TWO-DIMENSIONAL WATER QUALITY MODELING OF WALTER F. GEORGE RESERVOIR FOR A COMPREHENSIVE STUDY INTRODUCTION

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INTRODUCTION

Future water uses and operations of water resources projects within the Apalachicola-Chattahoochee-Flint and Alabama-Coosa-Tallapoosa River basins (ACF/ACT) may have an impact on water quality. Changes, especially in operation procedures in the system, have caused concern for future water quality conditions affecting allowable waste loads, thus impacting future development. A system-wide water quality model (HEC-5Q) was used to address these concerns. However, this model is limited for detailed examination of reservoir water quality. HEC-5Q uses a one-dimensional (1D), longitudinal, and vertical spatial discretization for the river reaches and reservoirs, respectively, which is satisfactory for temperature, but can miss important processes affecting other water quality variables, especially nutrients, algae, and dissolved oxygen (DO) in reservoirs which exhibit strong longitudinal water quality gradients.

Since three of the participating states have expressed concerns about several reservoirs within the system, it was decided to model these reservoirs using CE-QUAL-W2 for a more realistic and accurate analysis by including more spatial dimensionality. The three reservoirs were Weiss and Neely Henry, located on the Coosa River, and Walter F. George (WFG) located on the lower Chattahoochee River. This paper will only present the thermal calibration/ verification and scenario results for temperature at WFG.

Study Objective

The objective of this study is to provide calibrated and verified 2D water quality models for Weiss, Neely Henry, and Walter F. George capable of predicting future water quality conditions resulting from potential changes in upstream water allocations, upstream waste loads, and/or reservoir operations.

Approach

The 2D (laterally-averaged) hydrodynamic and water quality model, CE-QUAL-W2, was applied to three reservoirs, Weiss, Neely Henry, and WFG, within the ACF/ACT river basins. CE-QUAL-W2 is recognized as the state-of-the-art for 2D (longitudinal and vertical) water quality modeling of reservoirs. CE-QUAL-W2 contains a hydrodynamic module which predicts water surface elevations and horizontal and vertical velocities. The predicted velocities are used for transporting constituents in the water quality module. The hydrodynamics are influenced by variable water density (i.e., stratification) resulting from variations in temperature, salinity (or total dissolved solids), and suspended solids. Seventeen transported state variables are included in the water quality module.

Site Description

Walter F. George is located at RM 75.2 on the Chattahoochee River (Figure 1). Construction on this dam was completed in 1963 and is operated by the Mobile District. Some of the benefits derived from this project are hydropower, navigation, and recreation. The principal features of the dam are: 1) a 130,000 KW powerhouse (four units), with an intake section constituting a portion of the dam; 2) a concrete gravity-type ogee spillway, 692 feet long with crest at elevation 163.0 feet, surmounted by 14 tainter gates, each 42 feet long by 29 feet high; 3) a single-lift lock, 82 feet wide and 450 feet long, with top of lock walls at elevation 197.0 feet; and 4) a grout-protected, riprapped, rolled-fill earth embankment with top at elevation 215.0 feet, which flanks the concrete structure and extends to high ground on each side (U.S. Army Engineer Waterways Experiment Station 1959).

CALIBRATION/VERIFICATION

CE-QUAL-W2 was applied to two years of data on Walter F. George. Usually, it is preferable to have two extreme water years (i.e., dry and wet year) for calibration/verification. However, water quality data were limited on Walter F. George so the model years were chosen based on data availability. The database of water quality data for Walter F. George had in-pool profiles for temperature and DO only with the other constituents collected as photic zone averages (equal to four times secchi depth). Initially, 1992 was chosen for calibration because this year had the most water quality data collected. However, after recommendation was made for more profile data for all water quality constituents of interest to be collected in 1994, 1994 became the calibration year. Having observed profile data for all water quality constituents of interest for the calibration year gave more confidence in the modeling effort.

Since 1992 was already set up to simulate, this year became the verification year.

