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TWO-DIMENSIONAL WATER QUALITY MODELING OF WHEELER RESERVOIR

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EXECUTIVE SUMMARY

The water quality and aquatic biological resources of Wheeler Reservoir and its tributaries are being adversely impacted by point and nonpoint pollution sources, flow regulations, and natural processes. Among the Tennessee Valley Authority (TVA) mainstem reservoirs, Wheeler Reservoir ranked second most eutrophic, preceded only by Guntersville Reservoir. Available data indicate the assimilative capacity of Wheeler Reservoir is occasionally marginal or inadequate for existing discharges. This lack of assimilative capacity was especially severe during drought conditions in 1988 when release dissolved oxygen (DO) concentrations from Wheeler Reservoir were less than 5 mg/L for more than 50 days. The assimilative capacity of the reservoir is a function of several factors including ambient DO, temperature, and wasteloads, as well as river flow which is determined by hydro operations at Guntersville and Wheeler Dams. To better understand the reservoir DO dynamics, a two-dimensional Box Exchange, Transport, Temperature, and Ecology of a Reservoir (BETTER) model of Wheeler Reservoir was calibrated.

The BETTER model calculates flow exchange in a two-dimensional array of boxes representing reservoir geometry. The model has both heat budget and DO balance components. The heat budget component, which includes wind mixing and convective cooling, simulates the seasonal patterns of warm surface wedge and cold bottom water. The DO balance components, including biochemical oxygen demand (BOD), ammonia, sediment oxygen demand (SOD), surface reaeration, and photosynthesis and respiration from algae, produce a seasonal DO pattern.

The Wheeler BETTER model was calibrated with 1988 and 1991 data. The year 1988 was severely dry, while wet conditions prevailed during 1991. For both years, the observed seasonal temperature patterns in the Tennessee River were adequately reproduced by the model. Thermal stratification in the Elk River was slightly overestimated in 1988, primarily due to the lack of measured inflow temperatures. The 1988 and 1991 observed seasonal DO patterns were also well simulated in the Tennessee River. Performing well in a dry year like 1988 is especially significant because it indicates that the model adequately simulates reservoir DO processes such as algal activity, nutrient recycling, and SOD. These DO processes tend to influence more of the reservoir DO dynamics in a dry year. In a wet year like 1991, inflow water quality is normally the primary factor determining DO in the reservoir. Measured chlorophyll-a concentrations and observed pH profiles were used to provide a qualitative assessment of modeled algal productivity. The model reproduced the 1991 early summer algal bloom, and the computed algal biomass was comparable with field observations.

A mass balance of 1988 and 1991 loading contributions from all inflows and point source waste discharges indicated:

- over 75 percent of the total BOD load and over 50 percent of the total inorganic nitrogen load was contributed by Guntersville releases;
- between 30 to 60 percent of the total phosphorus load was released by point sources; and
- local runoff accounted for about 1/3 of suspended solids.

The model can be used to evaluate reservoir assimilative capacity under various reservoir operations and waste allocation practices. A simulation with all point source wasteloads eliminated showed that reservoir volume with DO less than 2 mg/L was reduced by more than half from the 1988 basecase, and the number of days with DO below 2 mg/L was decreased from 121 days to 91 days in the forebay under 1988 hydrology. Another simulation showed that increasing all point source waste discharges to their permit loads increased the volume of reservoir with DO below 2 mg/L by about 50 percent over the 1988 basecase. Implementation of the Lake Improvement Plan (LIP) improved reservoir DO in early summer due to increased releases at Guntersville and Wheeler. Release DO at Wheeler Dam was increased between 0.5 to 1.0 mg/L in June over the 1988 basecase.

The Wheeler BETTER model has been given to the Alabama Department of Environmental Management (ADEM) to use as a planning tool to address issues such as the impacts of adding new wasteloads and animal waste reduction measures on reservoir waste assimilative capacity. Trade-offs between point and nonpoint waste reduction can be examined quantitatively on a reservoir-wide basis.

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I. INTRODUCTION

The water quality and aquatic biological resources of Wheeler Reservoir and its tributaries are being adversely impacted by point and nonpoint pollution sources, flow regulations, and natural processes. Among the Tennessee Valley Authority (TVA) mainstem reservoirs, Wheeler Reservoir ranked as the second most eutrophic, preceded only by Guntersville Reservoir (Placke, 1983). Available data indicate the assimilative capacity of Wheeler Reservoir is occasionally marginal or inadequate for existing discharges (TVA, 1990). This lack of assimilative capacity was especially severe under drought conditions in 1988 when release dissolved oxygen (DO) concentrations from Wheeler Reservoir were less than 5 mg/L for more than 50 days. The assimilative capacity of the reservoir is a function of several factors including ambient DO, temperature, and wasteload, as well as river flow which is determined by hydro operations at Guntersville and Wheeler Dams. To better understand the reservoir DO dynamics, a two-dimensional BETTER model (Bender et al., 1990) of Wheeler Reservoir was developed and calibrated.

The model was calibrated using two years of field data, i.e., 1988 and 1991. Hydrologically, 1988 was a severely dry year while wet conditions prevailed during 1991. In 1988, available field data were limited allowing only a preliminary model calibration for reservoir temperature and DO. An extensive water quality survey was conducted in 1991. Water quality and nutrient profiles in 1991 were used for a more complete calibration of the model. Major industrial and municipal waste discharges were estimated using flow and nutrient concentrations reported in Discharge Monitoring Reports (DMR) provided by the Alabama Department of Environmental Management (ADEM). The model has been given to ADEM to use as a planning tool to study reservoir assimilative capacity under various reservoir operations, waste allocation practices, and meteorological conditions.

II. SITE DESCRIPTION

Wheeler Dam is located on the Tennessee River approximately 18 miles upstream from Florence, Alabama, at Tennessee River Mile (TRM) 274.9. As shown in Figure 1, the reservoir extends 74.1 miles upstream to Guntersville Dam at TRM 349.0. At full pool (elevation 556.0 ft), Wheeler Reservoir is approximately 58 feet deep at the dam and the water surface covers 67,100 acres, or approximately 105 square miles. Physical features of Wheeler Reservoir are summarized in Table 1 (TVA, 1990). Under normal operation, the reservoir starts filling on March 15 and achieves full pool by April 15. Historically, reservoir drawdown begins on July 1 and reaches normal minimum pool (elevation 550.0 ft) by December 1. In 1991, TVA implemented the Lake Improvement Plan (LIP) which extended full pool through July.

The main channel of Wheeler Reservoir varies from 20 to 60 feet deep. While the riverine section of the reservoir tends to be fully mixed, the downstream lacustrine section

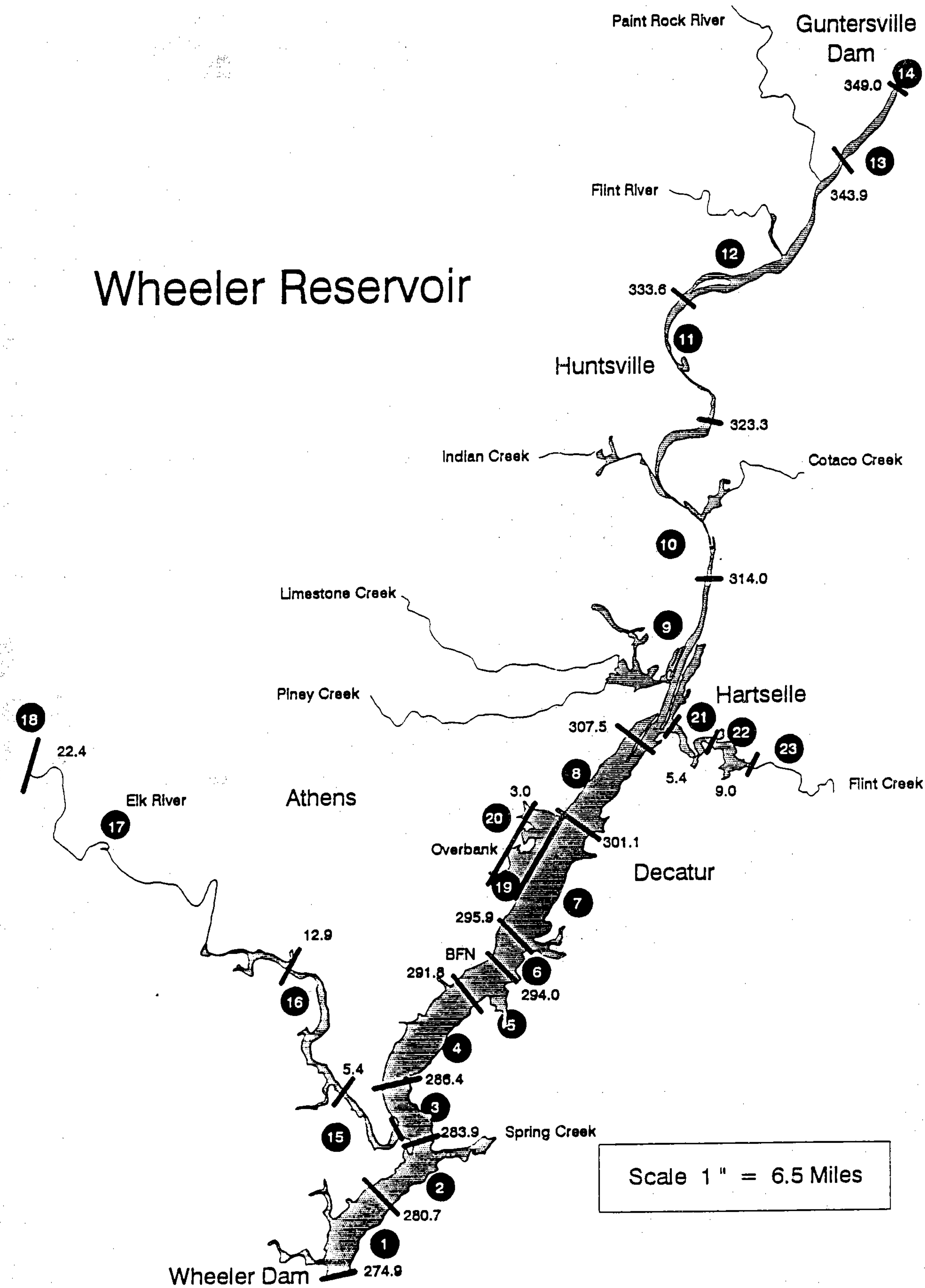


Figure 1. Map of Wheeler Reservoir

sometimes exhibits a thermal stratification with as much as a 6°F gradient top to bottom from late spring to mid-summer (1988 field data), but under normal flow conditions such periods are generally short-lived. Thermal stratification is weakened by warm inflows and increased hydro operation at Wheeler Dam in late summer and becomes fully mixed in early to mid-fall.

TABLE 1

Physical Characteristics of Wheeler Reservoir

Location: TRM 349.0 (Guntersville Dam) to TRM 274.9 (Wheeler Dam)
Reservoir Length: 74.1 mi
Elevation (msl): Normal maximum pool: 556.0 Normal minimum pool: 550.0
Area: Normal maximum pool: 67,070 ac Normal minimum pool: 45,450 ac
Volume: Normal maximum pool: 1,050,000 ac-ft Normal minimum pool: 720,000 ac-ft
Drainage area: Total upstream from Wheeler Dam: 29,590 mi^2 Local between Guntersville and Wheeler Dams: 5,140 mi^2 Uncontrolled (below Guntersville and Tims Ford Dams): 4,611 mi^2
Major tributaries and drainage areas: Elk River: 2,249 mi^2 Flint Creek: 455 mi^2 Limestone Creek: 286 mi^2 Cotaco Creek: 243 mi^2 Flint River: 568 mi^2 Paint Rock River: 458 mi^2
Flows at Wheeler Dam: Estimated average unregulated: 49,500 cfs Estimated 7Q10: 7,570 cfs

III. MODEL DESCRIPTION

Geometry and Flow Patterns

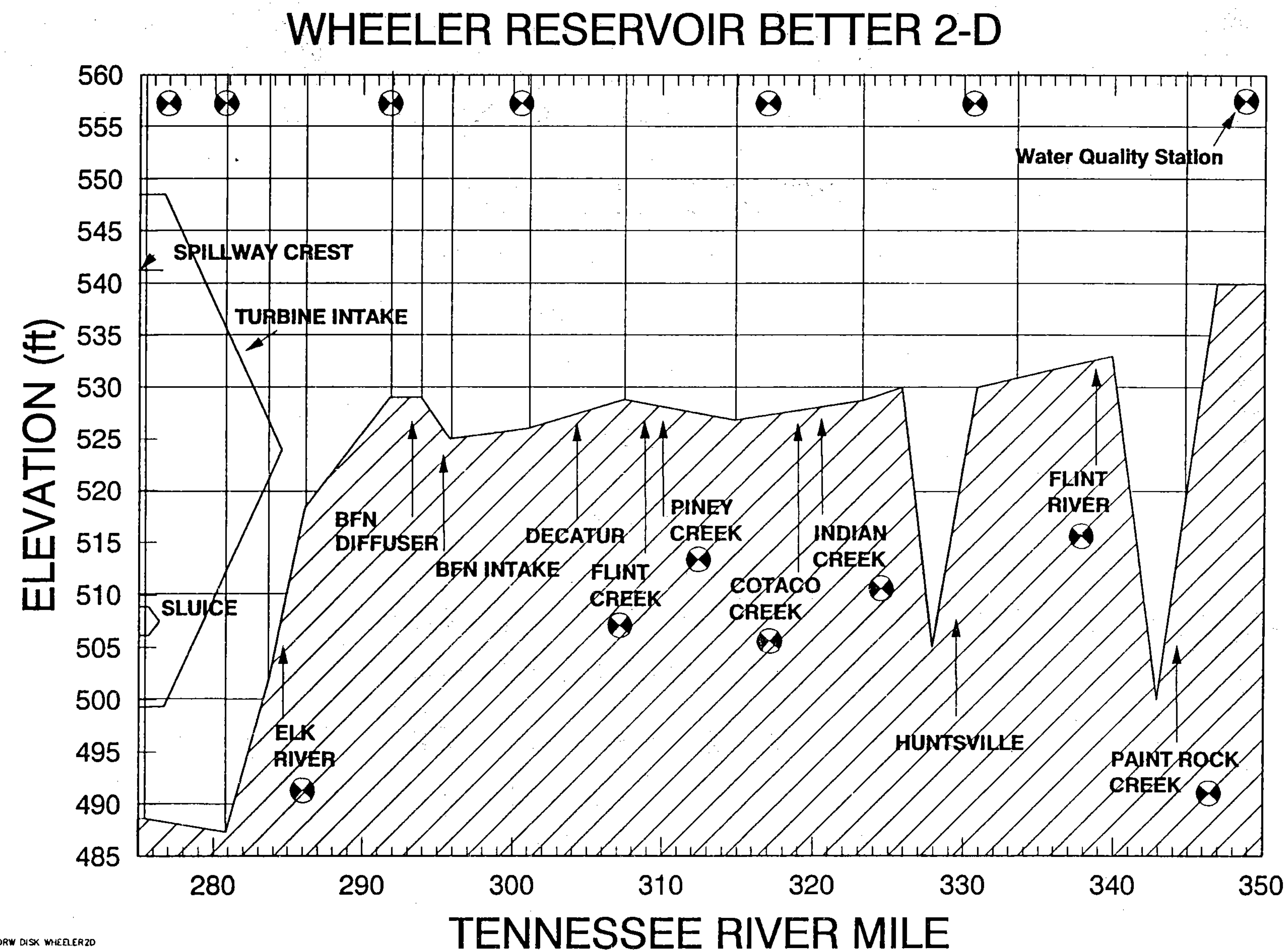
The Box Exchange, Transport, Temperature, and Ecology of a Reservoir (BETTER) model (Bender et al., 1990) calculates flow exchange among elements of a two-dimensional array of boxes representing reservoir geometry. A heat budget including wind mixing and convective cooling simulates the seasonal patterns of a warm surface wedge and cold bottom water. Based on a DO balance that includes biochemical oxygen demand (BOD), ammonia, sediment oxygen demand (SOD), surface reaeration, and photosynthesis and respiration from algae, the model produces a seasonal pattern of DO throughout the reservoir. Important model components with relevance to Wheeler Reservoir are highlighted briefly in this section. For more details on the model algorithms, the reader is referred to Bender et al. (1990).

The Wheeler Reservoir BETTER model was segmented into a two-dimensional array of volume elements as shown in Figure 2. Volume elements are smaller for surface layers where the largest gradients in water quality are expected. A floating layer scheme is used so that all layers remain at specified depths from the surface. This preserves near-surface gradients and allows direct comparison with field surveys at fixed depths. The reservoir was segmented longitudinally based on sampling locations and transition zones between reasonably homogeneous segments of the reservoir (see Figure 1). Element volumes and conveyance area tables were determined from cross-sectional surveys, maps, and sediment ranges and adjusted as necessary to preserve the correct volume-elevation relationship. For each element, the model determines volume, downstream conveyance area, and surface interfacial area at each time step.

The model computes water quality in the main channel of the Tennessee River, in the Elk River arm, in the Flint Creek embayment, and in the overbank area near TRM 300. The overbank area was modeled as a branch with no inflow except local inflow. Local reservoir inflows were determined using daily dam releases and midnight reservoir elevations so that the model simulates daily changes in reservoir volume.

Water quality in each volume element is assumed to be fully mixed and a set of volume averaged concentrations is calculated at each time step for the element. Thus, model results are more likely to be representative of main channel than overbank areas. Due to the coarse geometry used by the BETTER model, near-field effects such as patches of hot water or pockets of high BOD water normally found immediately below a point source cannot be adequately simulated by the model.

Flow patterns are estimated in the model with a procedure that distributes inflow and outflow based on geometric properties (surface area and conveyance area) of the volume elements. Inflows are deflected vertically toward layers with matching densities using a densimetric Froude number, which represents the relative importance of downstream flow momentum compared to the buoyancy force due to the density gradient. Thus, during high flows, large flow momentum tends to reduce density deflections. During low flows and strong



WHELLER2.DRW DISK WHEELER2D
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Figure 2. Geometric Representation of Wheeler Reservoir

stratification, maximum density deflections occur. Outflows are withdrawn from a withdrawal zone that increases with flow rate and decreases with temperature gradient. Thus, during low flows and strong stratification, a smaller withdrawal zone is used.

Three distinct mixing mechanisms that induce vertical mixing between layers are simulated. These are convective mixing due to surface cooling and sinking of more dense water, wind mixing due to wind shear at the surface, and turbulent mixing between layers driven by ambient flow pattern.

Four major point source discharges were identified for the Wheeler BETTER model. They are: (1) Champion Paper Company at TRM 282.3, (2) Browns Ferry Nuclear Plant (BFN) at TRM 293.6, (3) Decatur Industrial and Municipal Discharges at TRM 303, and (4) Huntsville Industrial and Municipal Discharges at TRM 334.

Heat Budget

Reservoir temperatures are the result of a reservoir heat budget which depends on the rate and temperature of the inflow and outflow and heat transfer across the air/water interface. Surface heat transfer includes long wave radiation from the atmosphere and water surface, wind driven evaporation and conduction (using Bowen's ratio), and absorption of solar radiation at the water surface. The BETTER model assumes that 50 percent of incoming solar radiation is absorbed as heat at the surface, with the remaining 50 percent absorbed by lower layers according to an exponentially decreasing light extinction formulation. The extinction coefficient for solar radiation is composed of a background light extinction coefficient (0.5) and the shading effects of algae and suspended solids. The extinction coefficient is the only feedback mechanism in the model for biochemical processes to influence the heat budget.

Wind mixing of near-surface layers is simulated using an energy balance approach that iteratively increases the mixing depth until the potential energy required to mix layers equals the kinetic energy transferred from the wind.

Dissolved Oxygen Balance

Dissolved oxygen in the reservoir is governed largely by inflow concentrations, decay of organic materials, algal productivity, oxidation of ammonia, and sediment oxygen demand (SOD). Organic materials in the model consist of two components: detritus (particulate organics) and dissolved organics. Both enter the reservoir with inflow and waste discharges. Detritus, which settles in the reservoir and has a smaller decay rate than that of dissolved organics, is also replenished by algal mortality. Ammonia enters the reservoir in the inflow and waste discharges, undergoes nitrification to nitrate, and is released during algal respiration, detritus decay, and anaerobic sediment decomposition. SOD is modeled as an areal demand (g O_2/m^2/day) specified for each longitudinal segment. All these modeled processes are temperature dependent.

Algal photosynthesis adds oxygen to surface layers where light conditions are favorable. This DO production depends on algal biomass and growth rate and can produce supersaturation in the surface layer. Algal respiration, on the other hand, can be a major oxygen demand in the metalimnion and hypolimnion. Both algal growth and respiration are modeled as first order kinetics. Reaeration, another pathway for oxygen replenishment in the surface, is modeled as a function of windspeed and DO deficit below saturation.

Aquatic macrophytes also contribute surface DO via photosynthesis and consume DO via respiration. Macrophytes obtain their nutrients via roots and therefore grow best in shallow water (< 10 ft) with nutrient-rich sediments. Excessive macrophyte growth can sometimes create local DO stratification, especially in shallow overbank areas. Photosynthesis enriches DO at surface layers while vertical mixing (a primary mechanism to transfer DO to the DO-depleted bottom layers) is hindered by the surface mat formed by macrophytes. Broken macrophytes, like algae, consume DO while decomposing. This usually happens in late fall and early winter when river flow is high. Since the residence time corresponding to high flow is relatively small (< 10 days) in Wheeler Reservoir, the effects of broken macrophytes on DO in the main water body is not considered significant; however, they may pose a DO problem to downstream reservoirs. Review of available field data showed that the observed effect of macrophytes on DO in the main river was not distinguishable from that of algae. Therefore, rather than add an additional set of uncertain process coefficients to the model for simulation of macrophytes, it was decided to simulate the combined photosynthetic and respiration effects of all aquatic plants using the algorithm existing in the model with coefficients calibrated to reproduce laterally averaged DO conditions.

Algae and Nutrients

Algae play an important role in affecting levels of DO and dissolved inorganic nutrients (nitrogen, phosphorus, carbon dioxide). Algal biomass in the model represents an assemblage of diatoms, greens, and blue-greens and is modeled as a function of temperature and growth-limiting factors including light and nutrient concentrations.

Light fluctuates daily, but usually remains adequate for plant growth. In a system with a dense algal population, however, several days of overcast weather can drastically limit growth while a large number of light-starved algae may die. The model assumes 50 percent of solar radiation to be photosynthetically active radiation (PAR) and useful for algae. Modeled PAR decreases exponentially as a function of depth based on an extinction coefficient that depends on concentrations of suspended solids, algae, and detritus. Light limitation is determined by a Monod expression with a half-saturation light coefficient.

The inorganic nutrient requirements are determined by the chemical composition of algae. The ratios of C/P and N/P for algae used in the model are 67 and 6.7, respectively. Nitrogen is available for uptake as ammonia (NH_3-N) and nitrate (NO_3-N) without preference. Phosphorus (in the form of PO_4-P) is assumed to be bioavailable. The source of carbon for algae growth is carbon dioxide. Any one of these three nutrients can limit algae productivity when the demands for growth exceed the supply. Nutrient limitations in the model are determined using a Monod expression and a corresponding half-saturation concentration. Through algal respiration and decomposition of dead algae cells, a portion of the absorbed nutrients are recycled back into the reservoir water body.

To avoid sudden crashes of algal biomass in the model, grazing of algae by zooplankton is not modeled. Instead, a first order mortality is used that allows a direct conversion of algae to detritus. This practice simulates a fairly uniform alga biomass over the summer period, responding only to temperature, light, and nutrient availability.

Capabilities and Limitations

Because of the lack of control over important environmental variables, field measurements are often difficult to interpret. The BETTER model serves as a tool where these variables can be evaluated independently or simultaneously and is useful for quantifying water quality responses to mitigation measures, identifying key causes and effects and suggesting appropriate solutions. However, models, at best, are simplifications of reality and are subjected to limitations. Many of the limitations in the BETTER model are associated to assumptions embedded in model formulations. For example, the BETTER model does not employ the momentum equation for solving the flow field; instead, the model uses empirical hydrodynamic formulations for inflow placement, density deflection, outflow withdrawal, and turbulent mixing. As a result, certain momentum-driven phenomena such as forebay circulation after turbine shutoff, shear-induced circulation at embayment junctions, waves, or seiching cannot be simulated by the model. A detailed discussion of BETTER model's capabilities and limitations can be found in the BETTER model technical reference manual and user's guide (Bender et al., 1990).

IV. MODEL INPUTS

Uncertainties exist in virtually all timeseries inputs, such as meteorology, hydrology, and inflow water quality. Meteorological data may have been taken from a nearby airport at a different elevation or altitude. Total inflows which are backcalculated using recorded discharges and headwater elevations are subjected to errors introduced by the flat pool assumption and/or badly calibrated flowmeters at hydroprojects. In addition, daily inflow quality timeseries often have to be developed from weekly or monthly grab data that do not capture important storm events. Discussions of preparing these timeseries inputs for the Wheeler BETTER model are given below.

Meteorology

Water temperature and surface heat exchange computations in the BETTER model require meteorological data such as dry bulb and dewpoint temperatures, wind speed, cloud cover, and solar radiation. To reproduce the diurnal variations of surface temperatures observed at BFN Stations 4 and 17, a timestep of 12 hours (day/night) was used by the Wheeler BETTER model. The 12-hour average values of dry bulb, dewpoint, wind speed, and solar radiation were computed using hourly meteorological data recorded at Huntsville Airport and are shown in Figures 3 and 4 for 1988 and 1991, respectively.

Flows

Guntersville Dam hourly releases were used to determine Tennessee River inflows. Day and night (12-hour) flows were computed by averaging hours 7 to 19 and hours 20 to 6, respectively. For the Elk River, daily average flows recorded at ERM 41.5 (1,748 square miles) were transferred to ERM 16.5 (1,951 square miles) by the ratio of drainage areas. The same method was used to transfer daily average flows recorded at Flint River Mile 35.6 (342 square miles) to Flint Creek Mile 12.0 (411 square miles). The 1988 and 1991 daily average releases from Guntersville Dam and Tims Ford Dam, which regulates the Elk River flow, are shown in Figures 5 and 6, respectively.

Local runoff is computed by a mass balance among measured inflows, outflows, and changes in reservoir storage (which is a function of headwater elevation). The computation works well under flat pool conditions. For a reservoir with great length, the flat pool assumption may sometimes produce a negative local runoff. This negative local runoff can normally be minimized by applying a running average scheme which computes average local runoff over a longer period than 12-hrs (for example, 3 or 5 days). Since a negative local runoff is physically impossible, it is treated as zero in water quality computations. If the nutrient concentration of local runoff is greater than that in the river, a large negative local runoff could result in an underestimated river concentration (i.e., excluding what should have been included). The opposite is true if the local runoff concentration is less than that in the river. Since mass balance will balance the negative local runoff over time, its effects on river concentration are temporary and will not alter the seasonal concentration pattern significantly.

