^{.5} \quad \text{for } W < 15 \text{ m/s}$$

$$C_d = 0.0026 \quad \text{for } W \geq 15 \text{ m/s}$$

W is wind speed.

When the lake is cooling, TKE_c is generated by penetrative convective energy is

$$TKE_c = -C_c Q_n A_s Z_{mix} g \alpha \frac{\Delta t}{c_p} \tag{B.7}$$

where C_c is the penetrative convection coefficient (0.3, as recommended), Q_n is net heat flux at water surface (>0 values only), Z_{mix} is the epilimnion depth, α is water thermal expansion coefficient per °C, and c_p is water specific heat.

To combine TKE_w and TKE_c into total TKE, dissipation and inefficiencies must be considered using a the following Richardson number conversion

$$TKE = (TKE_w + TKE_c)\left[0.057\,Ri\left(\frac{29.46-\sqrt{Ri}}{14.20+Ri}\right)\right] \tag{B.8}$$

where Ri is the Richardson number given by

$$Ri = \frac{Z_{mix} g \Delta\rho}{\rho_w W_*^2} \tag{B.9}$$

Entrainment, or work, W_L, required to lift a layer of water from below the epilimnion to the center of mass of the epilimnion is

$$W_L = \Delta\rho\, \Delta V\, g\, (Z_{mix} - Z_g) \tag{B.10}$$

where $\Delta\rho$ is the density difference between the layer beneath the epilimnion and epilimnion water, ΔV is volume of the layer to be moved to epilimnion, Z_{mix} is the epilimnion depth, and Z_g is the depth to the epilimnion center of mass.

III. Diffusion Coefficients

The eddy diffusion coefficient, DC(I), is defined by

$$DC(I) = \Delta t^2 \left(\left[\frac{CDIFW \cdot DISW}{1 + Ri} \right] + \left[\frac{CDIFF \cdot (DISF(I) + DISF(I+1))/2}{1 + (\frac{1}{Fr})^2} \right] \right) \quad \text{(B.11)}$$

where CDIFW, and CDIFF are wind and advection coefficients, Ri is Richardson's number, DISW is dissipation of wind generated energy per unit mass given by

$$DISW = \frac{TKE_w}{\rho_w V \Delta t} \quad \text{(B.12)}$$

where V is lake volume, DISF is dissipation of inflow and outflow generated energy per unit mass given by

$$DISF = \frac{\left[\frac{1}{2} \rho_w q(I) \Delta t \left(\frac{q(I)}{B(I)\,\Delta Z(I)} \right)^2 \right]}{[\rho_w \Delta V(I)\,\Delta t]} \quad \text{(B.13)}$$

where $\Delta V(I)$ is layer I volume, q(I) is inflow rate, B(I) is the layer width, ΔZ is the

layer thickness, and Fr is the densimetric Froude number,

$$Fr = \frac{u}{\left(\frac{\Delta\rho}{\rho_w} g \Delta z\right)^{0.5}} \tag{B.14}$$

where $\Delta\rho$ is the local density change, Δz is the thickness of a layer, and u is longitudinal velocity given by

$$u = \frac{q(I)\, RLEN}{\Delta V(I)} \tag{B.15}$$

where RLEN is the length of the lake (from primary inflow area to outlet)

The maximum value for eddy diffusion coefficient, DC(I), is 20.0 m^2 / hr, and if it falls below 0.0005148 m^2/hr, the molecular diffusion coefficient, it is set to the molecular diffusion coefficient.