Data Requirements

CE-QUAL-W2 requires reservoir geometry (bathymetry), initial conditions, reservoir operations, outlet descriptive data (e.g., port elevation, width, etc.), and time sequences of inflow rates and water quality, meteorological data, and water surface elevations. Calibration/verification is highly dependent on the availability of observed in-pool water quality constituent concentrations at several locations within the reservoir. Observed release water quality data is also needed to evaluate predicted release conditions. Various parameters (e.g., rate coefficients) are also required input.

Bathymetry. CE-QUAL-W2 requires that the reservoir be discretized into longitudinal segments and vertical layers that may vary in length and height. An average width must then be defined for each active cell where an active cell is defined as potentially containing water. Additionally, every branch has inactive cells at the upstream and downstream segments and top layer. Inactive cells are also located below the bottom active cell in each segment. Segment layer heights for all three reservoirs were constant while segment lengths varied.

Once the segment lengths and layer heights were finalized for each reservoir, average widths were determined for each cell. Average widths for Walter F. George were determined from sediment range survey data taken in 1988 and provided by the Mobile District. Walter F. George had the simplest grid of the three reservoirs. It consisted of a single branch having 37 segments longitudinally and 16 layers vertically two meters (m) thick. Figure 2 shows the configuration of the grid. A comparison of computed volume-elevation curve and USACE data is presented in Figure 3.

In-pool Data. The model was calibrated (1994) using observed in-pool profile data collected by Alabama Department of Environmental Management (ADEM) and the US Environmental Protection Agency (EPA). Dr. David Bayne of the University of Auburn collected the data used for verification (1992) as part of the EPA's Clean Lakes Study. Observed data were collected on a monthly basis for both years.

Reservoir Operations Data. The Mobile District provided hourly release flows, water surface elevations, reservoir elevation-area-capacity table, and calculated inflow data for Walter F. George for 1994 and 1992.

Constituent Boundary/Initial Data. Inflow temperature and DO concentration data were not available for the main branch of WFG; therefore, these data were estimated using a program called the response temperature calculator (RTC) developed by J. E. Edinger Associates, Inc. (1984). The RTC uses meteorological data and depth of the stream to calculate water temperatures. Saturation DO values for the estimated temperature values were adjusted to match DO values at the most upstream in-pool station.

Likewise, water quality inflow concentrations for other constituents of the main branch for WFG were not available either. Additionally, historical data were not available to estimate constituent inflow concentrations using regression; thus, observed concentrations at the most upstream station of each reservoir were used as inflow boundary conditions.

Reservoir initial in-pool conditions for temperature and all other water quality constituents were set to values occurring on the first observed date calibration and verification data were collected. There are several options in setting initial conditions in CE-QUAL-W2 and are as follows: 1) use same concentration for temperature and constituents throughout reservoir, 2) use vertical varying profile of temperature and constituents at the dam to initialize all segments in grid, and 3) use vertical profiles of temperature and constituents varying longitudinally for each segment in the grid. Since simulations were started in July for calibration (1994), option 3 was chosen to initialize each reservoir. During verification (1992), option 1 was chosen because the simulation was started in January (isothermal conditions).

Meteorological Data. Meteorological data for 1992 and 1994 were obtained from the U.S. Air Force Environmental Technical Applications Center in Asheville, North Carolina, for Columbus, Georgia, a first-order meteorological station. Data requested were air temperature, dew point temperature, wind speed and wind direction, cloud cover, and barometric pressure.

Calibration

The calibration year for Walter F. George was 1994. Graphical comparisons of computed versus observed data were made to evaluate model performance. In addition, a root mean square error (RMS) was calculated to also evaluate model performance and is indicated on each graph. The RMS was calculated as:

$$RMS = \sqrt{\frac{\sum (Predicted - Observed)^2}{number\ of\ observations}} \quad (1)$$

The RMS is a measure of variability between predicted and observed concentrations (e.g., an RMS of 0.50 means predicted data are within ± 0.50 of the observed value 67 percent of the time).