Inflow Water Quality

For a weakly stratified reservoir with a relatively short residence time, like Wheeler Reservoir, inflow water quality usually plays an important role on water quality in the reservoir. For both 1988 and 1991, release temperatures and DO concentrations at Guntersville Dam were measured approximately weekly. Daily measurement of turbidity, pH, and alkalinity were available at Huntsville Utilities Water Treatment Plant, which obtains its water from the Tennessee River (TRM 319.4 and 334.2). Other water quality parameters (ammonia, nitrate, phosphorus, BOD_5, organic nitrogen, and organic carbon) in Guntersville release were monitored on a weekly basis in 1991. In 1988, there was no measurement of these water quality parameters; instead, a constant seasonal average concentration based on 1991 measurements was calculated for each parameter. Using a constant concentration has the advantage of reducing model uncertainties introduced by that parameter. Inflow detritus and dissolved organics were assumed to contribute equally to the ultimate BOD, which was assumed to be twice the measured

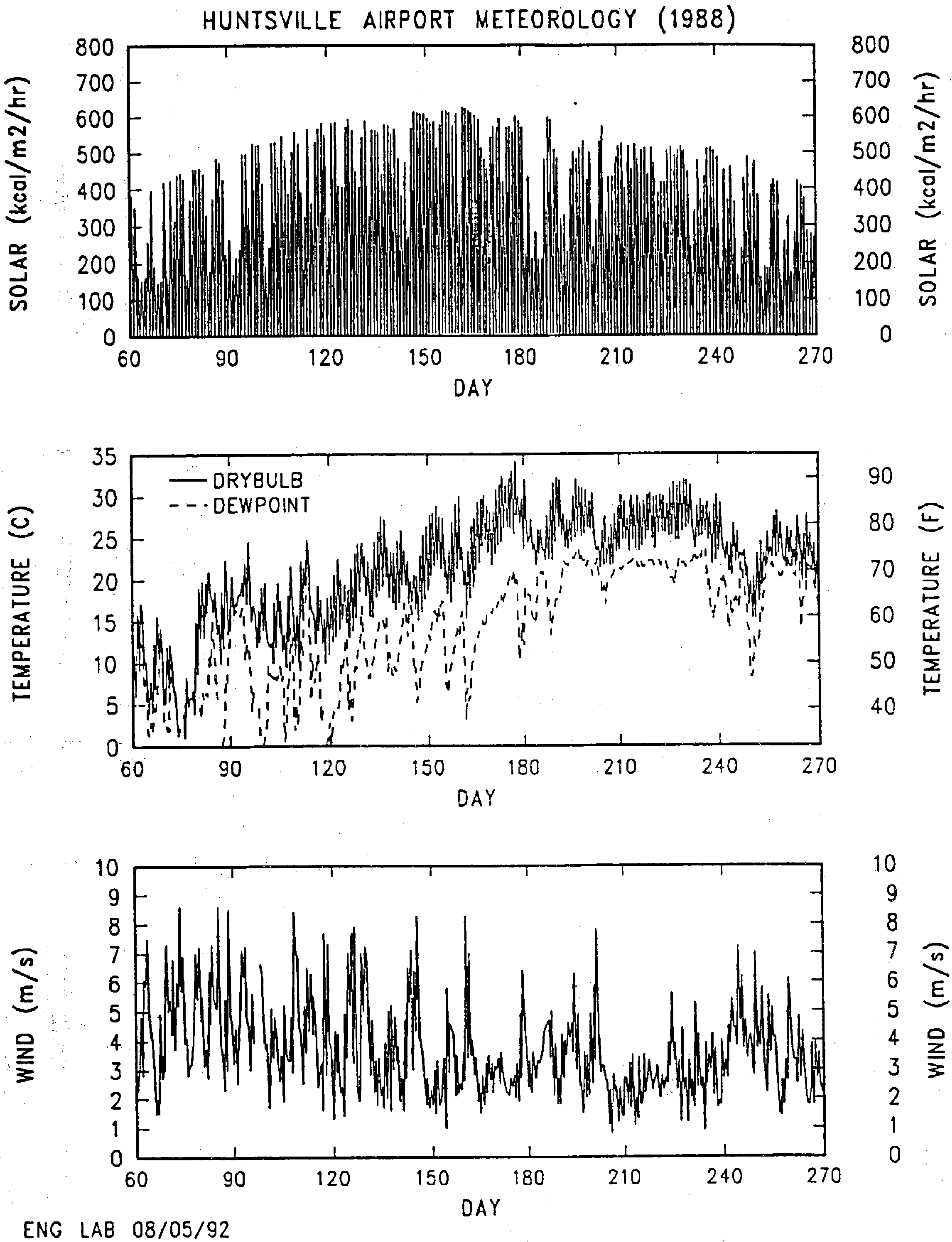


Figure 3. 1988 Huntsville Airport Meteorological Data

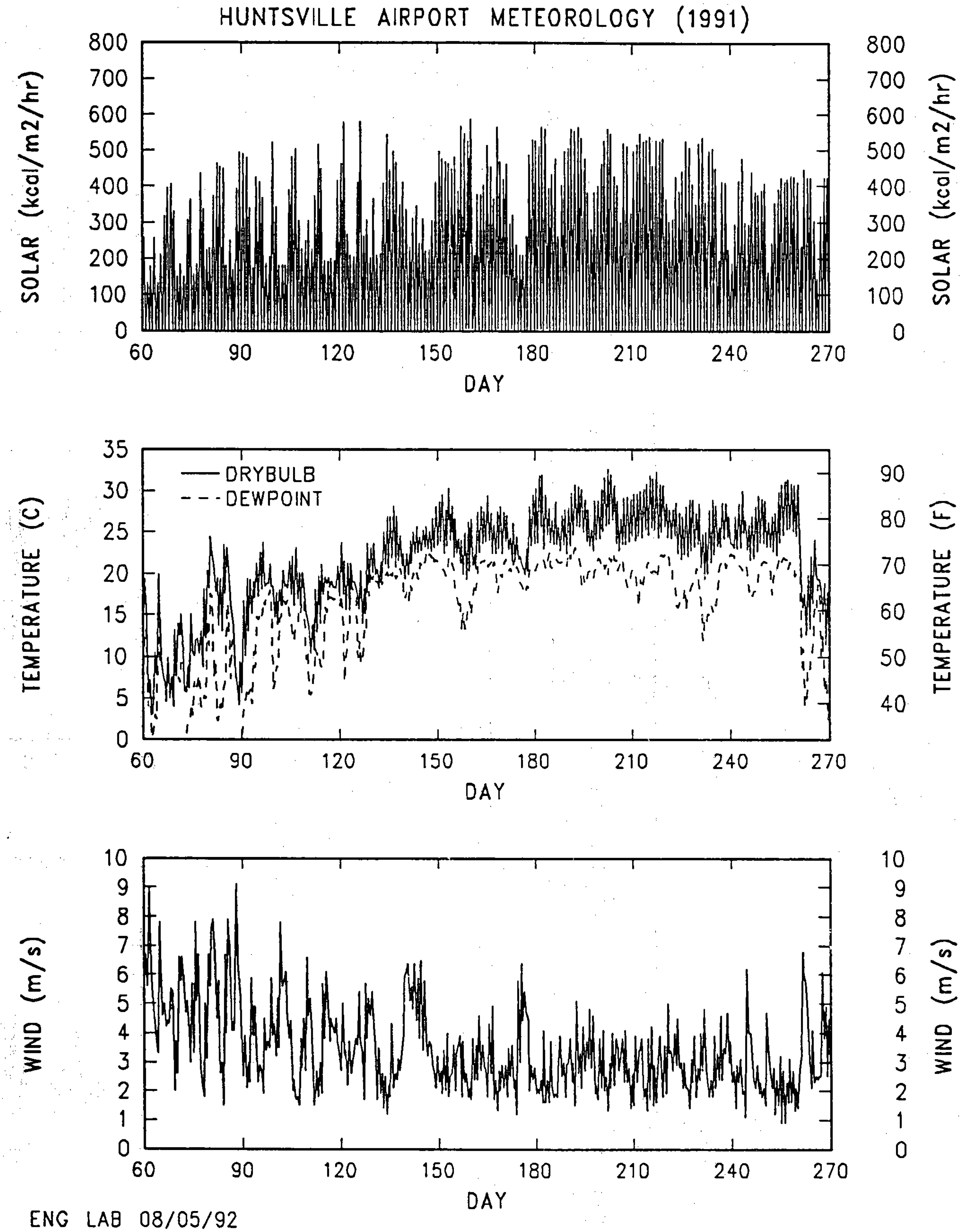


Figure 4. 1991 Huntsville Airport Meteorological Data

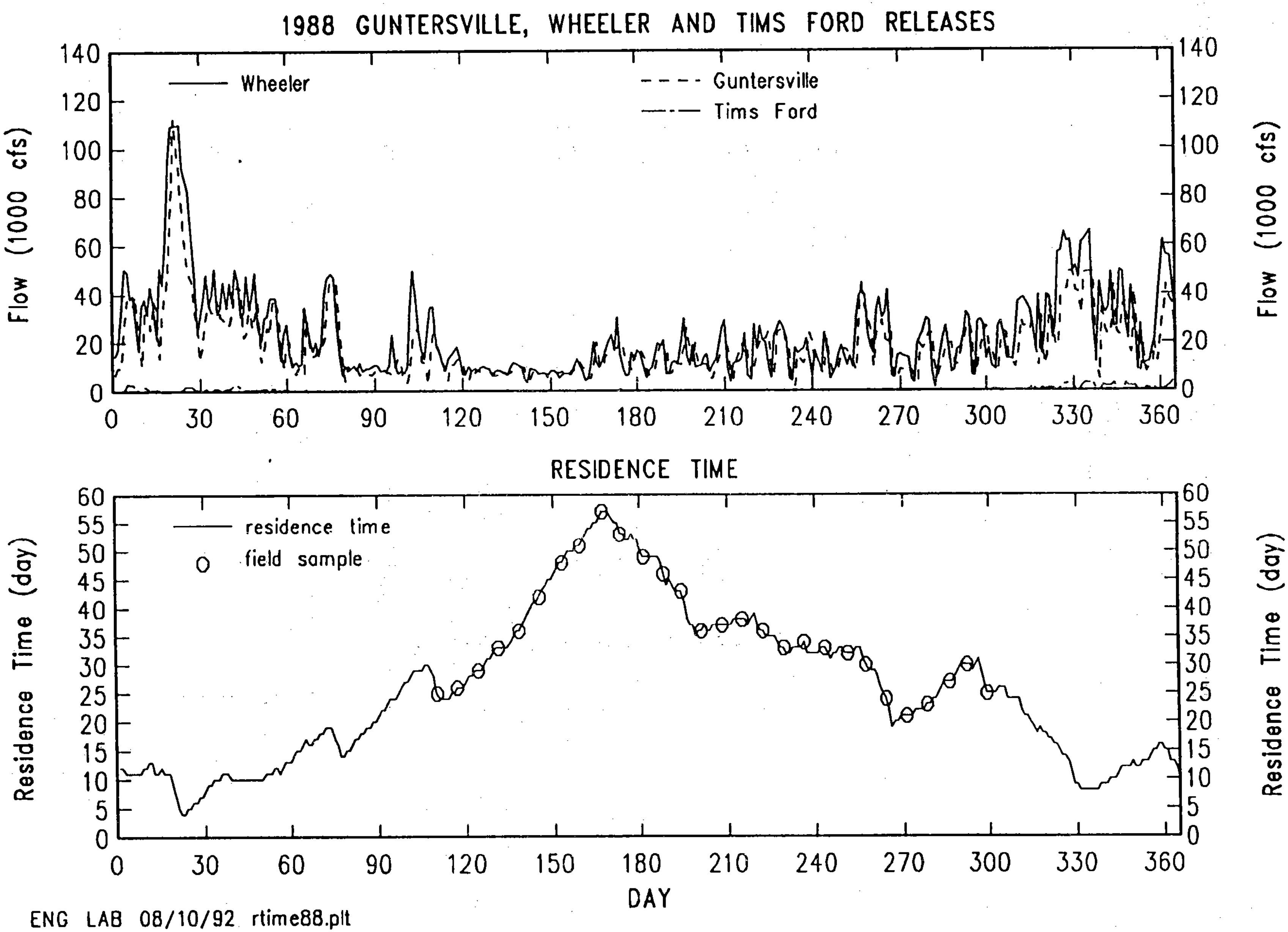


Figure 5. 1988 Wheeler, Guntersville, and Tims Ford Releases and Water Residence Time in Wheeler

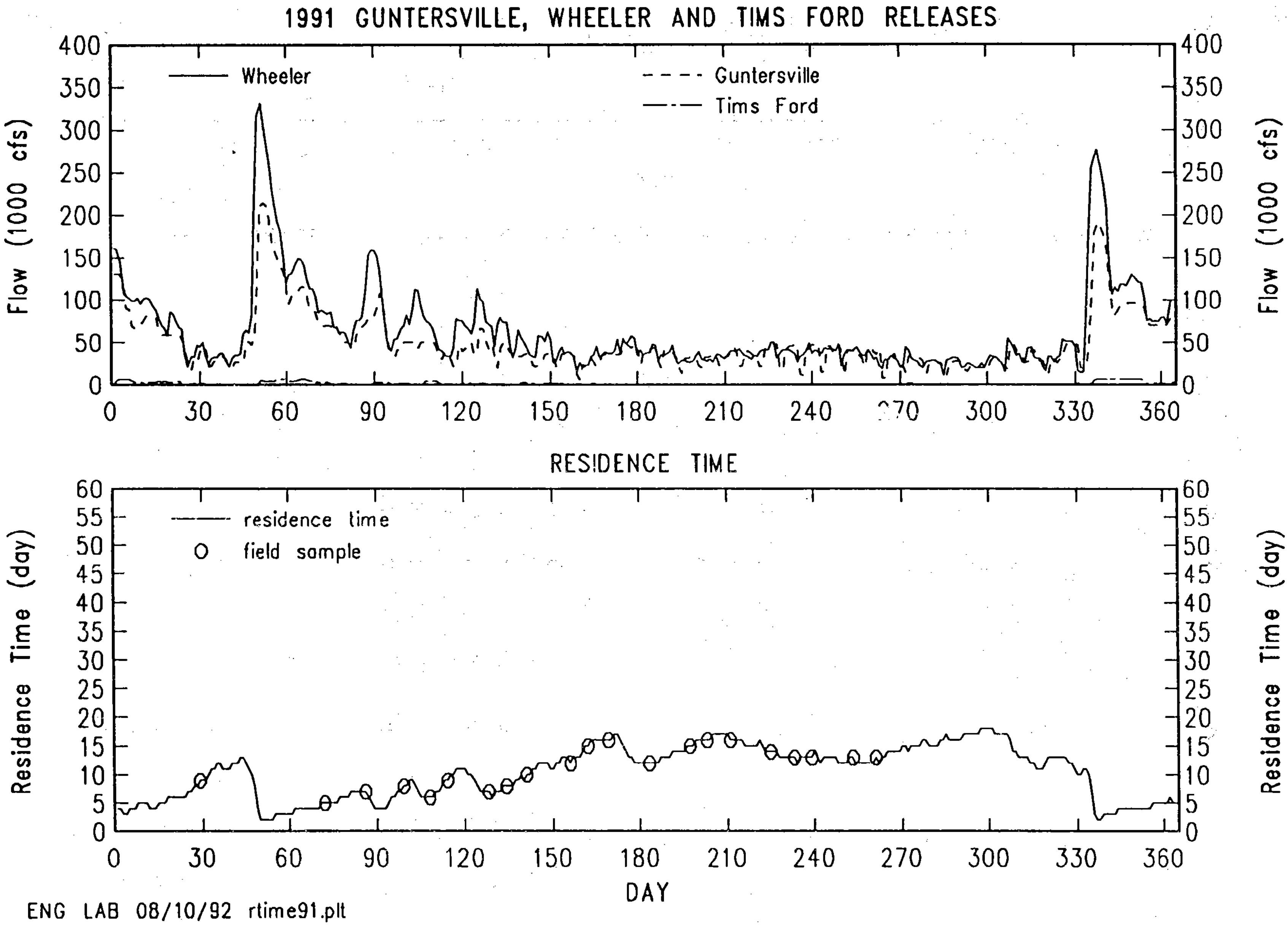


Figure 6. 1991 Wheeler, Guntersville, and Tims Ford Releases and Water Residence Time in Wheeler

BOD_5. Assuming a milligram of oxygen is consumed for each milligram of detritus or dissolved organics (Jorgensen, 1979; Bowie et al., 1985), dissolved organics and detritus are each equal to BOD_5. The inflow water quality for Wheeler Reservoir (Guntersville Dam release) is shown in Figures 7 and 8 for 1988 and 1991, respectively.

Inflow water quality for the Elk River Arm was derived the same way as Wheeler Reservoir, except that there were no measurements of inflow water quality in 1988. In 1991, the Elk River inflow water quality was measured at weekly intervals at ERM 30.4. Daily measurement of turbidity, pH, and alkalinity were obtained from Athens Water Treatment Plant (ERM 22.9). In 1988, the Elk inflow temperature was estimated as the average of dry bulb and dewpoint temperatures, and inflow DO was assumed to be at saturation. Constant average concentrations for other water quality parameters were determined using the 1991 survey data. The inflow water quality for the Elk River is also shown in Figures 7 and 9 for 1988 and 1991, respectively.

There were no water quality surveys for Flint Creek in either year. For both 1988 and 1991, the inflow temperature was estimated as the average of dry bulb and dewpoint temperatures, and inflow DO was assumed to be at saturation. Daily measurements of turbidity, pH, and alkalinity were acquired from Hartselle Water Treatment Plant (FCM 11.9). Constant average concentrations for other water quality parameters were estimated based on historical survey data. The inflow water quality for Flint Creek is shown in Figures 8 and 10 for 1988 and 1991, respectively.

As described before, a daily local runoff is computed by a mass balance among measured inflows, outflow, and change in reservoir storage (which is a function of headwater elevation). This daily runoff is distributed longitudinally to the surface layer of appropriate segments of Wheeler Reservoir and the Elk River Arm in proportion to drainage area. Inflow temperature for local runoff was assessed as the average of dry bulb and dewpoint temperatures, and inflow DO was assumed to be at saturation. Daily values of turbidity, pH, and alkalinity were obtained from Hartselle Water Treatment Plant. Constant average concentrations for other water quality parameters were estimated based on historical survey data. The inflow water quality for local runoff is shown in Figures 8 and 10 for 1988 and 1991, respectively.

Point Source Waste Discharges

Major industrial and municipal waste discharges in Wheeler Reservoir were grouped into four point source (PS) discharges. They are: (1) Huntsville waste discharge, near TRM 334; (2) Decatur/Athens waste discharge near TRM 303; (3) Browns Ferry Nuclear Plant thermal discharge, TRM 293.6; and (4) Champion Paper waste discharge, TRM 282.3. Average daily flow, BOD_5, ammonia, and total suspended solids (TSS) loadings for these point sources were estimated using flow and nutrient loadings reported in Discharge Monitoring Reports (DMR) provided by ADEM and are summarized in Tables 2 and 3 for 1988 and 1991, respectively. For Huntsville and Decatur/Athens, a set of average nutrient concentrations were computed based on these nutrient loadings and were used for the 1988 and 1991 model simulations. These nutrient concentrations are presented in Table 4. Since BOD_5 is derived

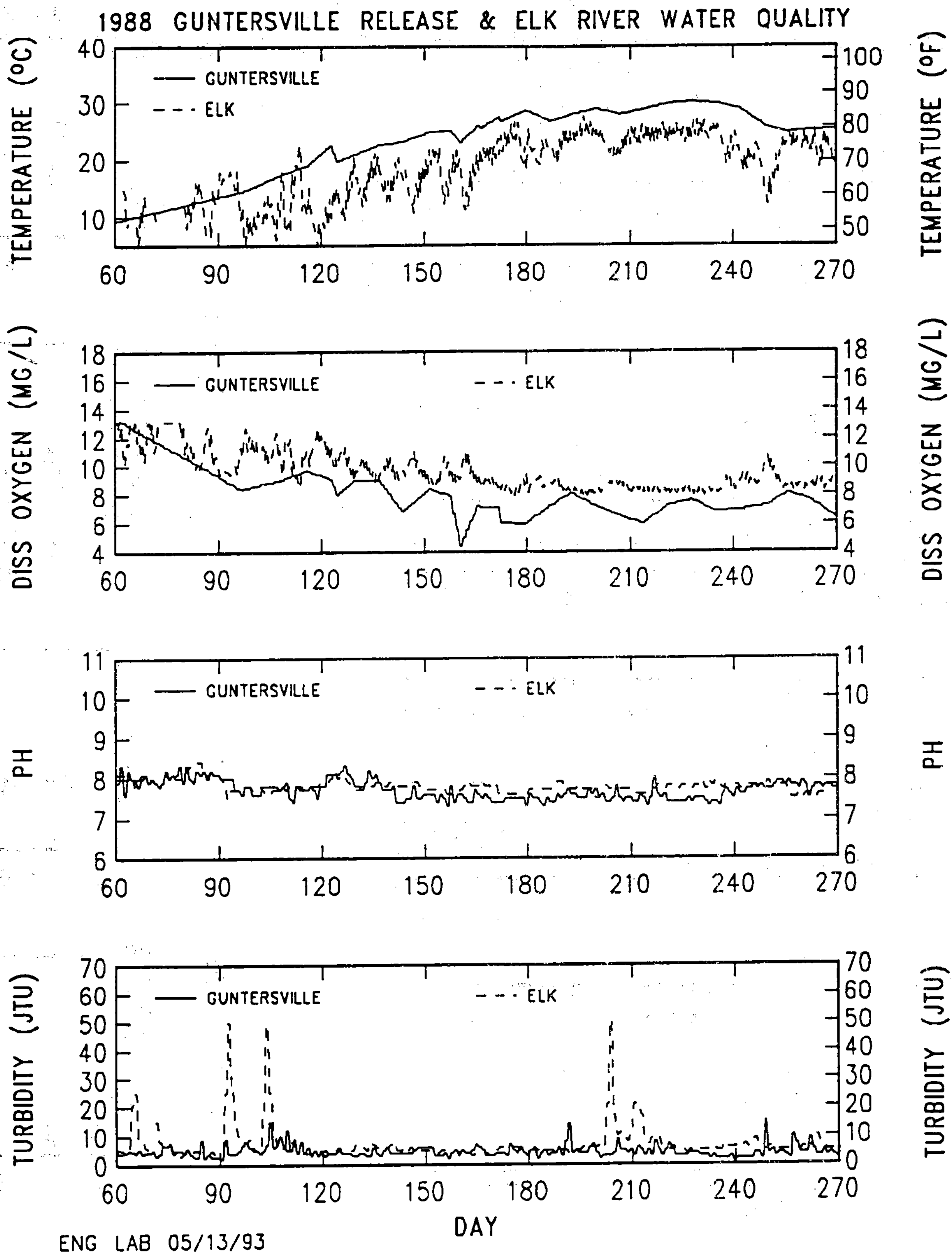


Figure 7. 1988 Guntersville Release and Elk River Inflow Water Quality

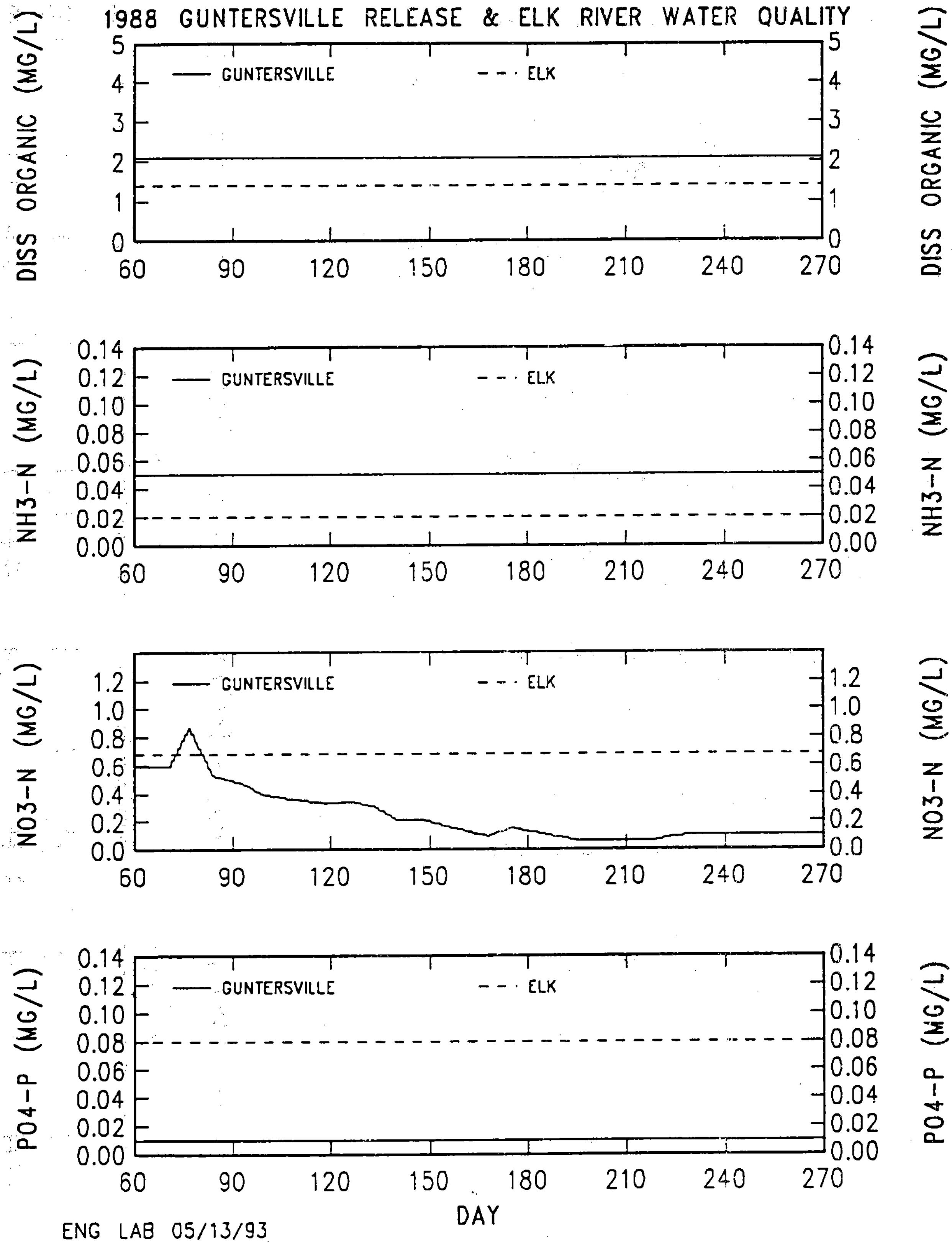


Figure 7. (continued)

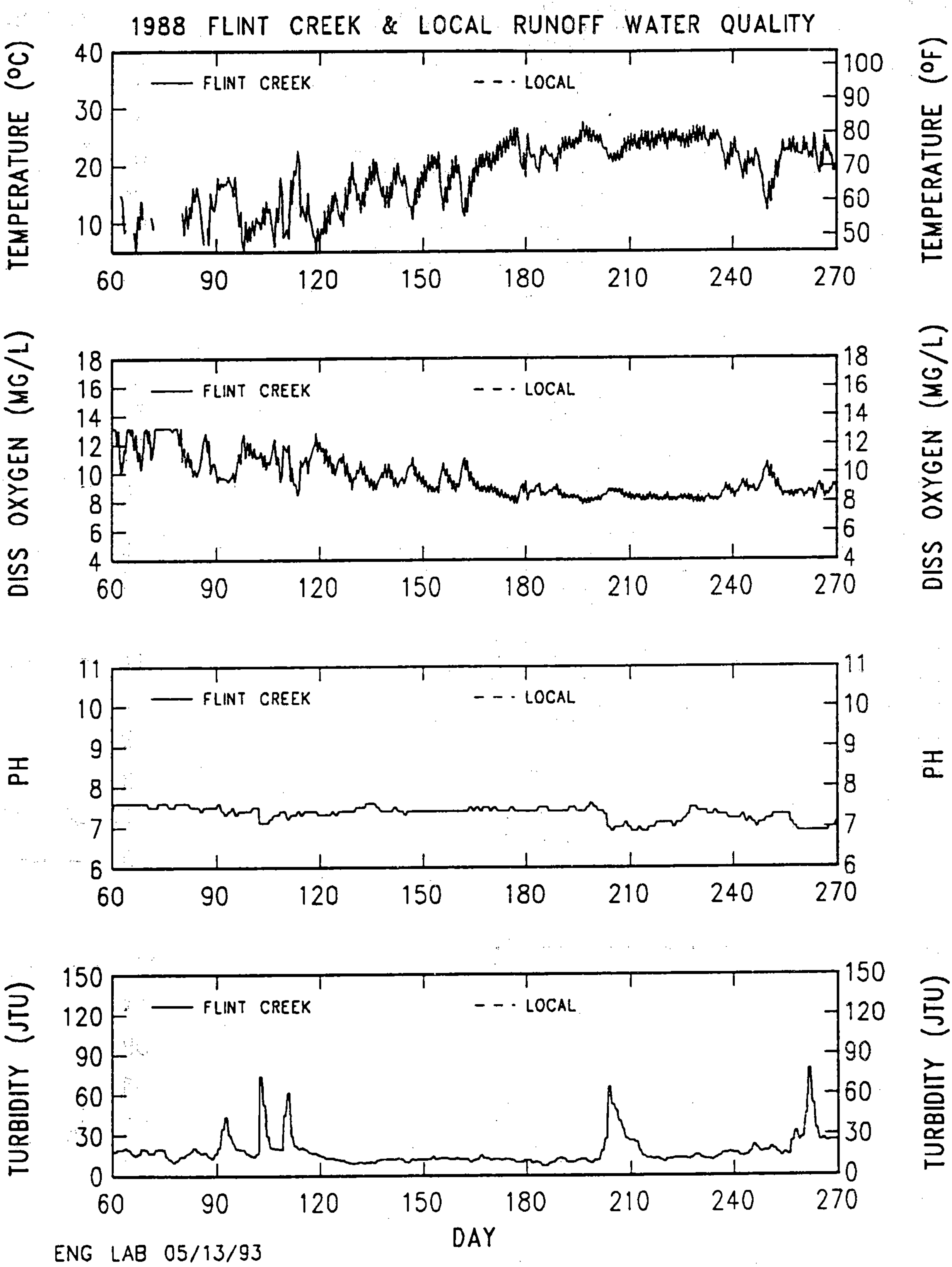


Figure 8. 1988 Flint Creek Inflow and Local Runoff Water Quality

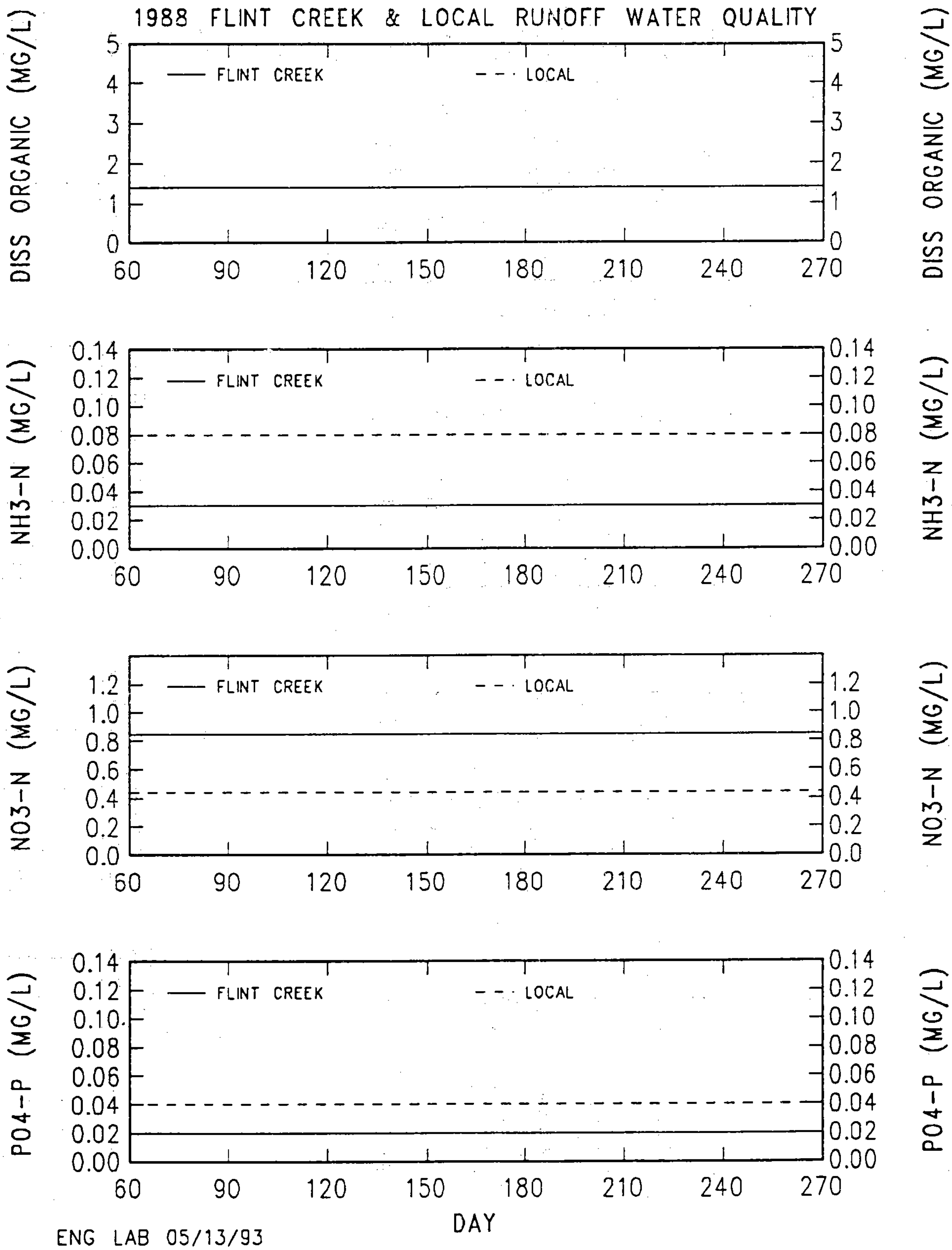


Figure 8. (continued)

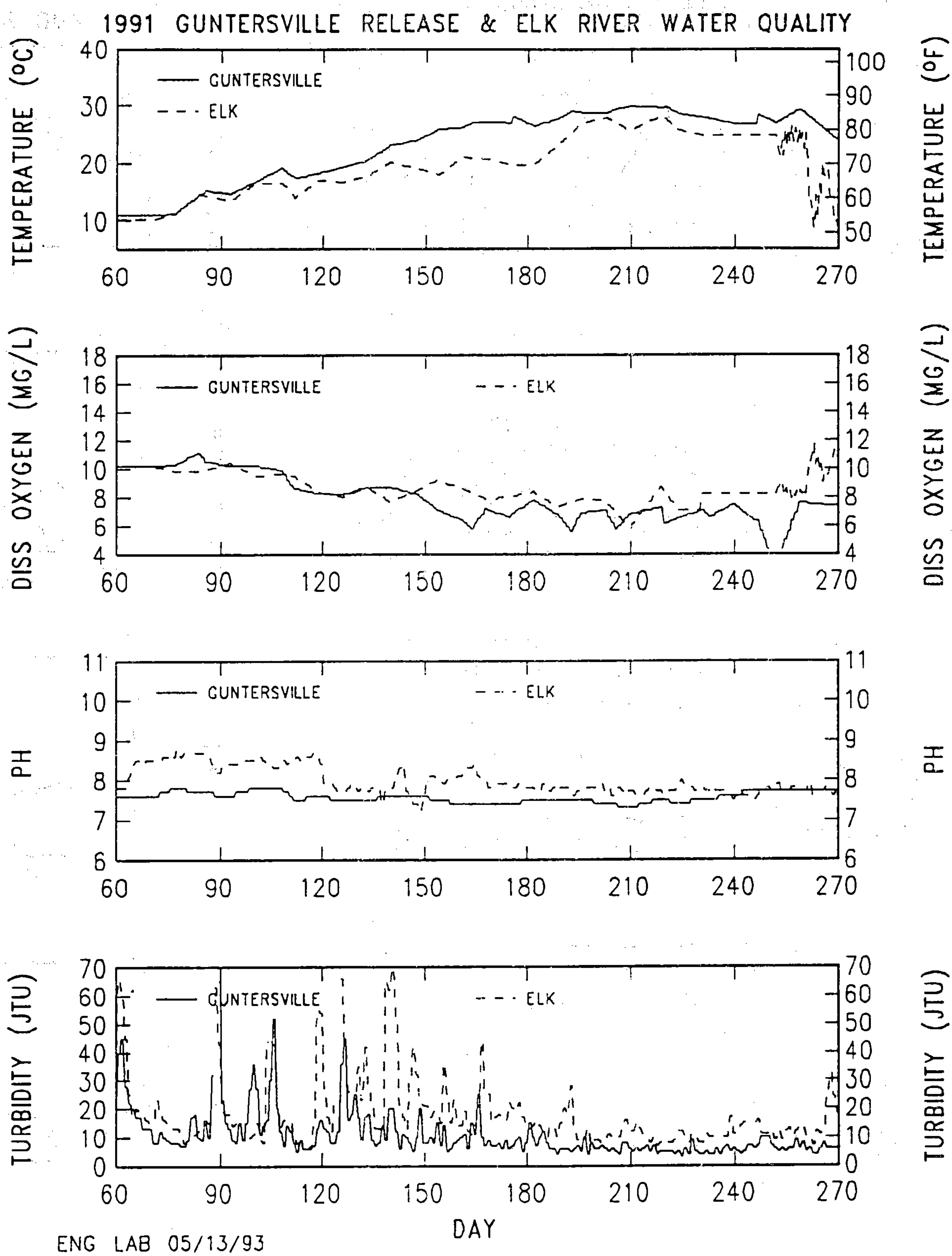
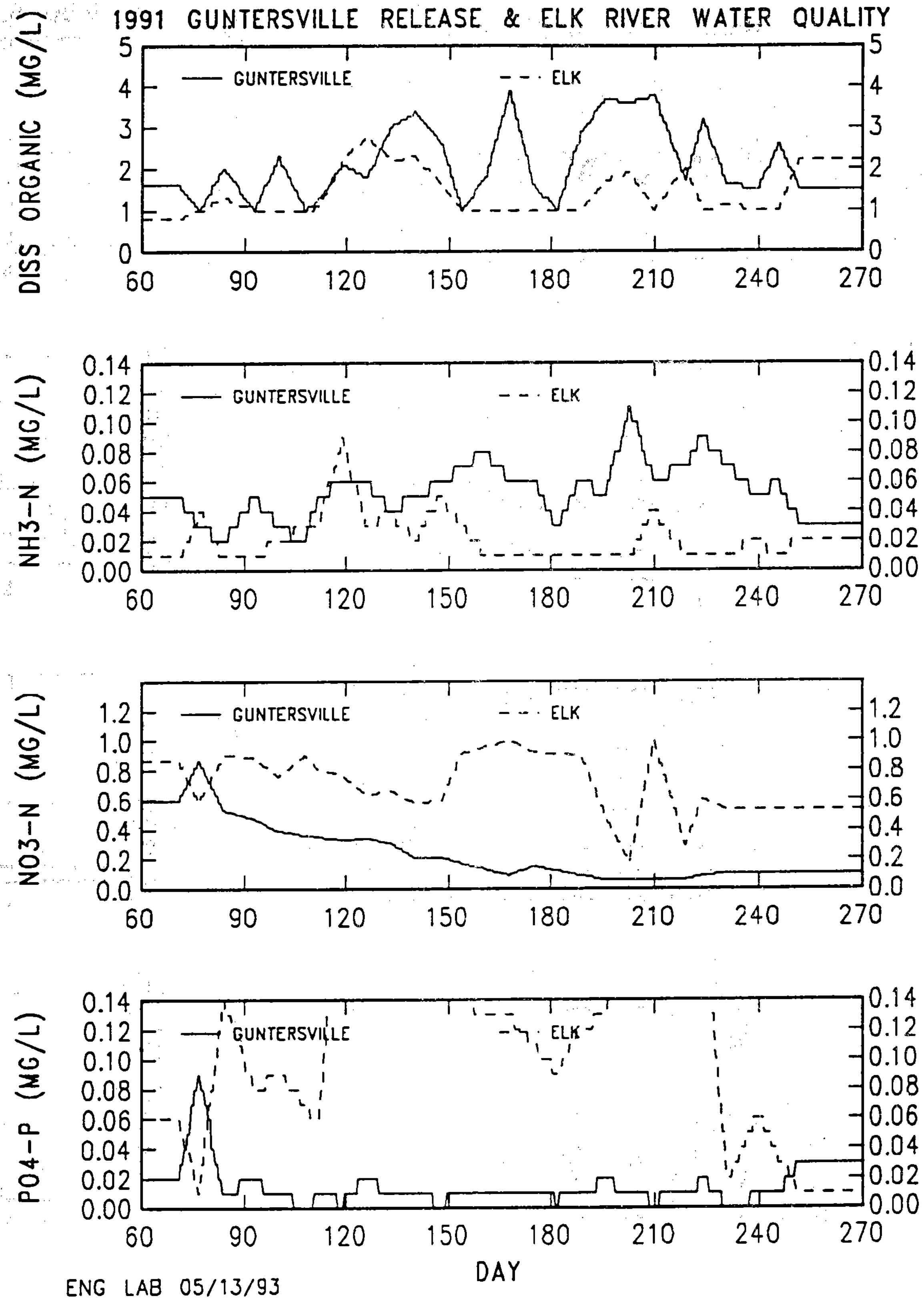


Figure 9. 1991 Guntersville Release and Elk River Inflow Water Quality



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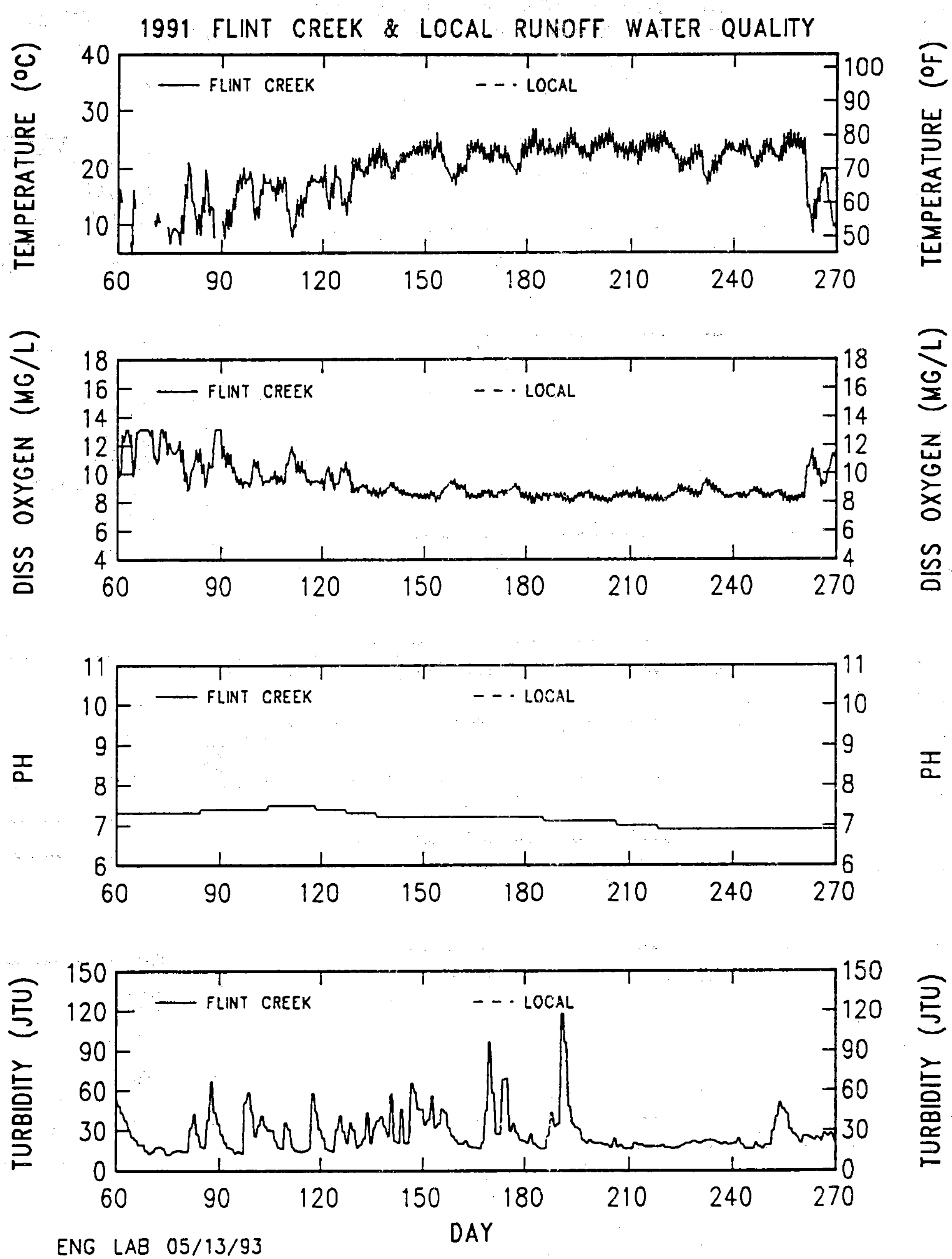

Figure 10. 1991 Flint Creek Inflow and Local Runoff Water Quality

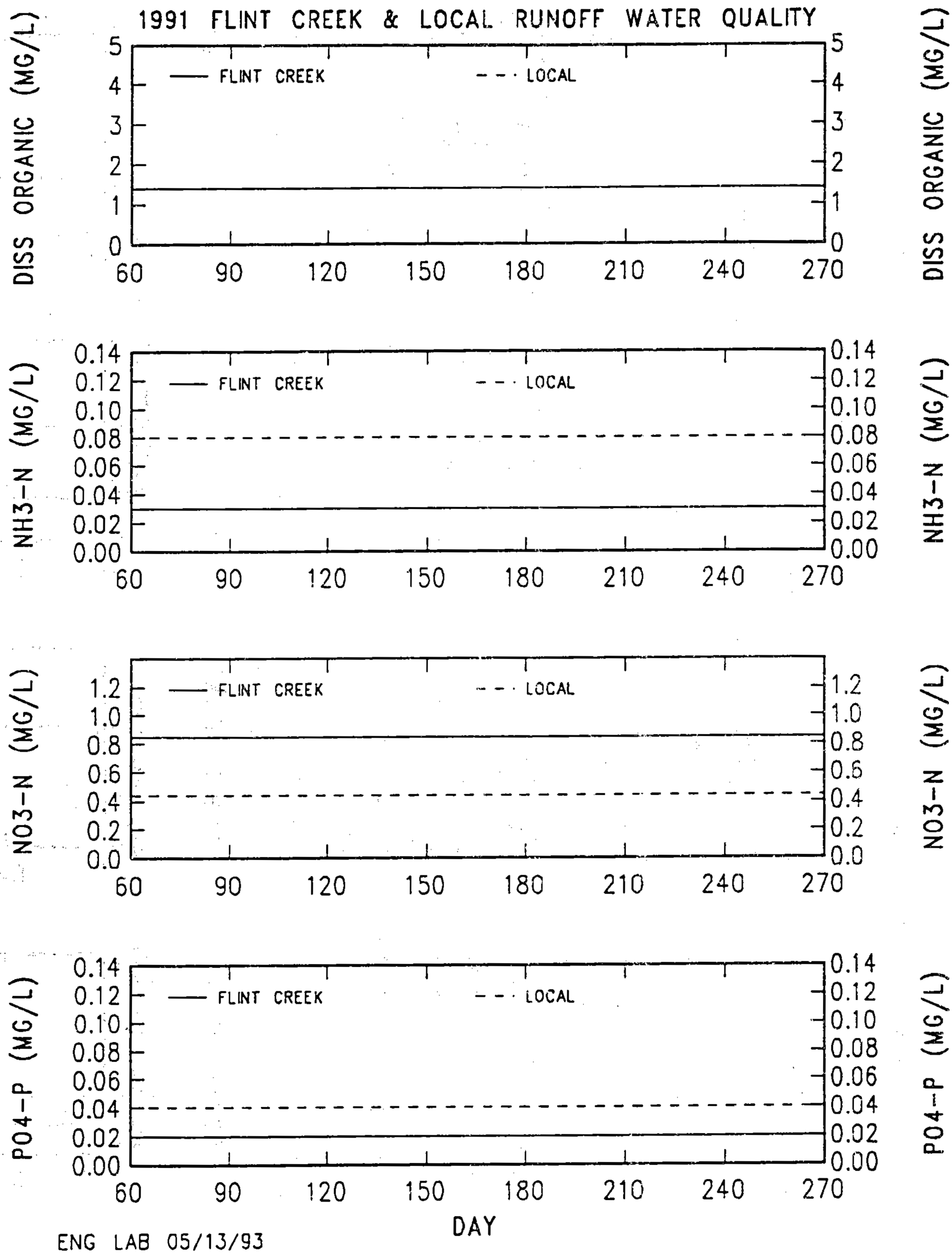

Figure 10. (continued)

TABLE 2

Summary of Wheeler Reservoir Municipal and Industrial Wastewater Discharge Loadings for 1988

1. Huntsville (Near TRM 334):

Municipal/Industrial	Flow (Mg/d)	BOD_5 (ppd)	NH_3-N (ppd)	TSS (ppd)
Spring Branch 1 & 1A	22.6	2313	4326	7157
Aldridge Cr.	5.4	631	432	621
West Area	2.8	92	99	185
Redstone Arsenal	2.1	217	86	181
Total	32.9	3253	4943	8144

2. Decatur/Athens (Near TRM 303):

Municipal/Industrial	Flow (Mg/d)	BOD_5 (ppd)	NH_3-N (ppd)	TSS (ppd)
Decatur Dry Creek	16.4	1703	13	1642
Moulton	0.4	34	2	563
Athens	4.1	719	647	638
Monsanto Co.	2.5	387	3526	1071
American Fructose	1.6	1497	14^+	5213
Amoco Chemical	1.3	864	119^+	723
3M	1.7	164	178^+	1500
Total	28.0	5368	4499	8507

3. Browns Ferry Nuclear Plant (TRM 293.6):

Cooling Water Intake (639.1 Mg/d)
Did not operate during 1988

4. Champion Paper Company (TRM 282.3):

Industrial	Flow (Mg/d)	BOD_5 (ppd)	NH_3-N (ppd)	TSS (ppd)
Champion Paper Co.	55.4	14125	3204	18136

$^+$No data for the year. 1991 data were used.

TABLE 3

Summary of Wheeler Reservoir Municipal and Industrial Wastewater Discharge Loadings for 1991

1. Huntsville (Near TRM 334):

Municipal/Industrial	Flow (Mg/d)	BOD_5 (ppd)	NH_3-N (ppd)	TSS (ppd)
Spring Branch 1 & 1A	36.9	3081	2168	7157
Aldridge Cr.	6.0	437	40	621
West Area	27.1	164	197	542
Big Cove	0.023	1.3	0.04	1
Redstone Arsenal	2.5	257	63	260
Total	52.5	3940	2468	8581

2. Decatur/Athens (Near TRM 303):

Municipal/Industrial	Flow (Mg/d)	BOD_5 (ppd)	NH_3-N (ppd)	TSS (ppd)
Decatur Dry Creek	20.1	1983	0	2519
Moulton	1.1	104	8	67
Athens	6.9	148	68	180
Monsanto Co.	2.3	295	3526	1123
American Fructose	1.7	1926	14	6039
Amoco Chemical	2.1	277	119	398
3M	3.8	149	178	248
Total	38.0	4882	3913	10574

3. Browns Ferry Nuclear Plant (TRM 293.6):

Cooling Water Intake (639.1 Mg/d)

4. Champion Paper Company (TRM 282.3):

Industrial	Flow (Mg/d)	BOD_5 (ppd)	NH_3-N (ppd)	TSS (ppd)
Champion Paper Co.	57.8	12458	2711	11924

TABLE 4

Point Source Nutrient Concentrations for 1988 and 1991

	Huntsville	Decatur/Athens	Champion Paper Co.
1988			
flow (cfs)	50.91	43.33	DMR+
NH_3-N (mg/L)	18.01	19.26	DMR+
NO_3-N (mg/L)	2.43	5.43	0.73
PO_4-P (mg/L)	2.81	3.96	1.14
detritus (mg/L)	11.85	22.98	0.0
diss. organics (mg/L)	11.85	22.98	3*BOD_5
turbidity/suspended solids (mg/L)	29.70	44.40	DMR+
1991			
flow (cfs)	81.24	58.80	DMR+
NH_3-N (mg/L)	5.64	12.34	DMR+
NO_3-N (mg/L)	2.67	4.50	0.73
PO_4-P (mg/L)	2.89	3.93	1.14
detritus (mg/L)	8.99	15.40	0.0
diss. organics (mg/L)	8.99	15.40	3*BOD_5
turbidity/suspended solids (mg/L)	19.60	33.40	DMR+

+Discharge concentration obtained from daily monitoring reports from both dissolved organics and detritus, each are set equal to the estimated BOD_5. For Champion Paper waste discharge, the main interest is in its effects on reservoir DO. For that reason, the actual waste flow, BOD_5, ammonia, and turbidity reported in DMR were used. Due to its high organic content, the entire wasteload of Champion Paper is assumed to be dissolved organics and is set to be three times measured BOD_5. For nitrate and dissolved phosphorus, seasonal average concentrations were used.