Also indicated on each plot is the mean error (ME) and absolute mean error (AME). ME is calculated as the arithmetic average using the equation:

$$ME = \frac{\sum (Predicted - Observed)}{number\ of\ observations} \qquad (2)$$

The sign of the ME (±) indicates whether the predicted results average higher or lower than the observed. The AME represents the absolute average error as compared with observed data and is calculated as:

$$AME = \frac{\sum \mid Predicted - Observed \mid}{number\ of\ observations} \qquad (3)$$

To distinguish between observed and computed data in profile plots, the dashed line represents computed values, and the "x" line represents observed values.

For Walter F. George, coefficient rate settings applied to the entire reservoir except sediment oxygen demand rates (SOD) which varied longitudinally per segment. The SOD rates were adjusted per segment or by increasing or decreasing all rates universally with the fraction of SOD (FSOD) parameter. For example, the SOD rates for segments 20 through 30 could be increased from 0.5 to 1.0, but if you wanted all segments rates to be doubled, you would increase FSOD from 1.0 to 2.0.

Table 1 shows final values of all coefficients that affect temperature. Temperature predictions were most sensitive to changes in the wind sheltering coefficient.

Water Surface Elevations. Computed and observed 1994 water surface elevations (WSEL) are shown in Figure 4a. Predicted WSEL were well within the 0.5 meter (m) error considered acceptable (Cole and Buchak 1995).

Temperature. When interpreting temperature predictions from CE-QUAL-W2 for this study, two key points were considered. First, temperature predictions from CE-QUAL-W2 are averaged over the length, height, and width of a cell, but observed data represented temperature at a specific point within the reservoirs. Secondly, meteorological data were applied over the entire reservoir; unfortunately, the closest meteorological station was approximately 50 miles from WFG.

Figures 5 and 6 present temperature profile results for WFG at two stations (1 and 8, see Figure 1 for location). Results are presented for each observed day from the most downstream station (Figure 1) and ending with the most upstream station (Figure 8). Figures 5 and 6 show very little thermal stratification in WFG. Differences in epilimnetic and hypolimnetic temperatures at station 1 (the closest to the dam - Figure 5) were 5°C or less throughout the simulation period. Computed and observed concentrations for all stations and dates compared favorably. The RMS values for most profiles were 1°C or less. Station 8 (Figure 6) is most influenced by inflow temperatures of the all stations (Figure 1). The figure indicates estimated inflow temperatures were close to the observed except on October 19 and 20 when over prediction occurs. The estimated inflow temperatures were obviously too high on these dates. Most differences between observed and computed temperatures at station 1 (Figure 5) are probably caused by having to use meteorological data that was approximately 50 miles from the project.

Verification

Water Surface Elevations. Computed and observed 1994 water surface elevations (WSEL) are shown in Figure 4b. As seen in Figure 4b, predicted WSEL were almost an overlay of the observed values excluding short periods of minor errors of approximately 0.3 m or less. Again, predicted WSEL for 1992 were well within the 0.5 meter (m) error considered acceptable (Cole and Buchak 1995).

Temperature. Figures 7 and 8 present temperature profile results for WFG at the same stations as discussed for calibration results. Results are presented in the same order as indicated above. As in 1994, Figures 7 and 8 show very little thermal stratification in WFG. Differences in epilimnetic and hypolimnetic temperatures at station 1 (Figure 7) were very similar to the differences in the calibration run (5°C or less throughout the simulation period). Computed and observed profiles for all stations compared favorably for most dates (RMS ≤ 1°C). Station 8 (Figure 8) show that estimated inflow temperatures were close to the observed since computed closely match observed for all dates. Most differences between observed and computed temperatures at station 1 (Figure 7) were again attributed to using meteorological data 50 miles from the project.

SCENARIO RESULTS FOR TEMPERATURE

Demonstration or trial scenarios were conducted once calibration and verification were achieved. The Water Quality Task Force (WQTF) recommended specific conditions to simulate during the scenario runs. The three trial scenarios were identified as:

a. base conditions (1994 conditions)
b. future conditions of lower water allocations but with existing waste loads; and

c. future conditions of lower water allocations but 20% higher waste loads.