A mass balance summary of 1988 (dry year) and 1991 (wet year) loading contributions from all major inflows and point source waste discharges is presented in Table 5. For both years, more than 75 percent of the total BOD load was contributed by Guntersville releases. In 1988, local runoff was low and BOD contributions from point sources represented a larger portion of the load. The opposite is true in 1991, when local runoff was the bigger contributor. For inorganic nitrogen, Guntersville releases again were the leading contributor representing about 50 percent of the total load. The second largest contributor of inorganic nitrogen was point sources (27 percent) in 1988 and local runoff (31 percent) in 1991. Phosphorus concentrations in reservoir releases are normally low. Even in 1991, contribution from Guntersville releases were only about 40 percent of the total phosphorus load while point sources represented almost 31 percent of the total. In 1988, the point source contribution jumped to more than 56 percent due to lower releases at Guntersville Dam. For suspended solids, the two biggest contributors are Guntersville releases and local runoff. Contributions of suspended solids from point sources are insignificantly small.

The BFN thermal discharge is simulated with a two-dimensional diffuser mixing model which determines entrainment of ambient water along the path of the buoyant plume and distributes loadings of water quality constituents into appropriate volume elements of the reservoir water quality model. Only far-field plant effects (beyond the mixing zone) are simulated because the diffuser mixing zone is smaller than the limit of resolution of the water quality model and its simplified hydrodynamic formulations. It should be pointed out that because the element is fully mixed, the actual heating below the mixing zone may be higher than that computed by the model. The decrease in DO in BFN condenser cooling water due to temperature increase is fairly small (<0.5 mg/L) and highly sporadic. In light of all the uncertainties and simplifications in model processes and in inflow loadings, this small decrease in BFN discharge DO will have little effect on model results. For model calibration, the DO concentration in the discharge was assumed to be equal to the concentration at the BFN intake.

V. MODEL CALIBRATION

All models must be compared to field data to provide real confidence in model results. Calibration must be based on intuition about existing model algorithms (that strive to reproduce reality) rather than intuition about the many processes occurring in reality. Knowledge of reality can reveal a need for additional model algorithms, but calibration itself must be performed based on a thorough knowledge of the algorithms that exist in the model at the time of calibration.

TABLE 5

1988 and 1991 Basecase Loadings (March-September)

	7-Month Average Flow (cfs)					
Year	Gunt Dam*	Elk R	Flint Ck	Local	PS+	All
1988	13184	939	244	1308	151	15826
1988	83.3%	5.9%	1.5%	8.3%	1.0%	100.0%
1991	42539	2148	946	9192	985	55811
1991	76.2%	3.8%	1.7%	16.5%	1.8%	100.0%
	BOD Ultimate (lb/7 months)					
Year	Gunt Dam*	Elk R	Flint Ck	Local	PS+	All
1988	61754532	3052483	759006	4922114	8453370	78941472
1988	78.2%	3.9%	1.0%	6.2%	10.7%	100.0%
1991	191114464	6512296	948061	31067474	8054375	239696624
1991	79.7%	2.7%	1.2%	13.0%	3.4%	100.0%
	Inorganic Nitrogen (lb/7 months)					
Year	Gunt Dam*	Elk R	Flint Ck	Local	PS+	All
1988	4549604	741381	144046	1538162	2522295	9505492
1988	47.9%	7.9%	1.5%	16.2%	26.5%	100.0%
1991	7311788	1862456	559485	9708583	1693362	31135680
1991	55.6%	6.0%	1.8%	31.2%	5.4%	100.0%
	Phosphorus (lb/7 months)					
Year	Gunt Dam*	Elk R	Flint Ck	Local	PS+	All
1988	194855	88585	11358	38674	430401	763873
1988	25.5%	11.6%	1.5%	5.1%	56.3%	100.0%
1991	797419	244903	44113	244103	603906	11934444
1991	41.2%	12.7%	2.3%	12.6%	31.2%	100.0%
	Turbidity or SS (tons/7 months)					
Year	Gunt Dam*	Elk R	Flint Ck	Local	PS+	All
1988	35425	7624	3603	23117	3263	73032
1988	48.5%	10.4%	4.9%	31.7%	4.5%	100.0%
1991	322221	28046	18560	178103	2786	549716
1991	58.6%	5.1%	3.4%	32.4%	0.5%	100.0%

*Guntersville Dam Release
+All Major Industrial and Municipal Waste Discharges

Because the wide field data interval can sometimes cause the field data to miss many of the important dynamics, statistical check for model performance is not used. Instead, model calibration was accomplished by visually comparing model results with field measurements. In this study, two years of field data, i.e., 1988 and 1991, were used. Hydrologically, 1988 was a severely dry year. As shown in Figure 5, the average daily release from Wheeler Reservoir was about 14,350 cfs for the spring and summer period while the historical median flow (1976-1991) was about 44,500 cfs for the same period. As part of a drought monitoring program, weekly temperature, DO, and pH profiles were measured in 1988 in the forebay of Wheeler Reservoir and near the mouth of the Elk River from April to October. These data allowed for a preliminary model calibration for reservoir temperature and DO. Emphasis was given to reproducing the reduced mixing and corresponding low DO in Wheeler Reservoir because of low flows and strong stratification.

Also shown in Figure 5 is hydraulic residence time, which approximates the duration that each parcel of water stays in the reservoir. It is computed as number of days that the accumulated reservoir inflows (backward from the current time) equals the current reservoir volume. Reservoir volume is estimated using the measured headwater elevation and known level storage relationships. In 1988, the computed water residence time varied from 15 to 20 days in early spring to about 55 to 60 days in early summer. Increases in water residence time are usually accompanied by reductions of DO in the hypolimnion of the reservoir.

An extensive water quality survey was conducted in 1991 (March to September) with biweekly Hydrolab profiles and nutrient samples taken at eight locations: TRM 277.0, TRM 281.0, TRM 291.8, TRM 300.3, TRM 317.0, TRM 330.3, ERM 2.7, and ERM 14.8. These data along with the hourly temperatures collected for temperature compliance of BFN at Stations 4 (TRM 297.8) and 17 (TRM 293.5) were used for final model calibration. Hydrologically, 1991 was a wet year with an average spring and summer flow of about 57,600 cfs (vs. historical median of 44,500 cfs). The 1991 Guntersville, Wheeler, and Tims Ford Dam releases and the computed water residence time are shown in Figure 6. Computed residence times on days that field surveys were conducted range from 5 to 20 days. This indicates that, for the most part, each new batch of water released from the upstream reservoir was sampled in a biweekly survey--meeting a criteria for designing field surveys in a reservoir with short water residence time.

Temperature Calibration

The main objective of temperature calibration was to reproduce observed seasonal temperature patterns in the reservoir under different hydrologic and meteorological conditions. Comparison with a few days of measured temperature does not guarantee that the overall seasonal patterns have been simulated properly, and can, sometimes, lead to erroneous conclusions. Results of temperature calibration are demonstrated with three types of plots: (1) time vs. depth temperature contour; (2) surface and bottom temperature time series at Stations 4 and 17; and (3) Wheeler Dam release temperatures.

Figure 11 compares 1991 simulated time-depth temperature contours (left-hand side) with measured data (right-hand side) at TRM 330.3, 317.0, 300.0, 291.8, 281.0, and 277.0 and ERM 30.4, 14.8, and 2.7. These stations represent conditions in upstream, middle, and downstream reservoir segments, as well as segments immediately upstream and downstream from BFN. The station at ERM 30.4 is outside the model domain of the Elk River arm which, as shown in Figure 1, terminates at ERM 22.4. Measured data at ERM 30.4 are used to formulate the Elk River inflow water quality shown at ERM 22.4. Note that measured data look smoother than modeled temperatures because field data are contoured based on a sparse time series. The observed pattern of longitudinal warming from upstream stations to downstream stations, and the development of a weakly stratified water body at the downstream stations were all adequately reproduced. The emergence of a cold bottom inflow in the forebay at the end of June was also reproduced. The computed surface temperature appeared consistently higher than the measured temperature in the summer period. However, a close examination of measured hourly temperatures at BFN Stations 4 and 17 (Figures 12 and 13) showed that surface and bottom temperatures were reproduced within 1°C over most of the year. Also the computed release temperature at Wheeler Dam presented in Figure 14 shows a close match with measured data.

As shown in Figure 11, summer stratification in the Elk River was slightly stronger than that in the Tennessee River primarily due to large cold releases at Tims Ford Dam during the second half of June. This inflow-induced stratification is reproduced by the model. In 1988, field temperatures were measured in the forebay of Wheeler Reservoir (TRM 275.1), near the mouth of the Elk River (ERM 2.7) and in the embayment of Spring Creek (SCM 1.5) which enters the Tennessee River at about TRM 283. As shown in Figure 15, observed stratification in the Tennessee River (TRM 275.1) was stronger than normal in 1988 due to low inflow in the late spring and early summer (right-hand side) and this effect was reproduced by the model (left-hand side). Stratification in the Elk River, however, was overestimated in the second half of the summer. In 1988, no inflow temperature was measured in the Elk River, therefore, inflow temperature was estimated using available meteorology. During the low flow summer months, inflow temperature probably was warmer than the estimated inflow temperature, which contributed to the late summer strong stratification in the model simulation. The model does not simulate water temperature in the Spring Creek Embayment. However, surface water temperature in the Tennessee River at Spring Creek Embayment is normally similar to that in the embayment. This is demonstrated in Figure 15 with the observed temperature in the Spring Creek Embayment on the right and the computed temperature in the main river on the left. The strong stratification observed in the embayment indicates that inflow during the summer period was small, resulting in a slow flushing of bottom cold water. As was the case in 1991, the observed release temperatures shown in Figure 16 were well reproduced, although not as well as 1991, due most likely to lack of inflow temperature data for 1988.

Dissolved Oxygen Calibration

The 1991 modeled time-depth DO contours (left-hand side) are compared with measured DO patterns (right-hand side) in Figure 17. Hydrologically, 1991 had an extremely wet spring and near average summer. Large spring flows curtailed algal blooms normally found in the early spring. Reservoir DO ranged from 6 to 10 mg/L with little DO stratification in this period. DO field measurements indicate that there was a weak algal bloom in mid-summer which is characterized by a patch of high surface DO extending from Wheeler Dam to about TRM 292 (approximately one-fourth of the reservoir length). This algal activity was only partially reproduced, primarily due to a short, intensive mixing induced by the large cold inflow

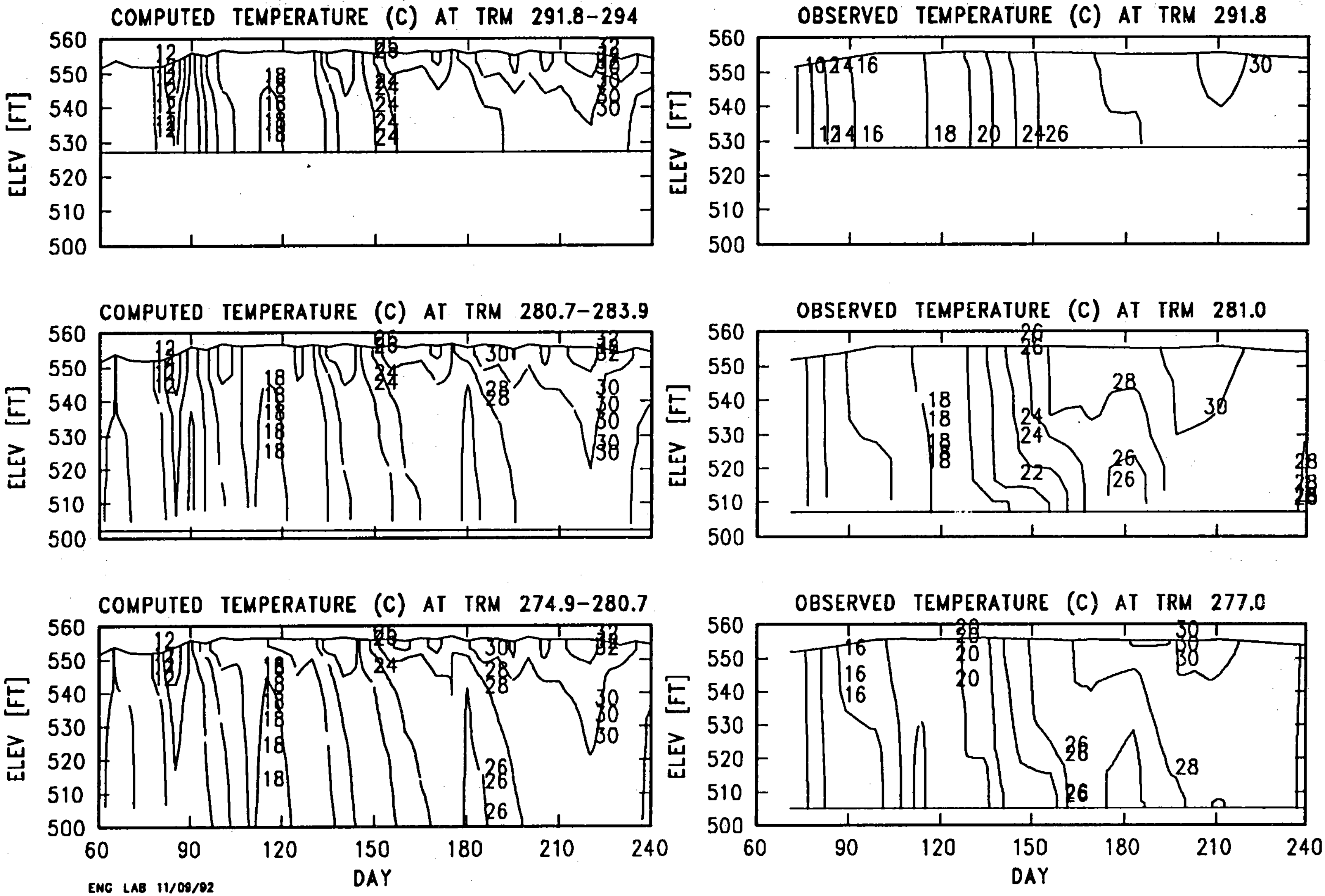

Figure 11. 1991 Computed (Left) and Observed (Right) Time-Depth Temperature Contours in Wheeler Reservoir

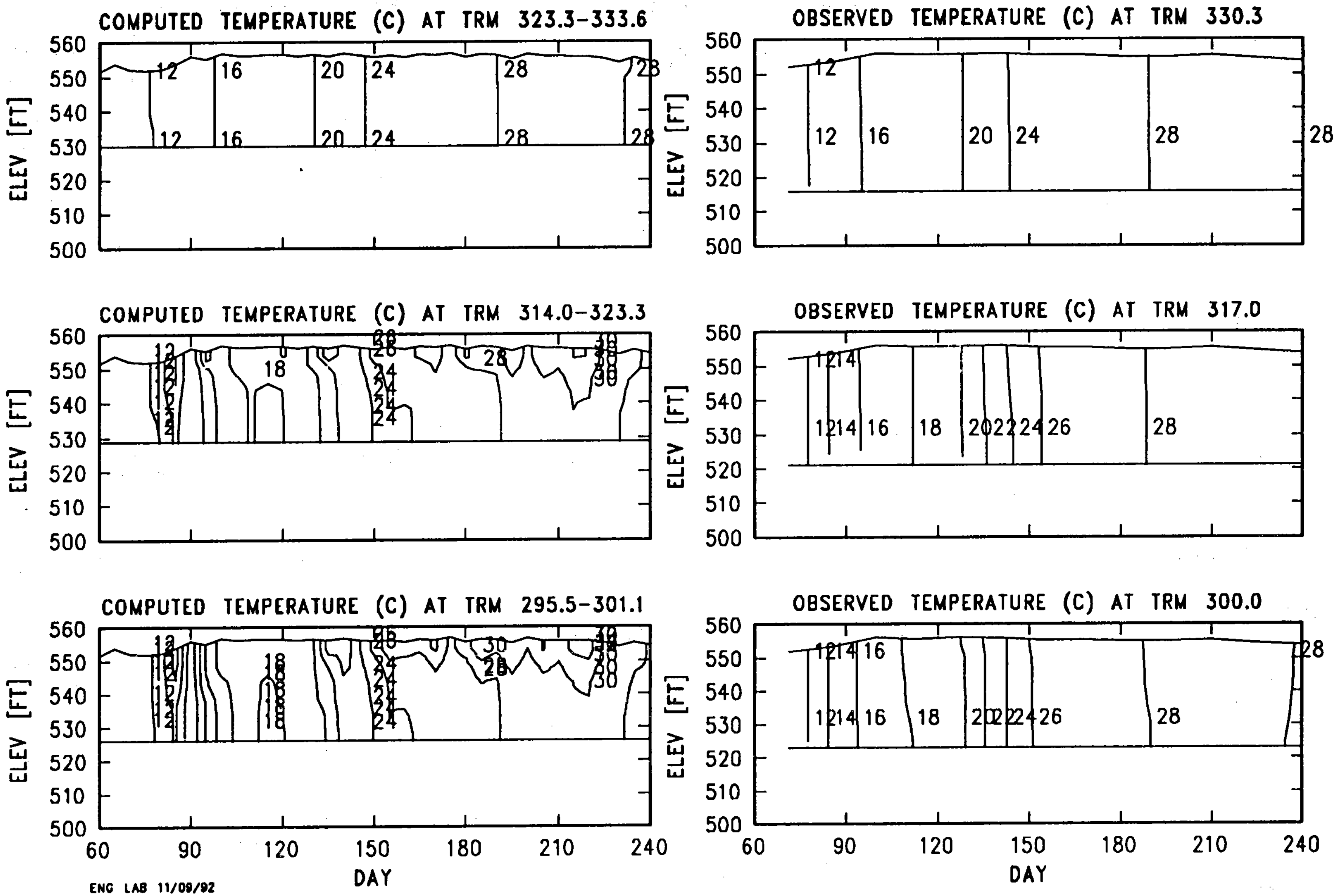

Figure 11. (continued)

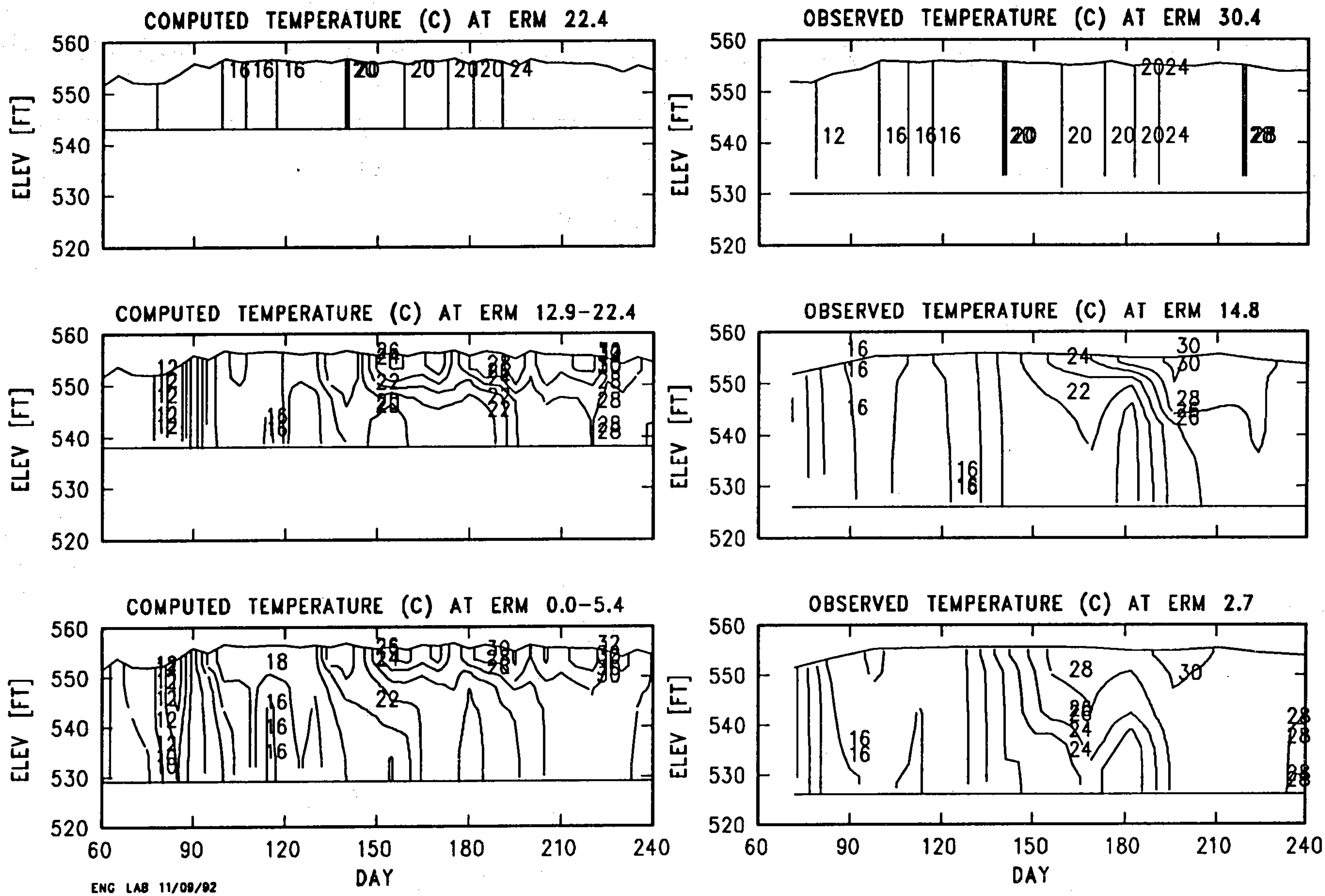

Figure 11. (continued)

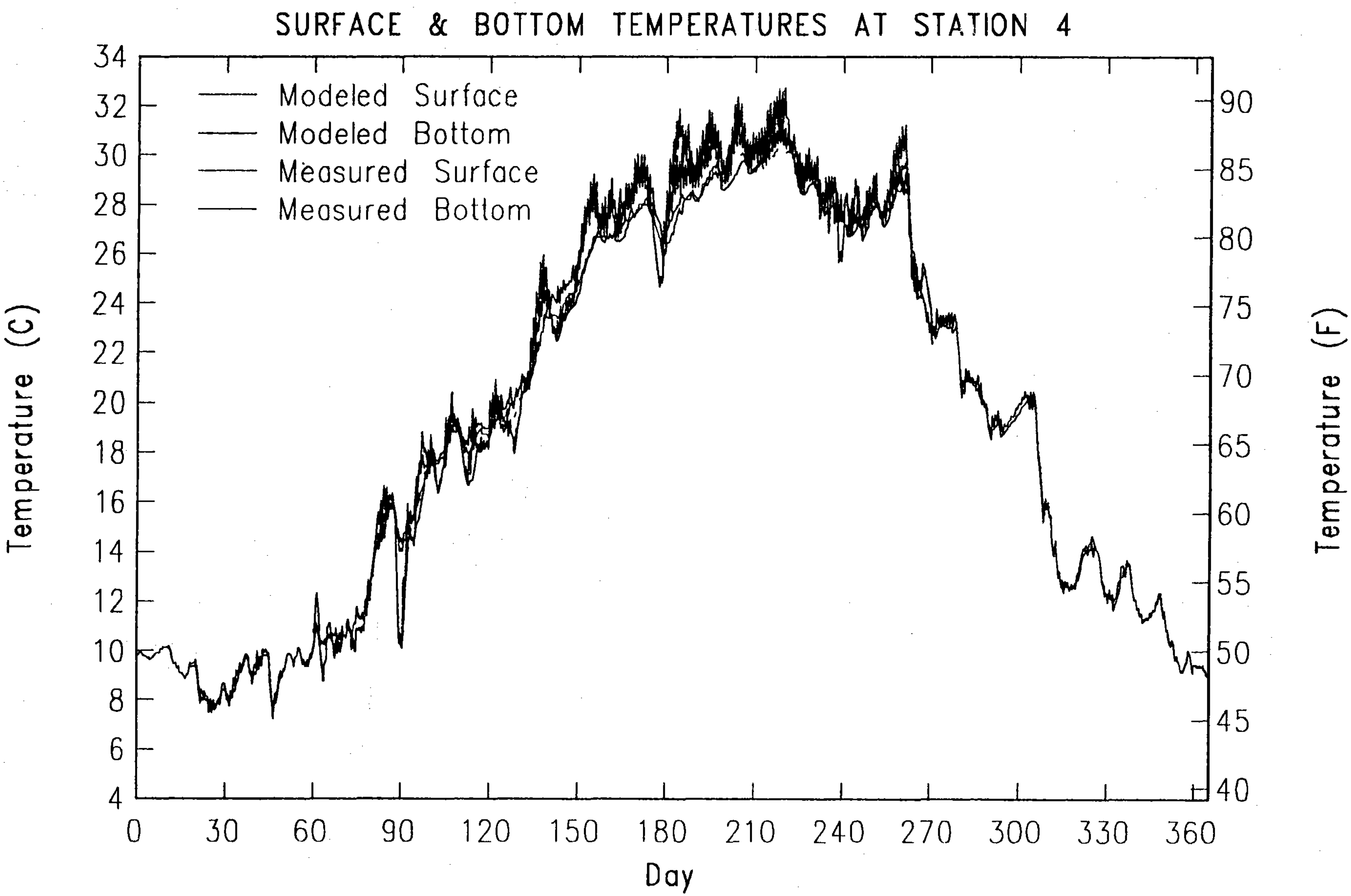

Figure 12. 1991 Computed and Observed Surface and Bottom Temperatures at Station 4 (TRM 297.8)

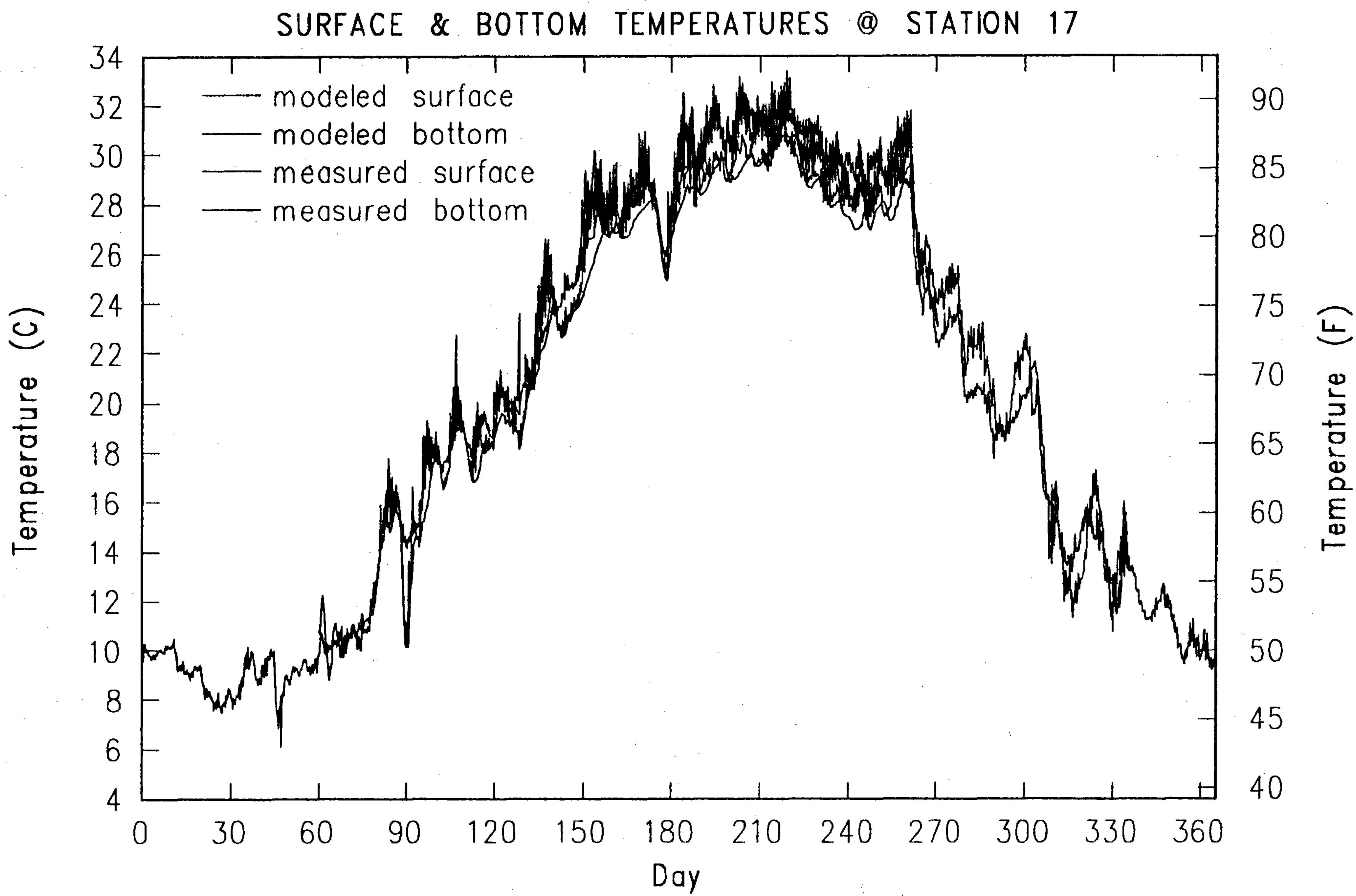

Figure 13. 1991 Computed and Observed Surface and Bottom Temperatures at Station 17 (TRM 293.5)

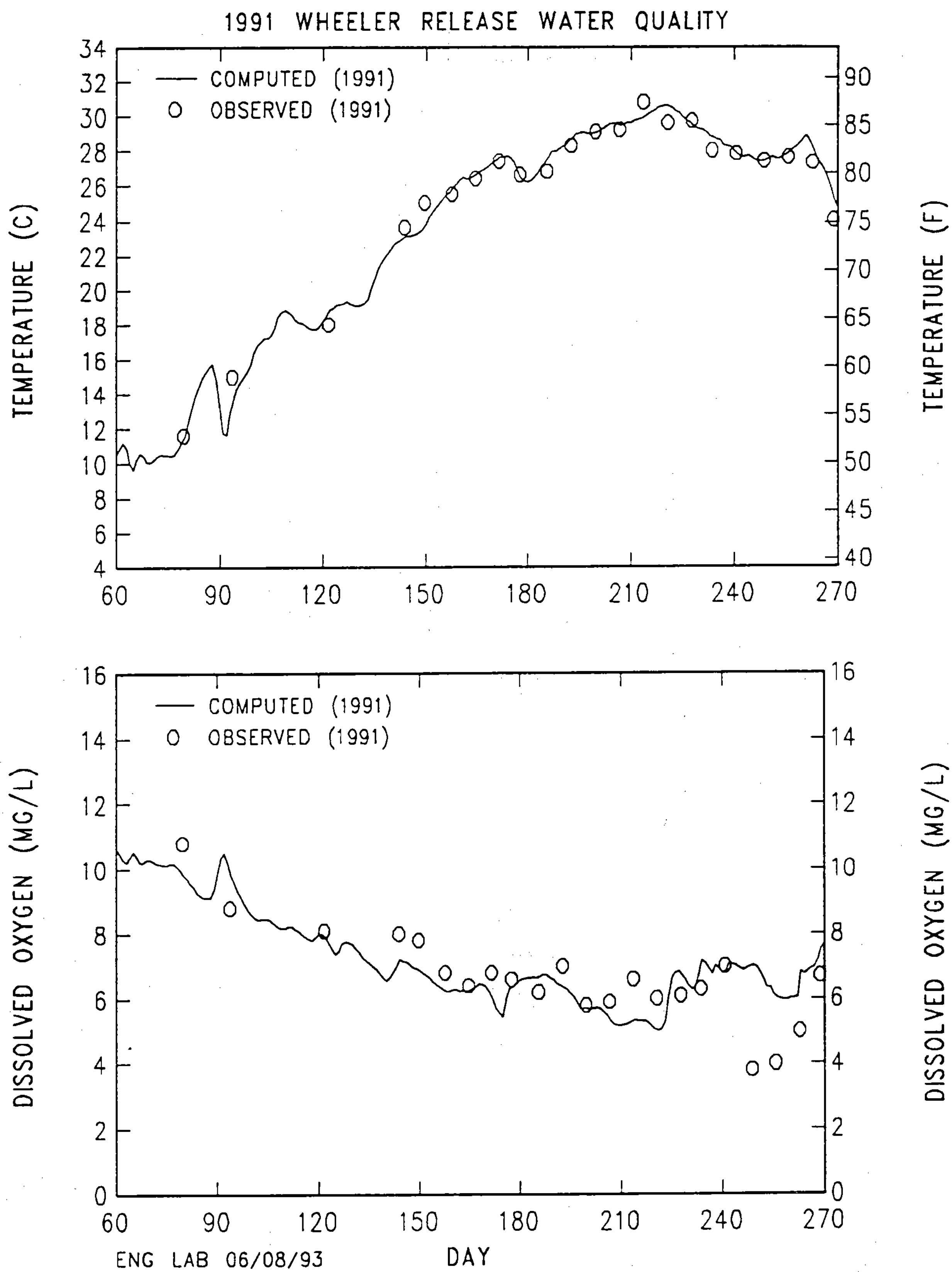

Figure 14. 1991 Computed and Observed Release Temperature and DO at Wheeler Reservoir

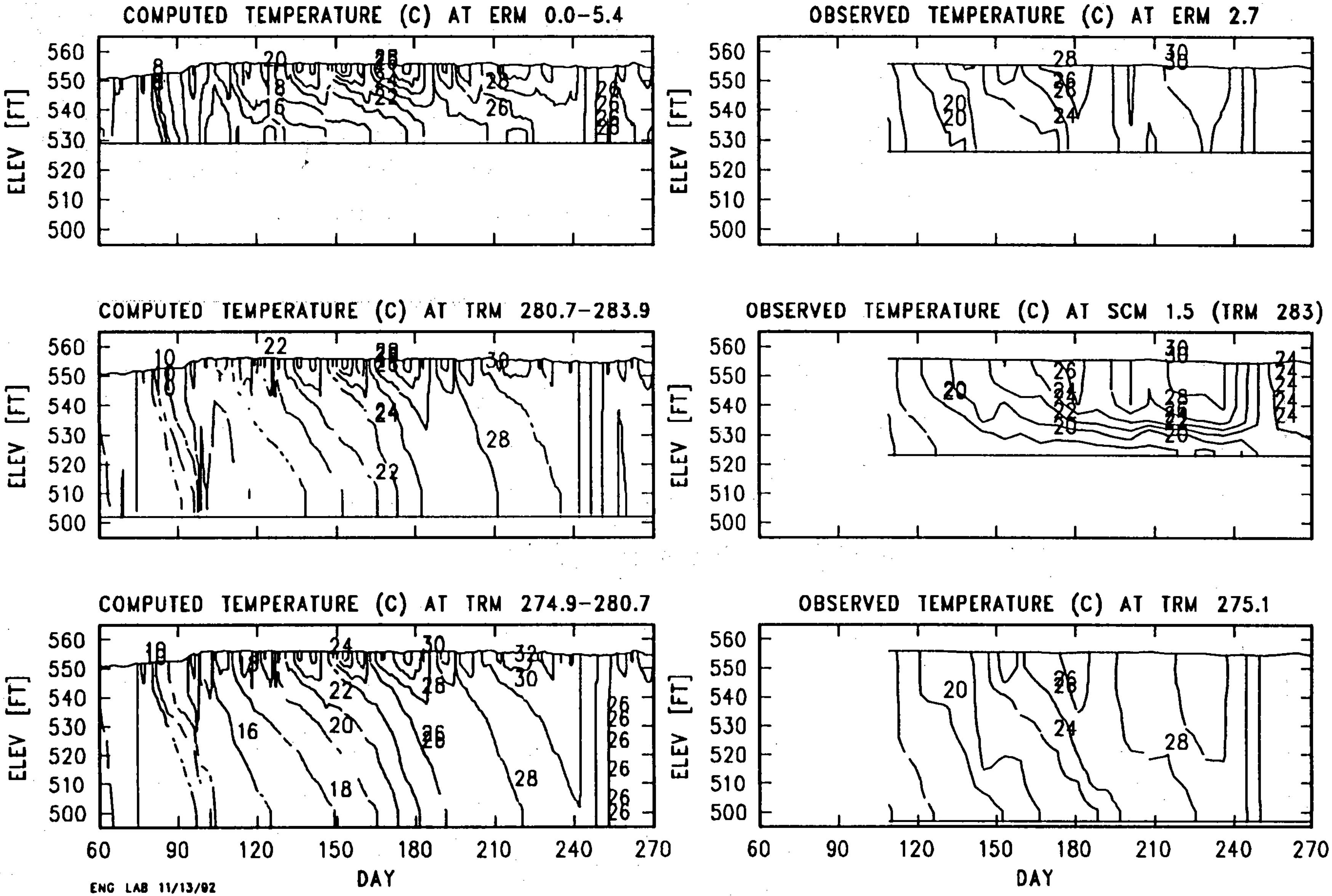

Figure 15. 1988 Computed (Left) and Observed (Right) Time-Depth-Temperature Contours in Wheeler Reservoir

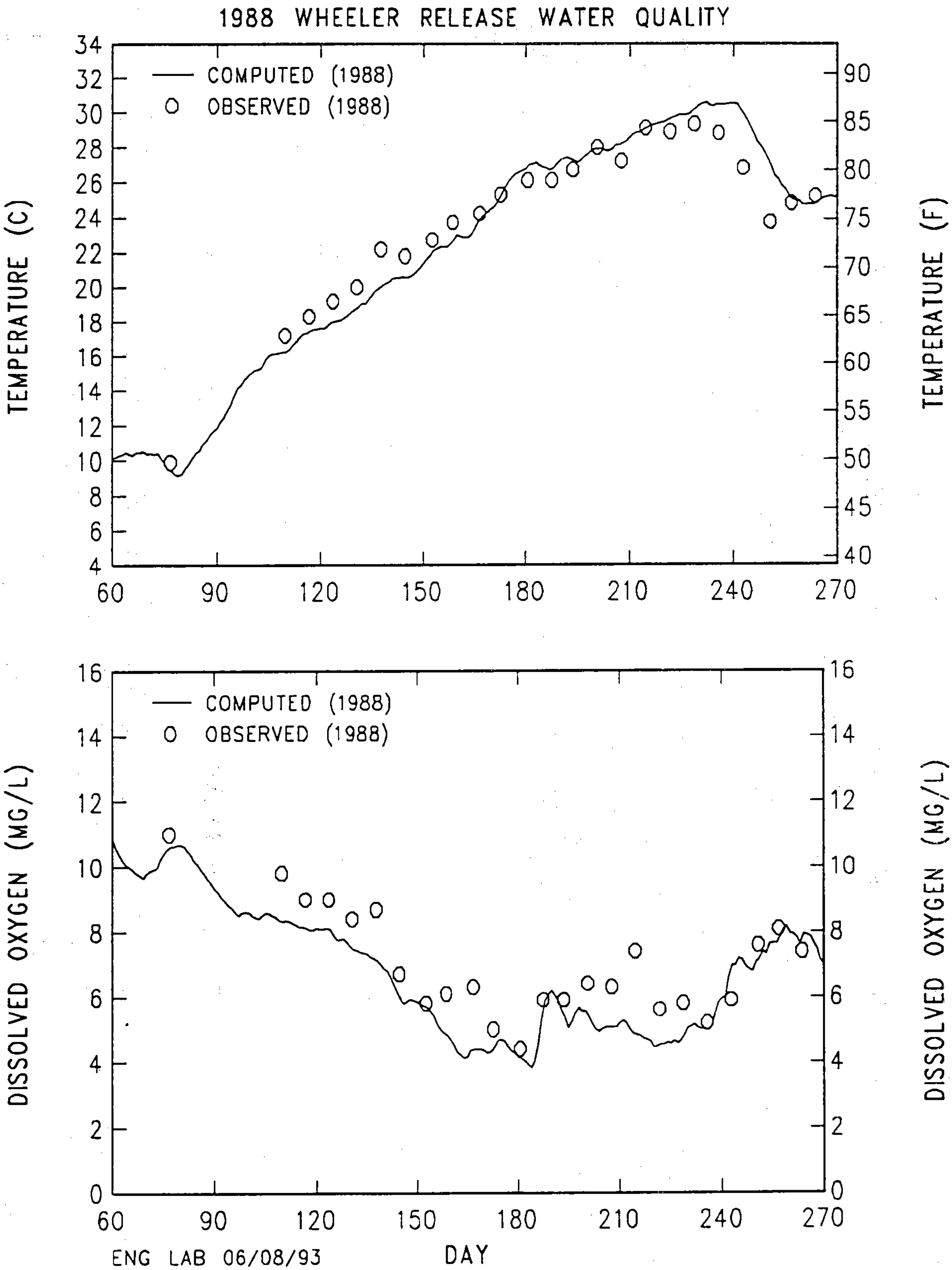

Figure 16. 1988 Computed and Observed Release Temperature and DO at Wheeler Reservoir

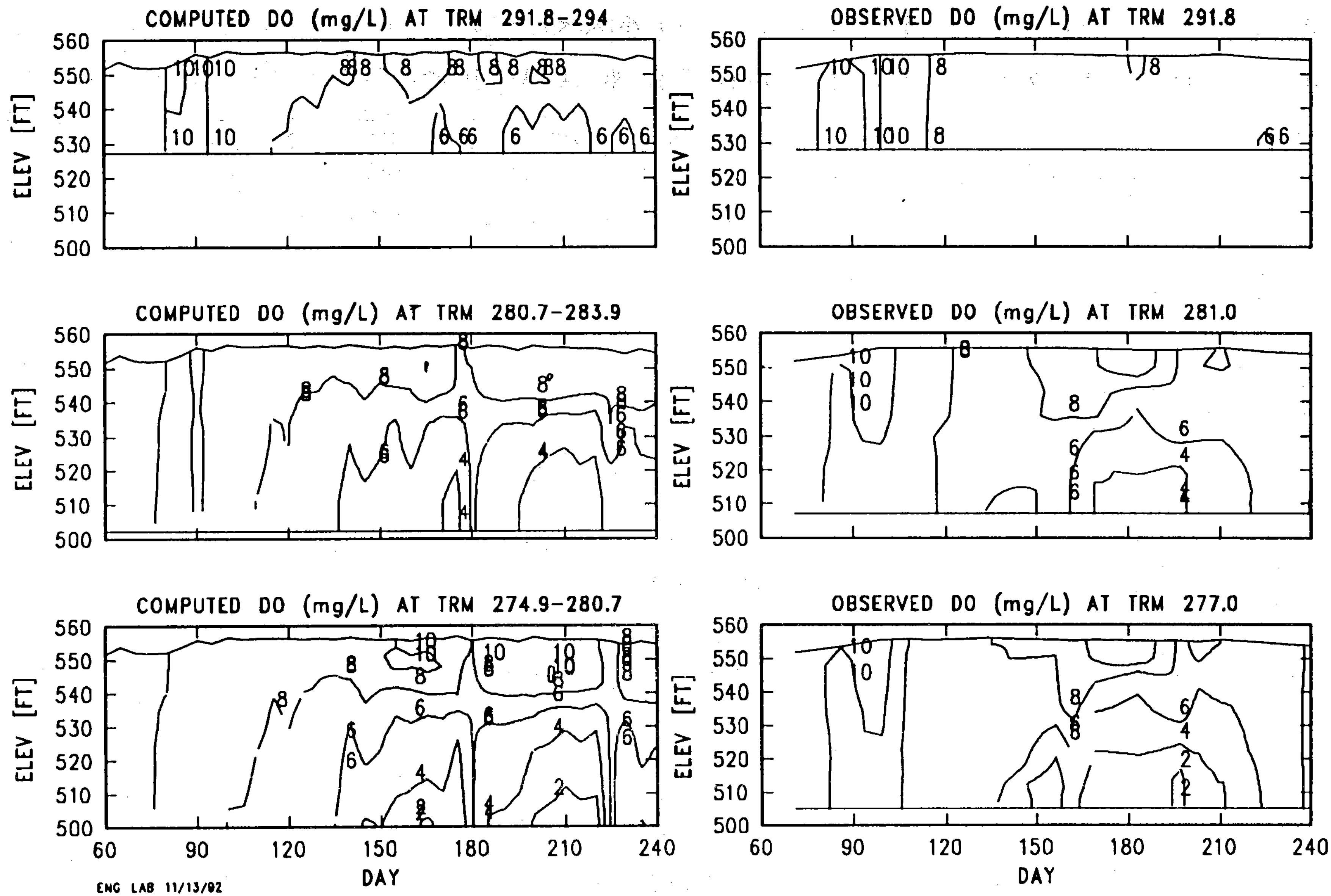

Figure 17. 1991 Computed (Left) and Observed (Right) Time-Depth-DO Contours in Wheeler Reservoir

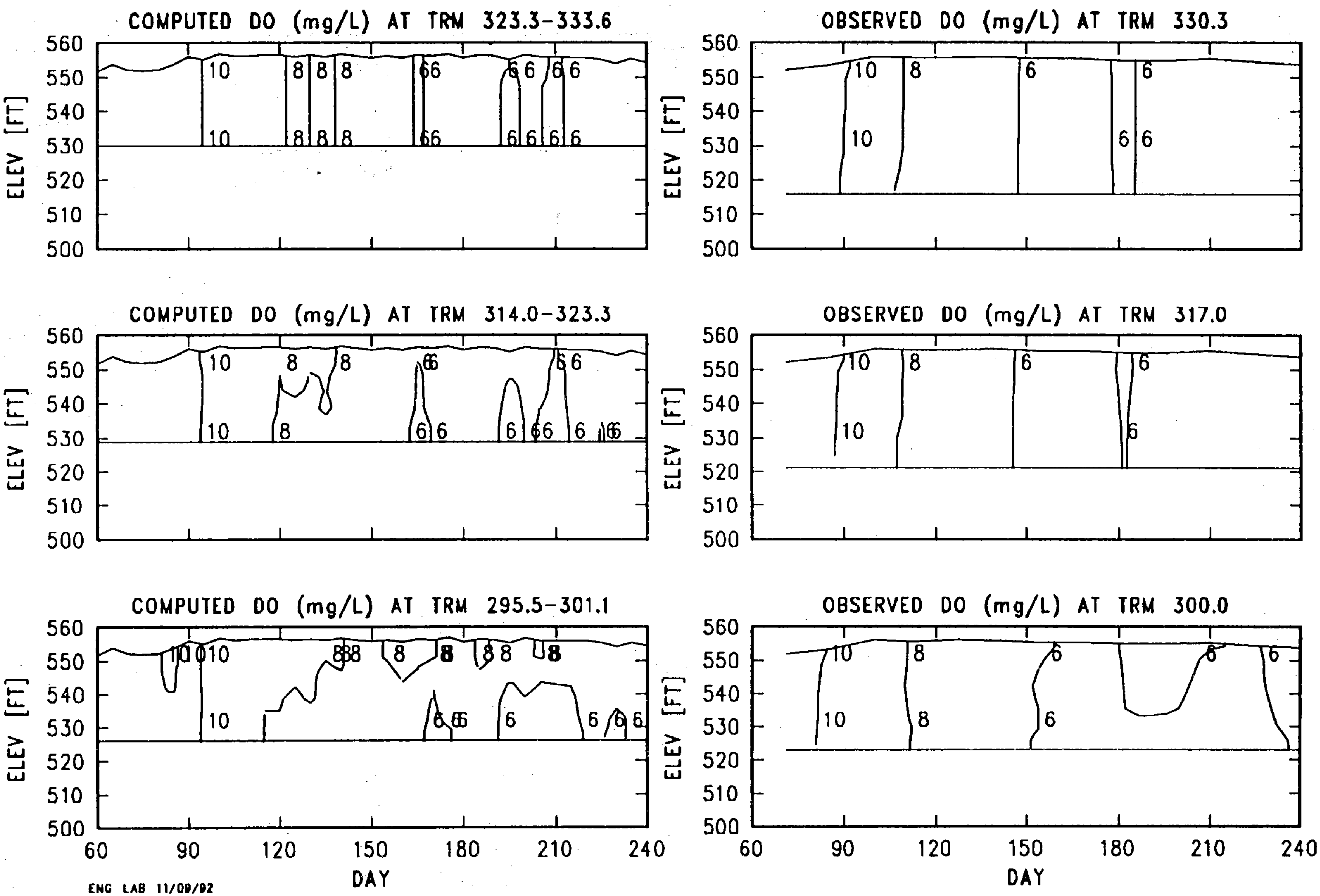

Figure 17. (continued)

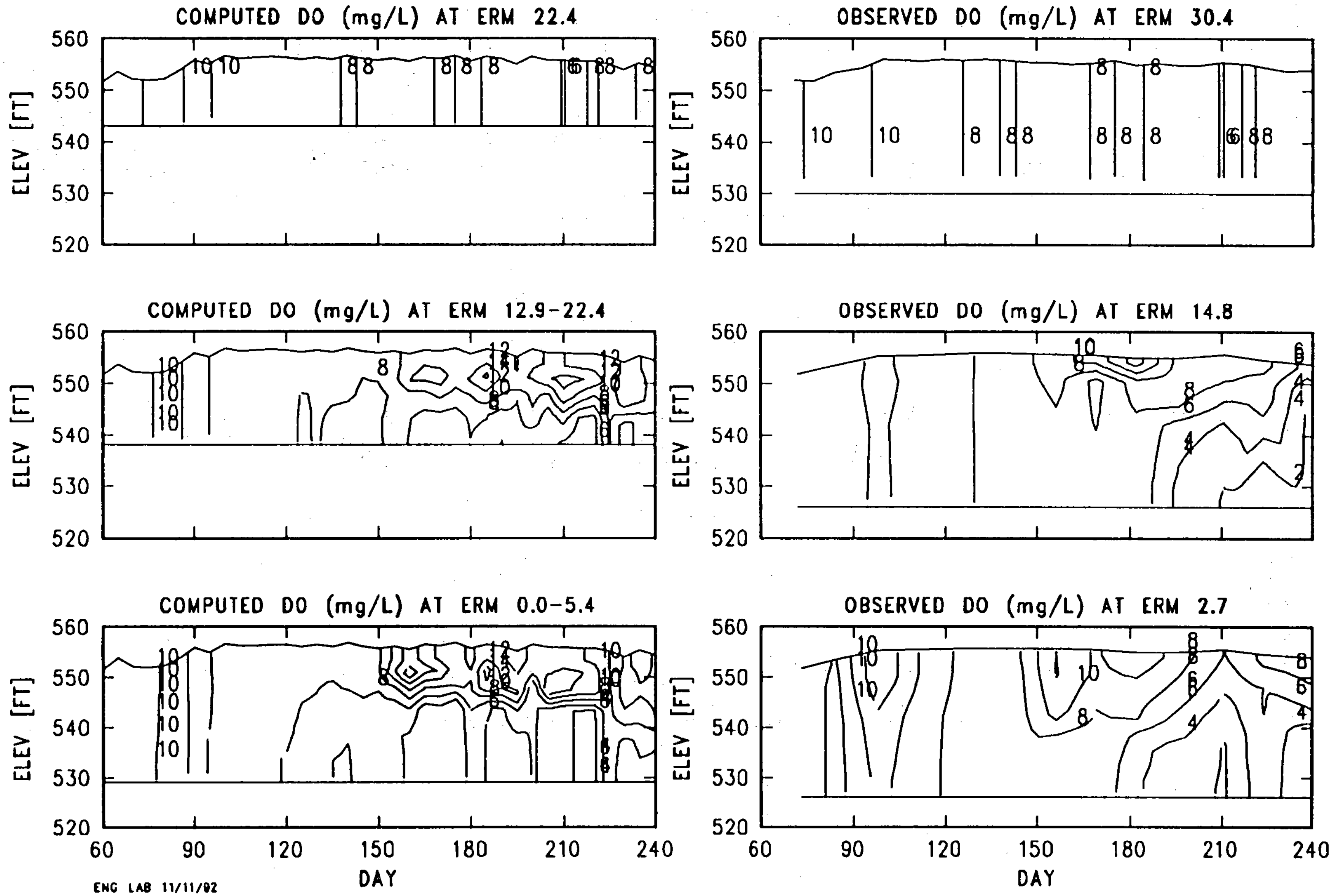

Figure 17. (continued)

that occurred at the end of June (see Figure 11). This mixing event was probably overestimated by the model. Low DO in the reservoir bottom developed in the summer period, confined mainly to the forebay area. This hypolimnetic low DO was reasonably well reproduced. The cold inflow-induced mixing probably played a role in the modeled oxygen replenishment around the end of June. The inflow organics loading at Guntersville Dam, which was estimated through interpolation of weekly grab samples could also contribute to differences between the modeled and measured DO values.

Observed 1991 DO in the Elk River indicated an algal bloom in the mid- to downstream section of the river in early summer. This algal bloom was properly reproduced by the model. Strong DO stratification was observed in the mid- and downstream part of the Elk River in late summer. Observed DO at ERM 14.8 indicated a strong bottom DO demand in early August. This bottom DO demand, however, was not observed at ERM 2.7 nor at ERM 40.4. Lack of information on local wasteloads made it difficult to analyze this localized phenomenon. The computed bottom DO (left-hand side) at the lower end of the river had a similar pattern as the observed one (right-hand side) but was overestimated. Due to lack of information, the same areal SOD (0.8 g O_2/m^2-day) was used for both the Tennessee River and the Elk River. This SOD may be underestimated in the Elk River.

As described previously, field DO measurements in 1988 were available only at three locations: in the forebay of Wheeler Reservoir (TRM 275.1), near the mouth of the Elk River (ERM 2.7) and in the embayment of Spring Creek (SCM 1.5). Computed and observed DO concentrations at these three locations are shown in Figure 18. In 1988, there was no measurement of inflow nutrient or organic concentrations at Guntersville Dam and no inflow measurements of temperature, DO, nutrients, or organics at the Elk River, so these inputs were estimated. The modeled seasonal DO patterns (left-hand side) conform with measured data (right-hand side) in both the forebay (TRM 275.1) and the mouth of the Elk River (ERM 2.7).

Depending on the size, shape, and its inflow organic loading, DO in an embayment can be quite different from that in the main river. A typical example would be the exceedingly low DO in the bottom layers of the Spring Creek embayment in 1988, which resulted from a strong thermal stratification and unseasoned low inflows. The comparison of modeled DO in the main river (TRM 280.7-283.9) and measured data in the embayment of Spring Creek (SCM 1.5) is, therefore, limited to DO in the surface layers only. As shown in Figure 18, surface DO concentrations in both the main river and the embayment are in the 8 to 10 mg/L range with intermittent algal blooms occurring in the spring period.

The large variation in measured Wheeler Dam release DO in 1988 (Figure 16) suggests a withdrawal zone that increases directly with dam release and decreases with vertical temperature gradient. Therefore, higher releases would tend to draw more surface (warm and high DO) water and result in a release with warmer temperature and higher DO than smaller releases. This effect is more pronounced in 1988 (a dry year) than in 1991 (a wet year) due to greater temperature and DO stratification. Actual release DO also varies depending on which turbine was in use. Bankward turbines releasing higher DO may explain some of the localized DO mismatch between the modeled and measured DO values.

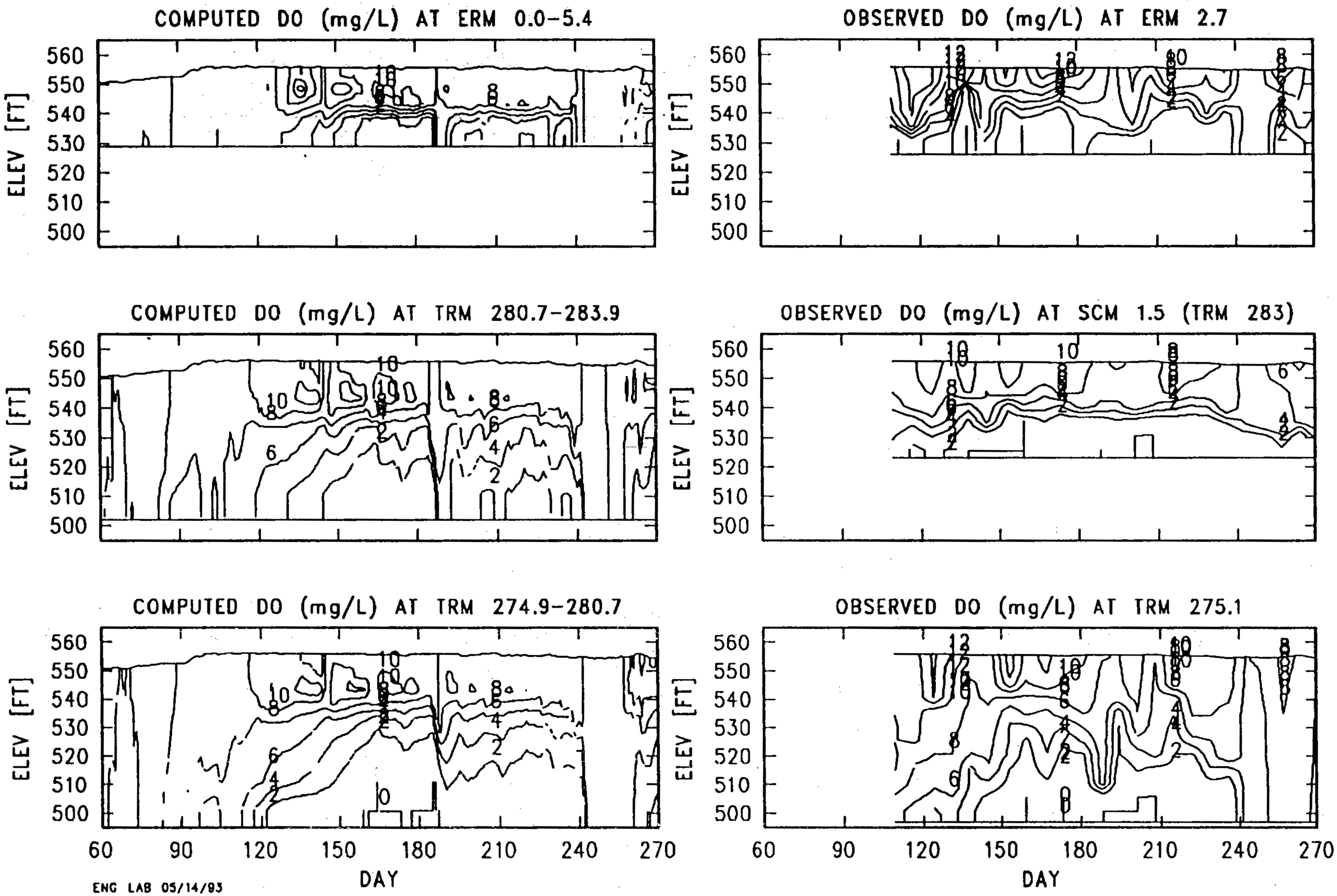

Figure 18. 1988 Computed (Left) and Observed (Right) Time-Depth-DO Contours in Wheeler Reservoir

Algae and pH Calibration

A direct quantitative comparison of computed and measured algal biomasses is not possible with present technology. Chlorophyll-a concentrations provide a measure of standing crop (i.e., all aquatic plants) in the water body. Translation of chlorophyll-a concentrations to algal biomass, however, requires a great deal of biological judgment.

Field measurements of chlorophyll-a concentration in 1991 at various locations in the reservoir are given in Table 6. Using a rough conversion of 1 mg/L algal biomass = 5 μg/l chlorophyll-a, an equivalent algal biomass might range from about 0.2 to 4 mg/L in the Tennessee River and about 0.2 to 8 mg/L in the Elk River. These values are in line with the computed algal concentrations shown in Figure 19 ranging from about 0.5 to 3.5 mg/L. Due to strong thermal stratification, the 1988 computed algal patterns (Figure 20) indicated algal activity in the middle part of the reservoir. Because there were no field measurements of chlorophyll-a (algal activity) in 1988, a direct confirmation of this algal productivity was not possible.

Indirect measures such as elevated pH, DO supersaturation, depletion of nutrients (PO_4-P, NO_3-N, etc.), and measurements of organics (TOC, TON, VSS, etc.), in most cases, can be used as surrogate (qualitative) indicators of algal activity. The 1991 computed and observed pH contours, shown in Figure 21, reveal that surface and bottom pH were adequately simulated with the exception that surface pH in the forebay of Wheeler Reservoir was underestimated in mid-summer and surface pH in the lower part of the Elk River was overestimated in late summer. The inflow-induced mixing produced by the model around day 180 (not shown in field data) apparently caused the underestimation in the Tennessee River. The model also simulated a prolonged thermal stratification in late summer which contributed to the overestimated surface pH in the Elk River.

The 1988 computed and observed pH contours are presented in Figure 22. Observed data indicate a strong algal activity in early summer which is reproduced by the model. Surface pH was slightly overestimated in the Elk River in late summer, a result of overestimated algal activity due to prolonged thermal stratification.

VI. MANAGEMENT SIMULATIONS

Management simulations are used to explore reservoir responses over a range of conditions that are difficult to test in the field. In this study, the main concern is the impact of municipal and industrial waste discharges on the assimilative capacity of Wheeler Reservoir. The 1988 calibration run described previously provides the base case with actual average wasteloads. Two scenarios were selected to evaluate reservoir DO under altered wasteloads: (1) zero wasteloads and (2) all point sources discharging at their permit wasteloads. Comparison of the zero loading case with the base case demonstrates the cumulative impact that current permitted loads are having on the reservoir. The permit load case illustrates the potential effect of current loads if all were to discharge at their monthly average permitted levels simultaneously. Both simulations used hydrologic conditions from 1988, a drought year. In 1991, TVA implemented the Lake Improvement Plan which extended full pool through July and provided

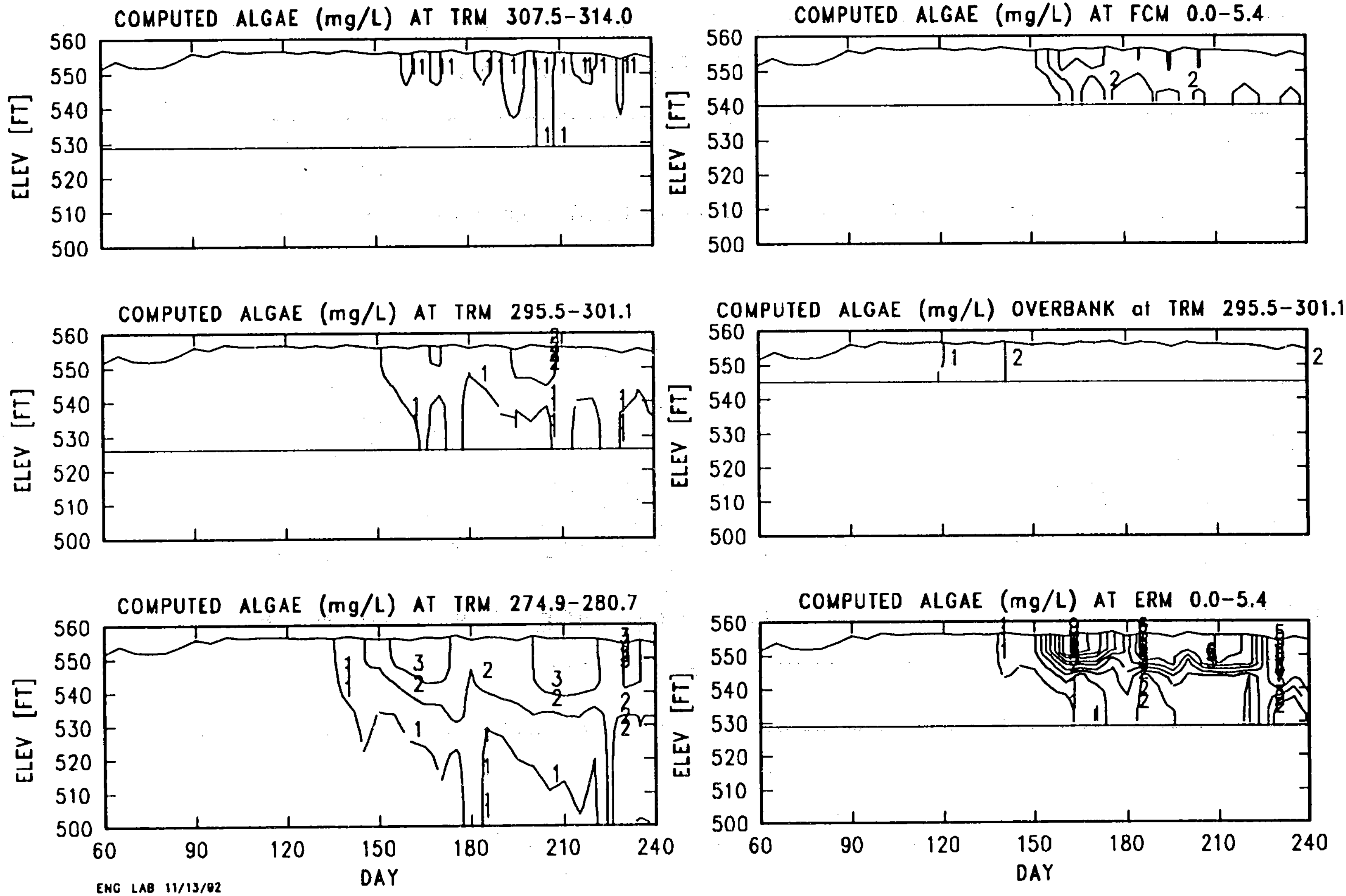

Figure 19. 1991 Computed Time-Depth-Algae Contours in Wheeler Reservoir

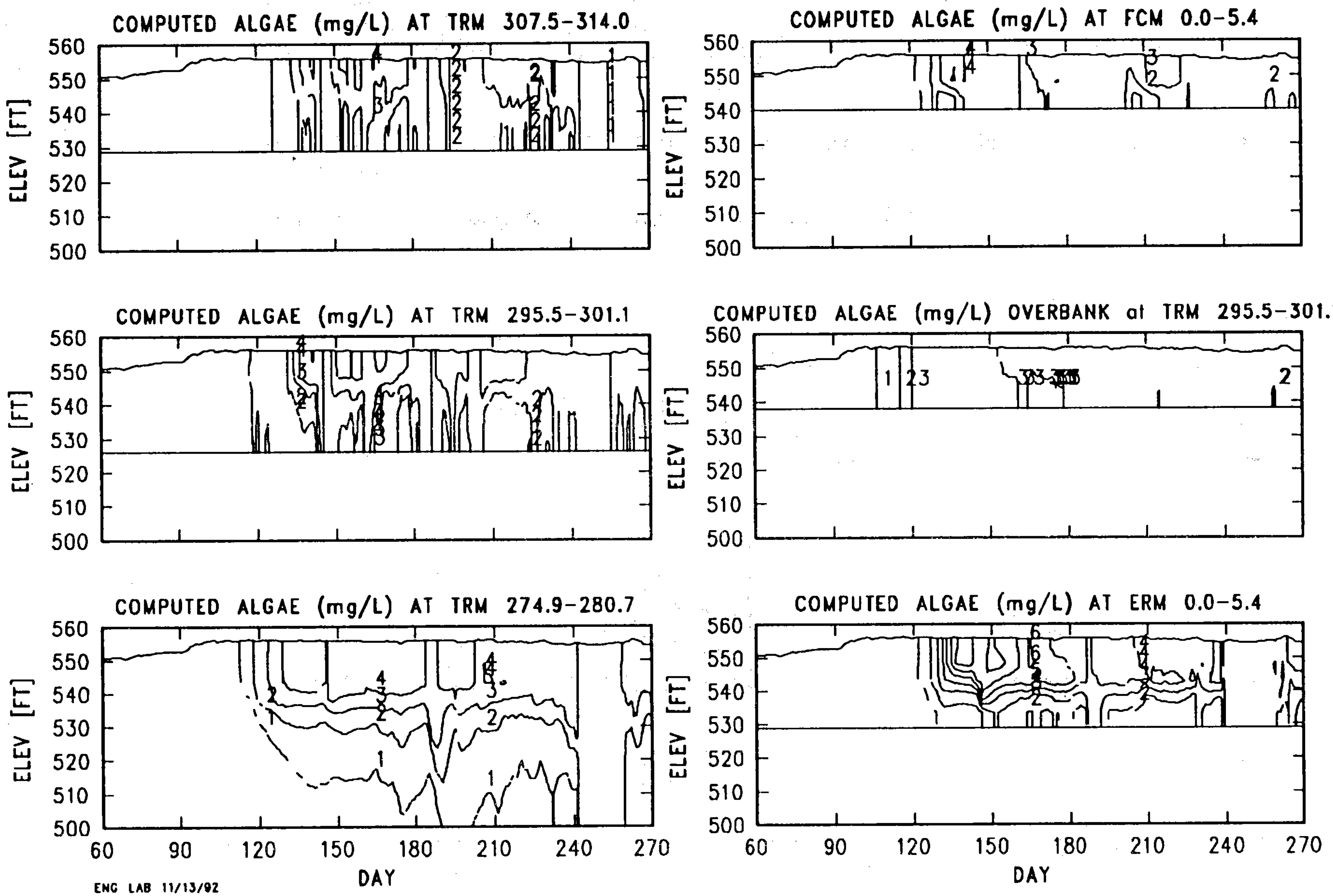

Figure 20. 1988 Computed Time-Depth-Algae Contours in Wheeler Reservoir

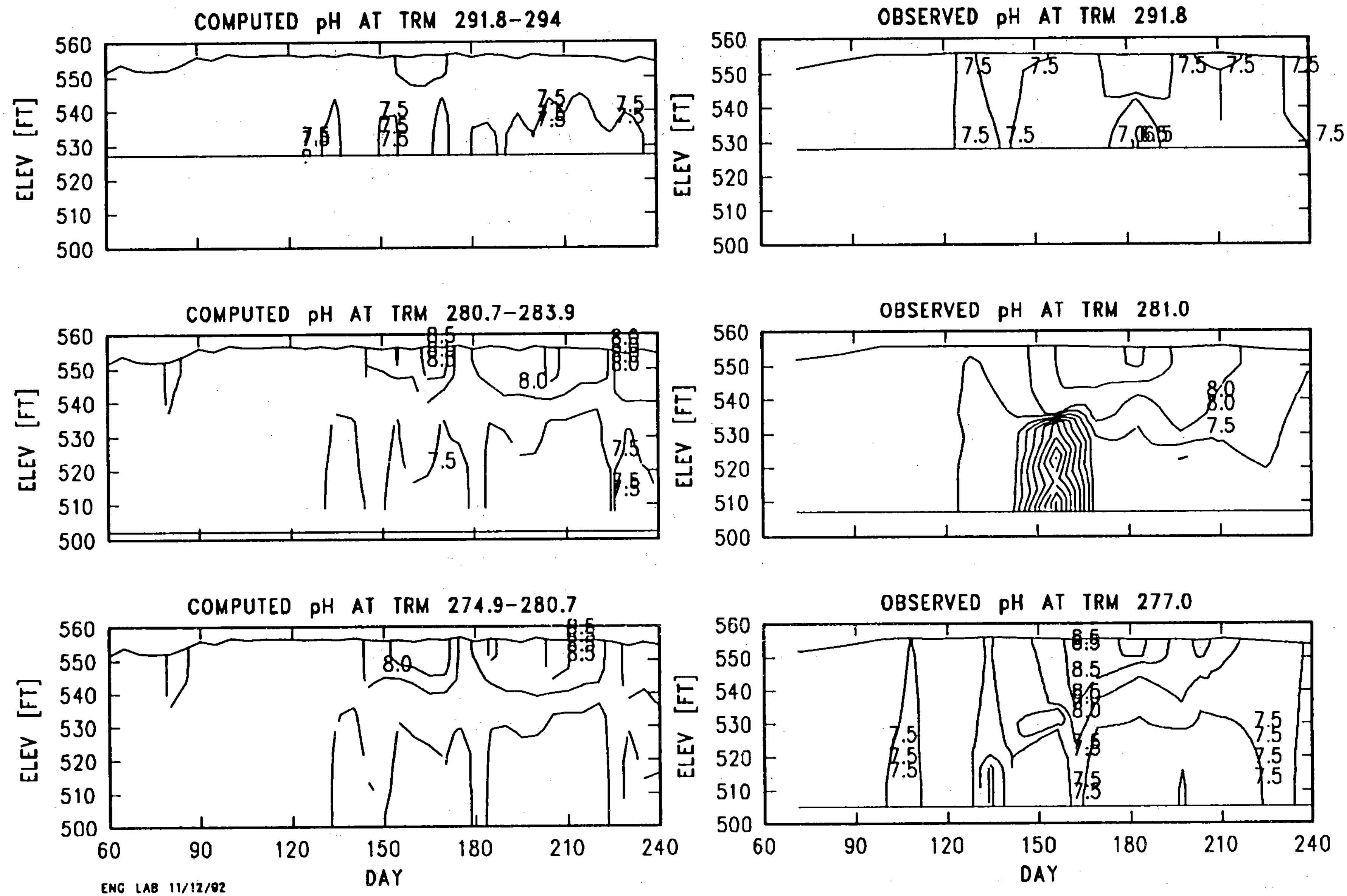

Figure 21. 1991 Computed (Left) and Observed (Right) Time-Depth-pH Contours in Wheeler Reservoir

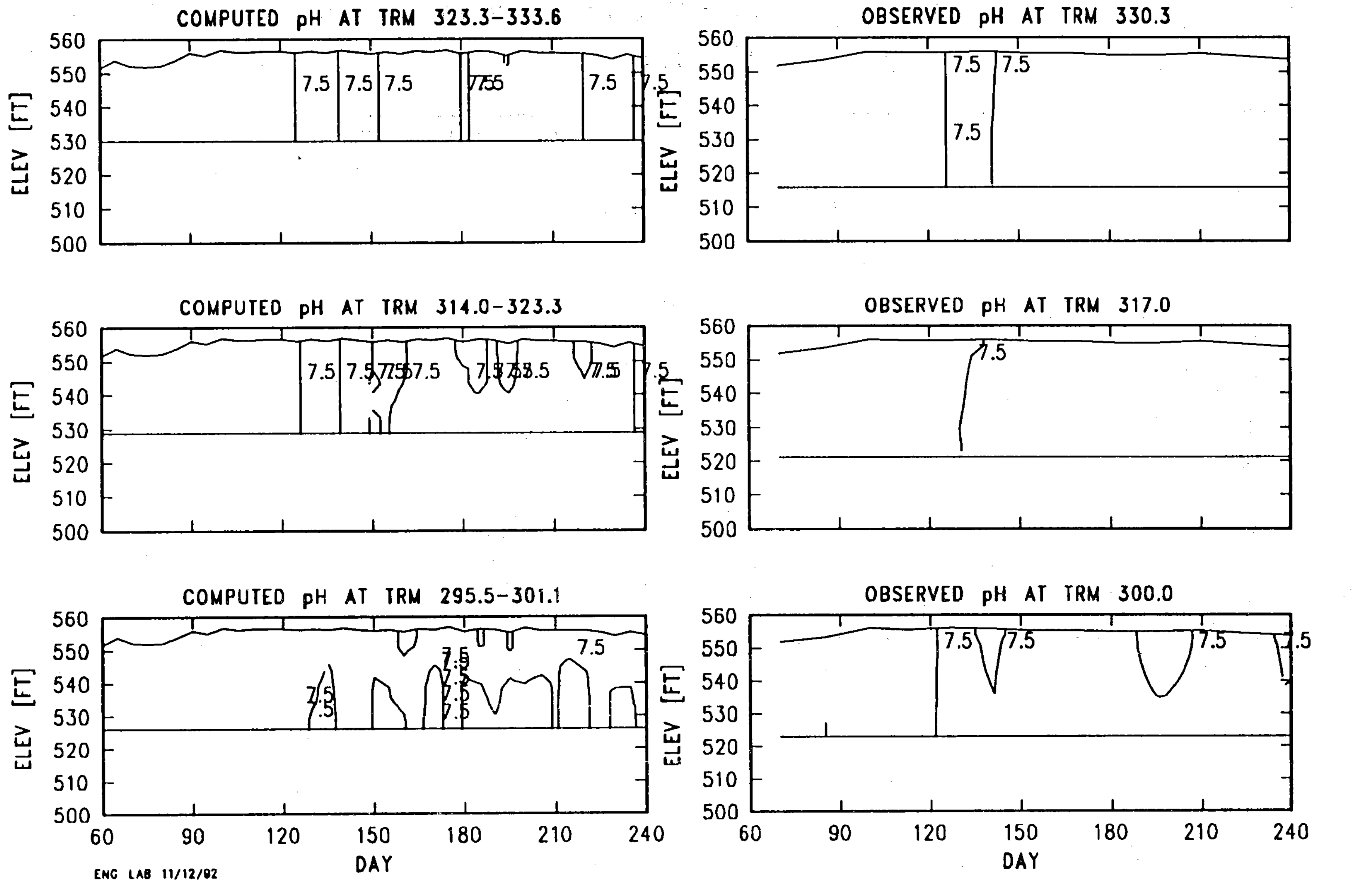

Figure 21. (continued)

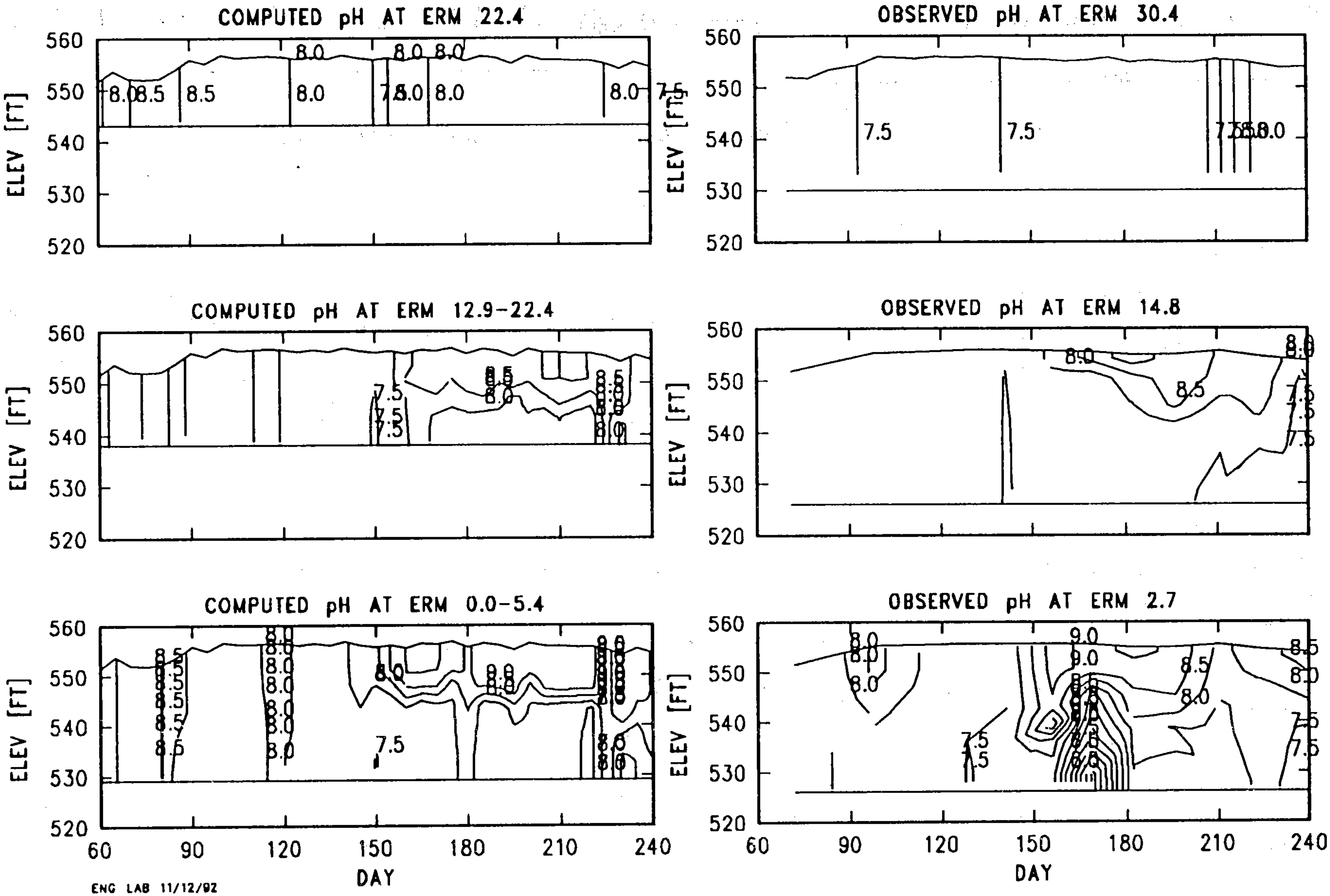

Figure 21. (continued)

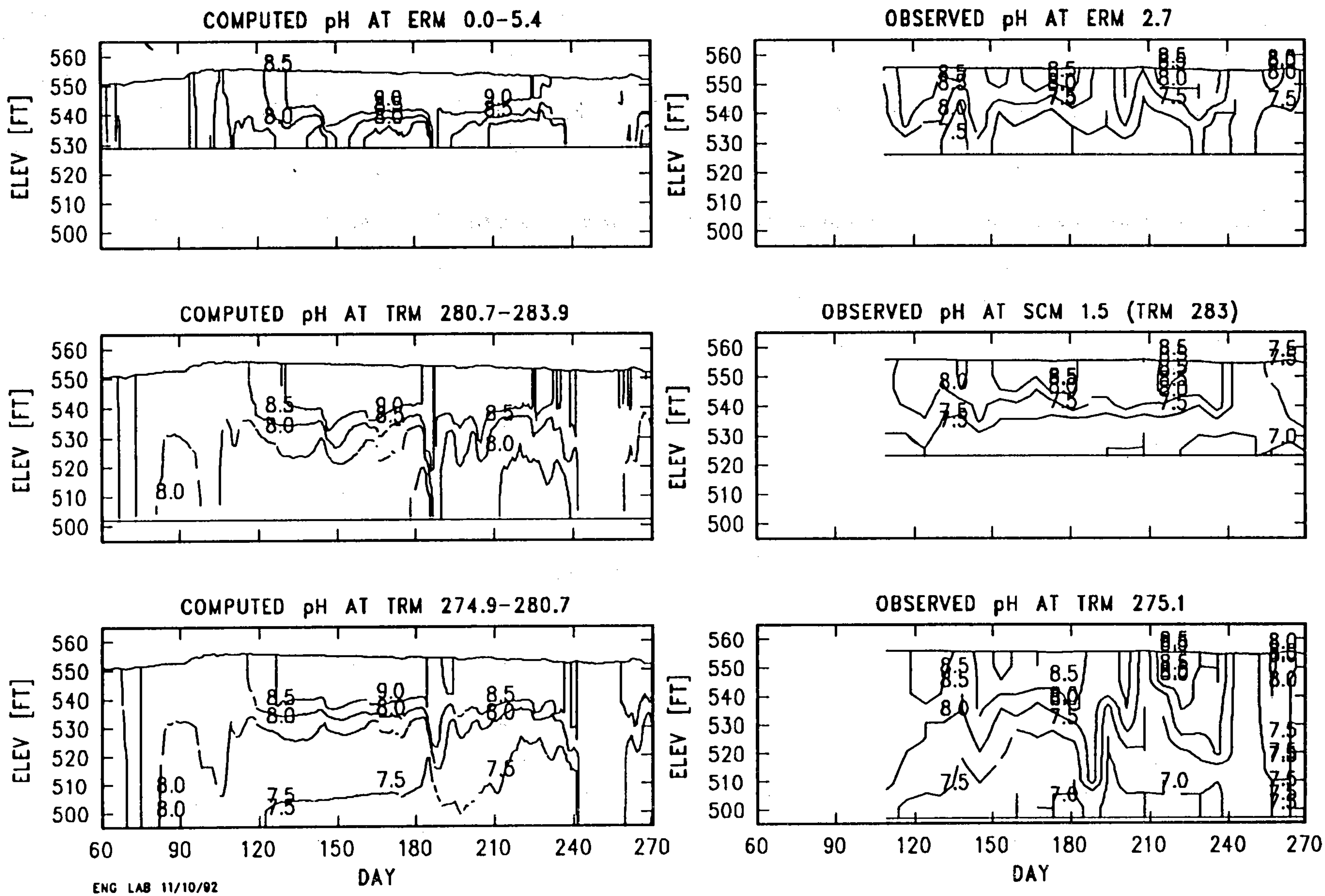

Figure 22. 1988 Computed (Left) and Observed (Right) Time-Depth-pH Contours in Wheeler Reservoir

TABLE 6

Measured Chlorophyll-a Concentrations - 1991

	Tennessee River Mile						Elk River Mile	
day	277 (μg/L)	281 (μg/L)	291 (μg/L)	300 (μg/L)	317 (μg/L)	330 (μg/L)	2 (μg/L)	14 (μg/L)
29	1							
72	2	2	2	1	1	2	3	1
86	7	7	1	3	1	6	3	3
99	16	9	4	3	3	5	43	13
108	6							
114	3	7	1	5	2	2	9	4
128	6	3	1	4	2	2	3	3
134	15							
141	14	10	3	8	2	2	9	2
156	4	4	5	11	1	2	18	16
162	17							
169	8	8	5	4	2	2	20	22
183	5	6	10	5	3	2	14	21
197	6	8	5	9	2	2	8	15
203	7							
211	13	9	13	11	2	2	13	22
225	8	15	5	4	2	3	23	21
233	7							
239	4	10	3	3	3	3	20	20
253	8	5	4	4	2	3	23	23
261	13							

biweekly average minimum flows at Guntersville and Wheeler Dams. Its impact on reservoir water quality was evaluated in the third management simulation. Due to uncertainties and simplifying assumptions used in modeling, emphasis should be placed on relative differences between runs rather than on absolute values from any given run.

Zero Point Source Wasteload

With all point source waste discharges eliminated, BOD concentrations in Wheeler Reservoir were reduced by about 1 mg/L with more reduction at reservoir bottom layers where wasteloads were introduced. As an example, a comparison of the time-depth-BOD contours in the forebay with and without wasteloads is presented in Figure 23. Bottom BOD was decreased from about 2 to 3 to less than 1 mg/L, a significant reduction due largely to the elimination of the Champion Paper wasteload. Surface BOD was reduced by about 50 percent (from 3.0 mg/L in base case to 1.5 mg/L) in the summer due to the shortage of nutrients (from waste discharges) which resulted in less algal productivity. As shown in Figure 24, eliminating all wasteloads resulted in a DO improvement in the hypolimnion where the duration of low DO (less than 2 mg/L) decreased from 121 days to about 91 days. The surface DO was sightly lower due to less algal activity. A comparison of release DO and BOD from Wheeler Dam, shown in Figure 25, reveals that release DO was improved by 0.5 to 1.0 mg/L after eliminating all wasteloads. Combined with the corresponding reduction in release BOD (about 1 mg/L), this scenario presents a significant improvement of waste assimilative capacity in the downstream Wilson Reservoir.

With Permit Wasteloads

In this scenario, all municipal and industrial waste discharges were increased to their monthly average permit levels (Table 7). The time-depth-BOD contours in the forebay shown in Figure 26 point out an increase in BOD of about 1 mg/L at both surface and bottom layers due to the added wasteloads. At the same time, bottom DO in the forebay (Figure 27) was depressed more. Surface DO, on the other hand, increased slightly in late summer due to increased algal activity promoted by the added nutrients. Due to river flow and hydrothermal conditions, the number of days with the forebay DO below 2 mg/L did not increase much from the 1988 basecase (122 days vs. 121 days). Figure 25 shows that the release BOD was increased by about 0.5 mg/L and release DO was decreased by about 0.2 mg/L with the largest decrease in June (about 0.5 mg/L).

The effect of wasteload changes on the entire reservoir can best be demonstrated by considering the volume of reservoir with low DO. Figure 28 shows the seasonal variation in the volume of reservoir with low DO (for example, less than 2 mg/L). With no wasteload, the low DO volume was reduced more than half from that of the 1988 basecase. With permit loads, the volume of reservoir with low DO (<2 mg/L) was increased by about 50 percent over the 1988 basecase.

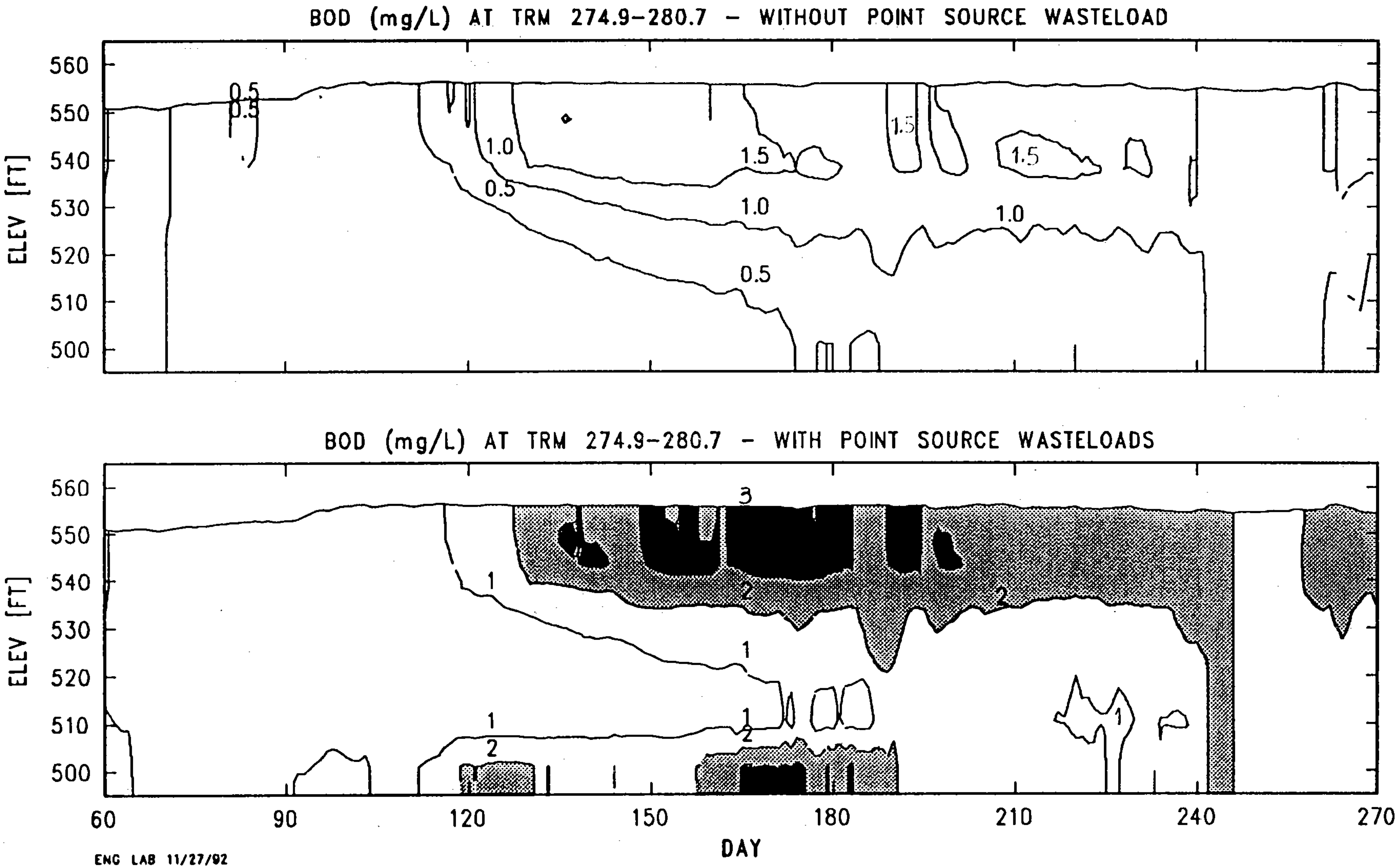

Figure 23. Impacts of Elimination of Point Source Wasteloads on Reservoir BOD in the Forebay Area - 1988 Conditions

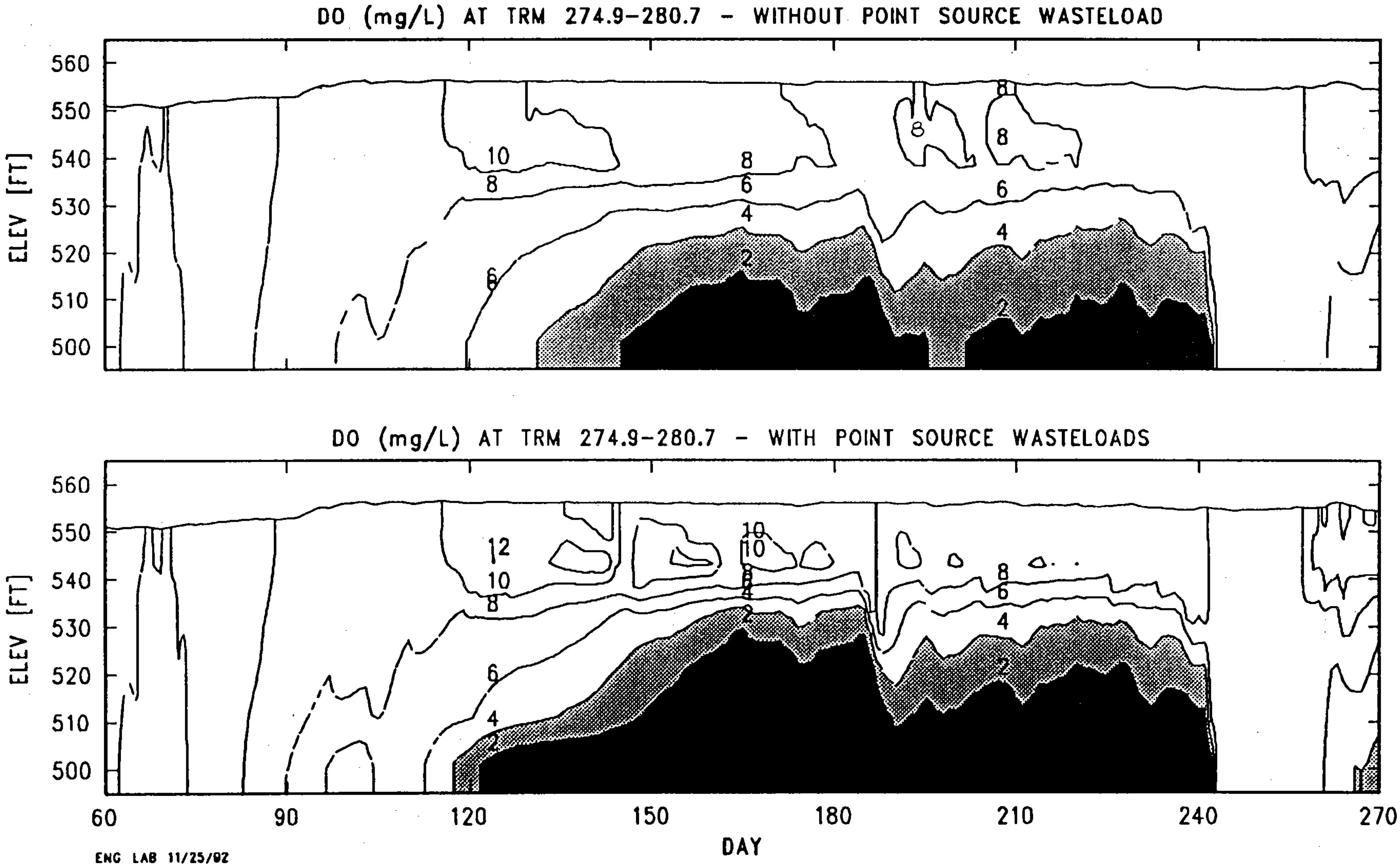

Figure 24. Impacts of Elimination of Point Source Wasteloads on Reservoir DO in the Forebay Area - 1988 Conditions

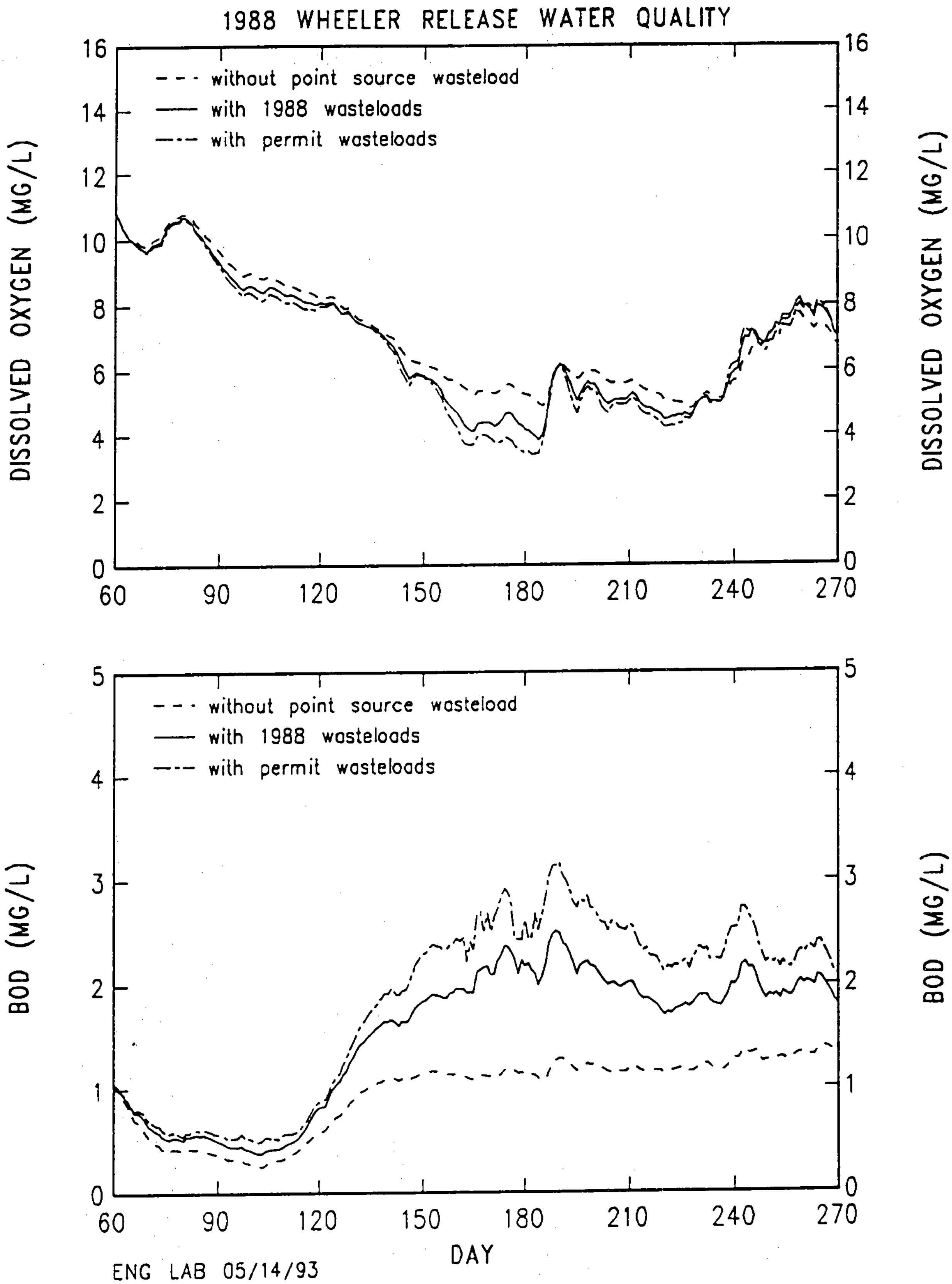

Figure 25. Effects of Wasteload Management on Wheeler Release DO and BOD (1988 Conditions)

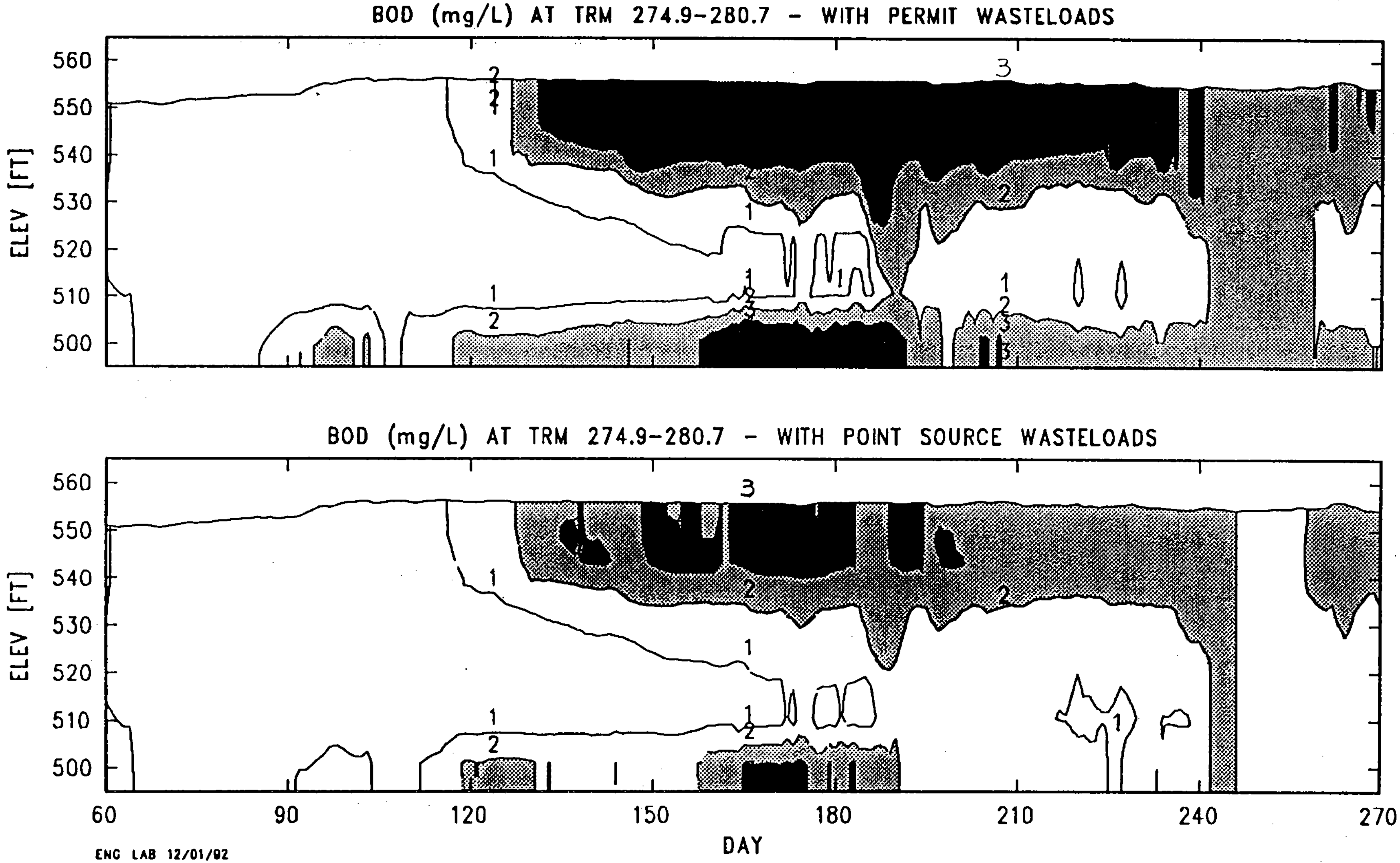

Figure 26. Impacts of Permit Wasteloads on Reservoir BOD in the Forebay Area - 1988 Conditions

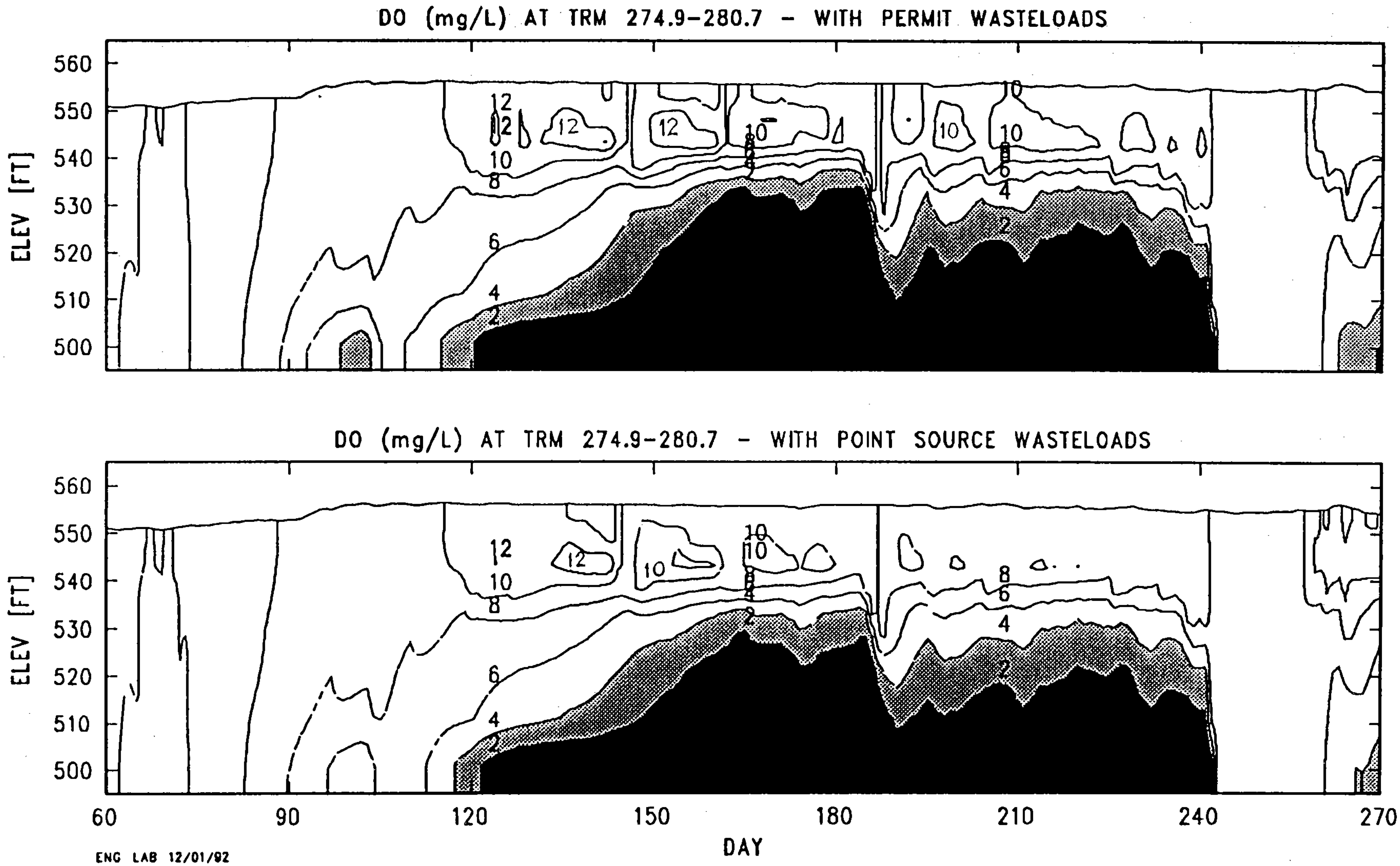

Figure 27. Impacts of Permit Wasteloads on Reservoir DO in the Forebay Area - 1988 Conditions

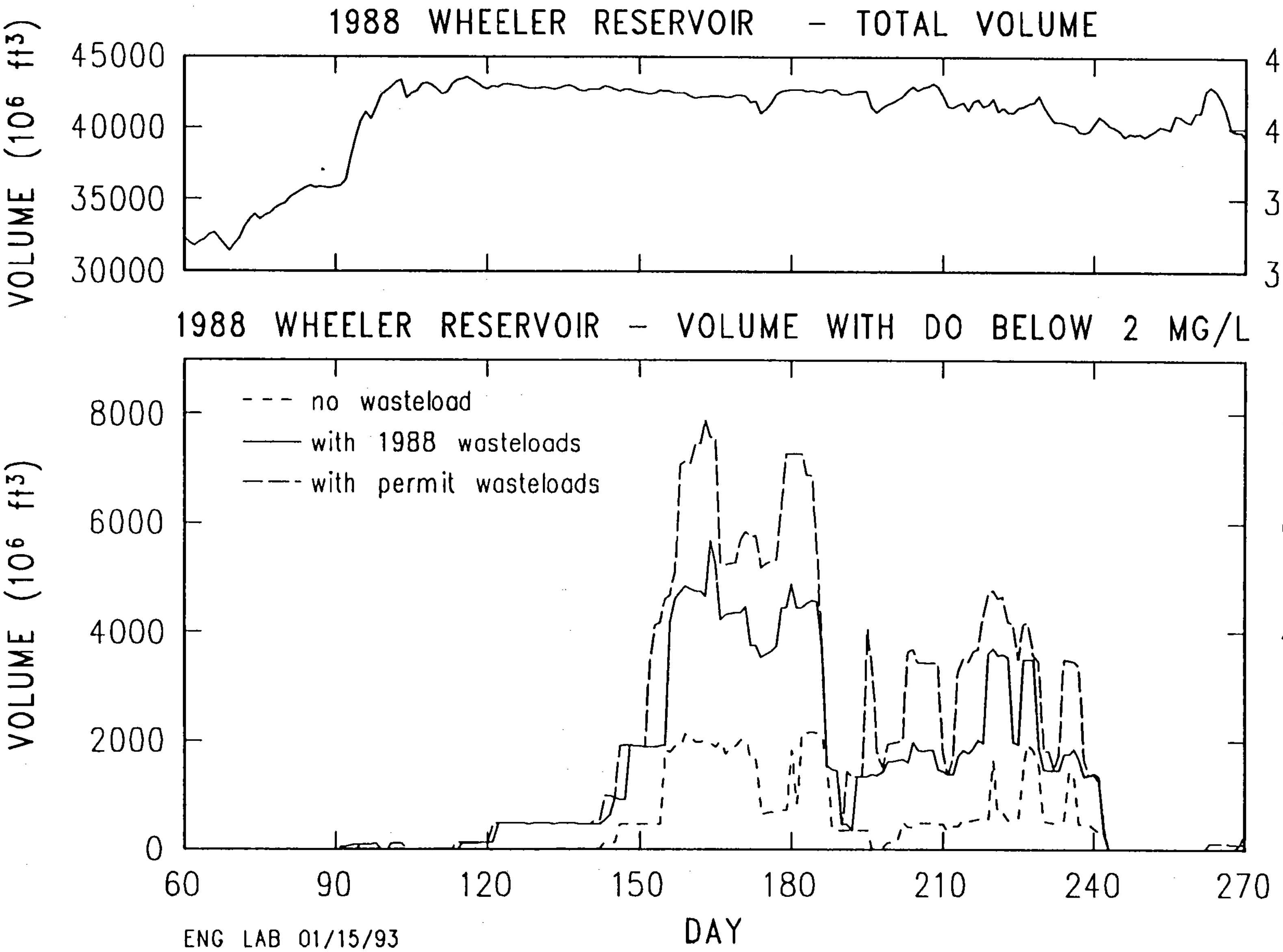

Figure 28. Effects of Wasteload Management on Low DO Volume in Wheeler Reservoir

TABLE 7

Permit Wasteloads for 1988

1. Huntsville (Near TRM 334):

Municipal/Industrial	Flow (Mg/d)	BOD_5 (ppd)	NH_3-N (ppd)	TSS (ppd)
Spring Branch 1 & 1A	41.0	8549	3421.5	10258
Aldridge Cr.	8.4	1751.4	701	2101.7
West Area	10.0	2502	834.5	2502
Big Cove	2.2	547.9	183.6	547.9
Redstone Arsenal	2.1	526	351	526
Total	63.7	13876.3	5491.6	15935.6

2. Decatur/Athens (Near TRM 303):

Municipal/Industrial	Flow (Mg/d)	BOD_5 (ppd)	NH_3-N (ppd)	TSS (ppd)
Decatur Dry Creek	24.0	6008.4	2002.8	6008.4
Moulton	1.1	229	27.5	275
Athens	7.0	1051	291.9	1751.4
Monsanto Co.	2.5	1071	3526	1596
American Fructose	1.6	5213	14	9800
Amoco Chemical	1.3	723	119	1148
3M	1.7	1500	178	667
Total	39.2	15795.4	6159.2	21245.8

3. Browns Ferry Nuclear Plant (TRM 293.6):

Cooling Water Intake (639.1 Mg/d)

4. Champion Paper Company (TRM 282.3):

Industrial	Flow (Mg/d)	BOD_5 (ppd)	NH_3-N (ppd)	TSS (ppd)
Champion Paper Co.				
(May-Oct)	55.4	12422	3204	27897
(Nov-Apr)	55.4	12422	3204	27897

Lake Improvement Plan

In this scenario, the impact of the LIP on reservoir water quality was evaluated using a weekly scheduling model (Parsly, 1988) to provide an emulation of how TVA would have operated in 1988 had the LIP been in place. In Figure 29, the modified 1988 LIP pool elevation and reservoir release are presented along with the 1988 actual operation. It should be noted that, due to the minimum flow requirements stipulated in the LIP at several upstream reservoirs, the annual Wheeler release for the 1988 LIP is slightly higher (about 2 percent) than that of the 1988 actual operation. A comparison of bottom DO concentrations in the forebay, shown in Figure 30, reveals a reduction of the low DO zone in mid-summer due to higher releases (higher throughflows) in June. This DO improvement is also evident in Figure 31 which shows a 50 percent reduction of reservoir volume with DO below 2 mg/L in June. The corresponding DO improvement in Wheeler release is demonstrated in Figure 32 showing almost a 1 mg/L increase in release DO in June along with a small increase (<0.3 mg/L) in release BOD.

VII. CONCLUSIONS

A two-dimensional BETTER model of Wheeler Reservoir water quality was calibrated using 1988 and 1991 data. The year 1988 was severely dry while wet conditions prevailed during 1991. For both years, the observed seasonal temperature patterns in the Tennessee River were adequately reproduced by the model. Thermal stratification in the Elk River was overestimated in 1988 primarily due to the lack of measured inflow temperatures. The 1988 and 1991 observed seasonal DO patterns were reasonably well simulated in the Tennessee River. Reasonable performance in a dry year like 1988 is significant because in dry years the importance of reservoir DO processes such as algal activity, nutrient recycling, and SOD is increased. It appears that, in a drought year like 1988, lack of inflow water quality and nutrient information did not significantly degenerate the model simulation. In a wet year like 1991, inflow water quality is normally the primary factor determining DO in the reservoir. Measured chlorophyll-a concentrations and observed pH profiles were used to provide a qualitative assessment of algal productivity produced by the model. The model reproduces the algal bloom observed in early summer and the computed algal biomass compares favorably with field observations.

Based on the mass balance comparison of all loading sources, Guntersville releases were the leading contributor of BOD and inorganic nitrogen to Wheeler Reservoir. In a dry year like 1988, local runoff and upstream inflows are reduced and the relative contribution from point sources represents a major portion of the total loads. Conversely, in a wet year like 1991, local runoff and upstream inflow became more important contributors. Point sources were the major source of phosphorus, especially in 1988 when reservoir inflows and local runoff were low. For suspended solids, Guntersville releases and local runoff contributed the major portion of the total load with little contribution from point source discharges.

The model was used to evaluate reservoir assimilative capacity under various reservoir operations and waste allocation practices. A simulation run (1988 hydrology) with all point source discharges eliminated showed that reservoir volume with DO less than 2 mg/L was reduced by more than half from the 1988 basecase and the number of days with DO below

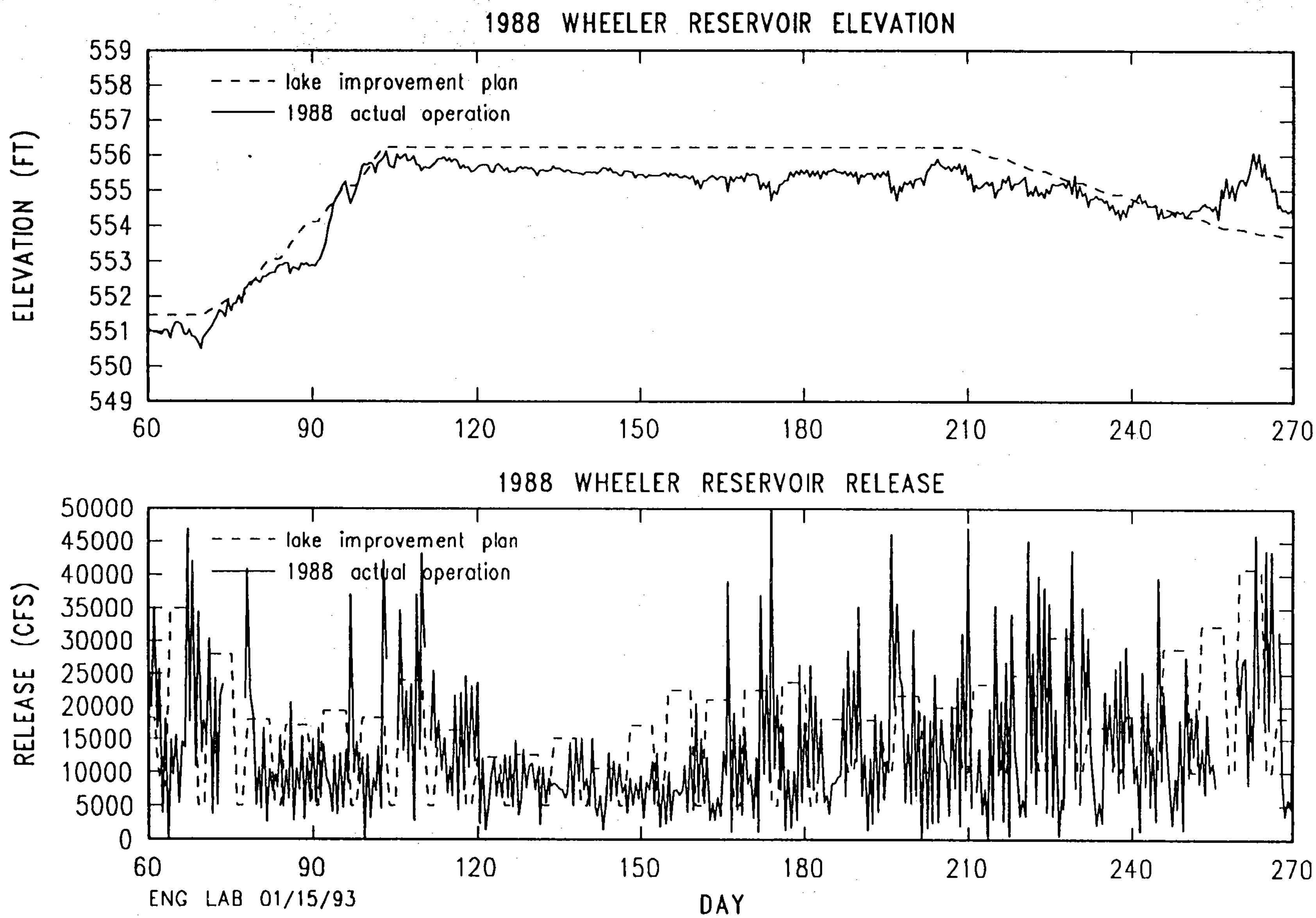

Figure 29. 1988 Wheeler Headwater Elevation and Discharge - Lake Improvement Plan

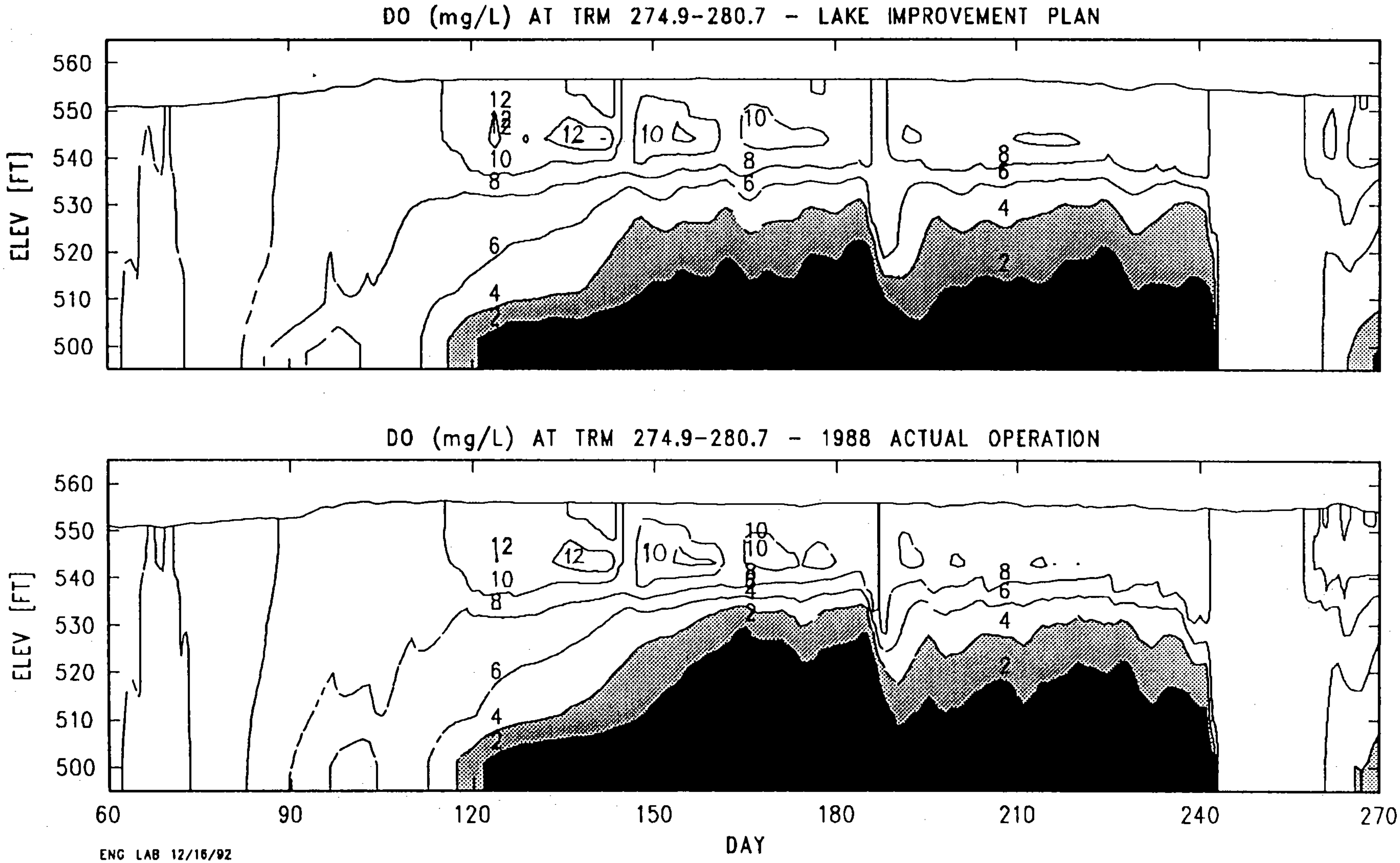

Figure 30. Impacts of Lake Improvement Plan on Reservoir DO in the Forebay Area

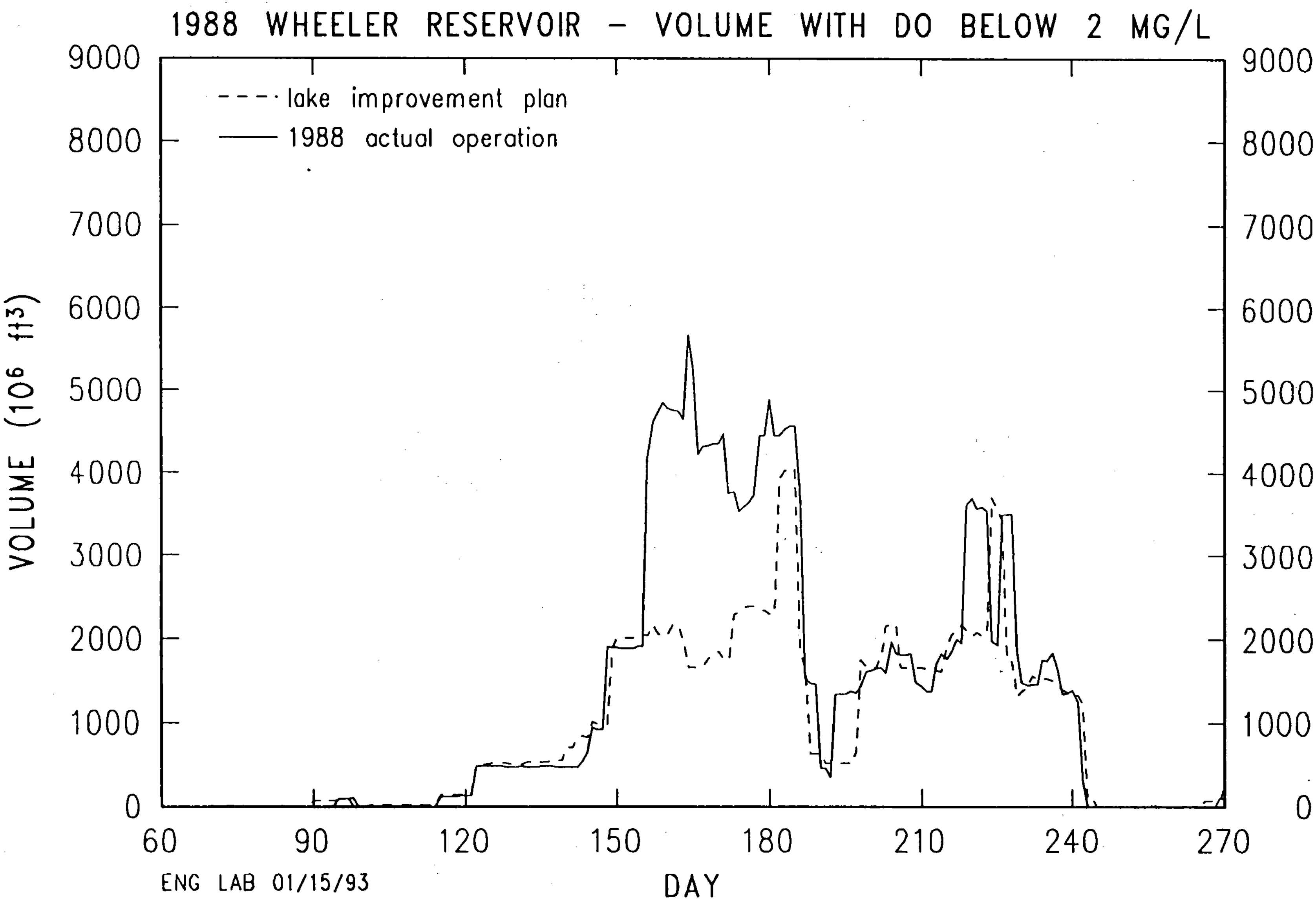

Figure 31. Effects of Lake Improvement Plan on Low DO Volume in Wheeler Reservoir

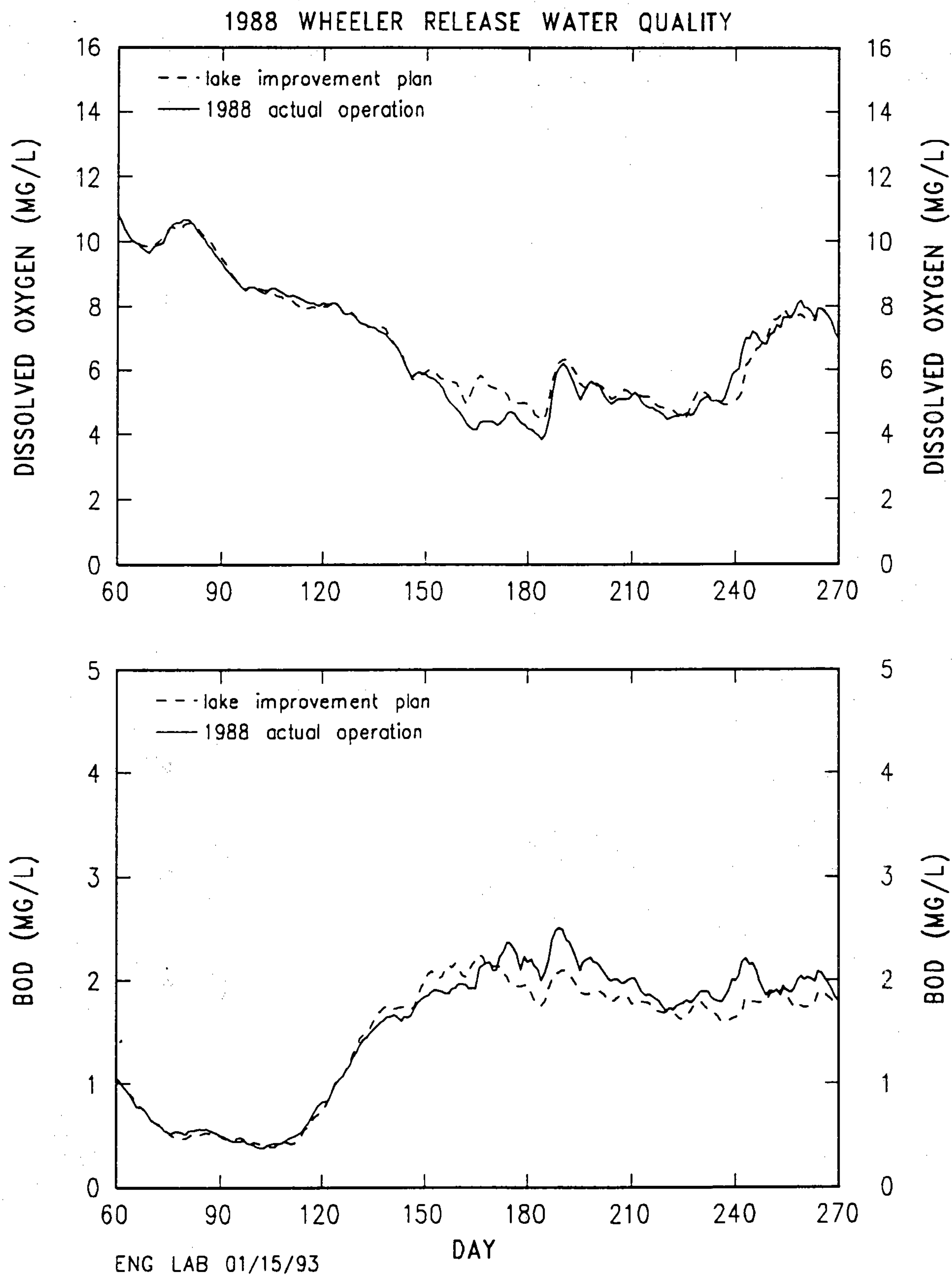

Figure 32. 1988 Wheeler Release DO and BOD - Lake Improvement Plan

2 mg/L was decreased from 121 days to 91 days in the forebay. Another simulation showed that increasing all point source discharges to their permit levels increased the volume of reservoir with DO less than 2 mg/L by about 50 percent over the 1988 basecase. Implementation of the LIP reduced reservoir volume with DO less than 2 mg/L by 50 percent in June and improved release DO by about 1 mg/L during the same period. These applications demonstrate that the model can be a useful planning tool to examine issues such as impacts of altered wasteloads, hydrology, and reservoir operations on reservoir waste assimilative capacity.

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