For scenario, a reservoir inflow, outflow, initial, and water quality boundary conditions were simply set to 1994 calibration conditions. Results from these runs were used as base conditions to compare runs from scenario b and c.

For scenario b and c, reservoir initial conditions, meteorological conditions, and inflow temperature values were set to values used in the 1994 calibration. To represent future lower water allocations, the WQTF recommended using 1988 inflows and outflows at WFG. This year was chosen because it was a drought year, thus meeting the first requirement for lower water allocation. These flow conditions were used for both scenario b and c runs.

For scenario b, the second requirement was to use existing loads from 1994. Waste load (units of mass/time) is calculated as the product of flow (units of volume/time) and concentration (units of mass/volume). Since CE-QUAL-W2 requires concentrations for constituents instead of waste loads, the following equation was used to calculate concentrations needed to produce the same waste load used in 1994:

$$C_{88} = \frac{Q_{94} * C_{94}}{Q_{88}} \qquad (4)$$

where

Q_{94} = inflows for 1994
C_{94} = inflow concentrations for 1994
Q_{88} = inflows for 1988.
C_{88} = calculated inflow concentrations for 1988.

Some concentrations were very high and very unrealistic, especially DO concentrations. Depending on environmental conditions, reduced flow conditions may produce reduced concentrations, slightly increased concentrations, or no change at all. Therefore, two scenario b runs were simulated: 1) one run using C_{88} concentrations from with the exception of using C_{94} DO concentrations and 1988 flow conditions, and 2) a second run using C_{94} concentrations and 1988 flow conditions. Results from both runs were compared with base condition results (scenario a) for all reservoirs. For scenario c, the second requirement was to use existing loads from 1994 increased by 20%. This was done by multiplying concentrations C_{94} and C_{88} (except for DO) by 20%. Like scenario b, two scenario runs were simulated: 1) one run using C_{88} concentrations increased 20% with C_{94} DO concentrations and 1988 flow conditions, and 2) a second run using C_{94} concentrations increased by 20% (except for DO) and 1988 flow conditions. Results from both these runs were compared with base condition results.

__Scenario b and c Temperature Results__

Since results for scenario b and c results were exactly the same (inflow temperature and meteorological conditions were the same) only scenario c results are presented (Figures 9-11). Results at stations 1, 5, and 8 were compared to base results. These stations were chosen because their location represented conditions found closest to the dam, close to the middle of the reservoir, and at the most upstream end of the reservoir, respectively.

There are differences between the base run (scenario a shown as a line) and scenario c. In the warmer months, temperature results show slightly more stratification. During October, temperature results for scenario c were decreased at stations 5 and 8, Figures 10 and 11, respectively. Slower travel time is producing temperature differences since inflow temperatures are the same.

SUMMARY AND CONCLUSIONS

CE-QUAL-W2 was applied to three reservoirs within the ACF/ACT River basins for two years. They were WFG, Neely Henry, and Weiss reservoirs. The initial year chosen for calibration (1992) represented the year with the most complete data available for calibration. As discussed earlier in this paper, these data lacked algal/nutrient profiles. Recalibration using profile data collected by ADEM in 1994 improved calibration results. The 1994 data provided more information which helped to describe processes of the algal/nutrient interactions (e.g., release of phosphorus and ammonia from the sediments). The original calibration year thus came the verification year.

After recalibration and verification were completed, three demonstration scenario runs were conducted: a) a base condition (1994 recalibration results); b) future conditions of lower water allocations (1988 flow conditions) with existing loads; and c) future conditions of lower water allocations (1988 flow conditions) with 20% higher waste loads. For scenario b, inflow concentrations were calculated using the lower 1988 and 1994 flows to produce the same loads that occurred in 1994 (see equation 4). In some cases, the calculated concentrations (C_{88}) were unrealistically high. Therefore, both scenarios b and c were also run using the observed 1994 concentrations (C_{94}), and a 20% increase in the C_{94} concentrations, respectively.

Temperature results for scenario b and c were the same since inflow temperatures were not changed in all scenario runs. However, when compared to scenario a results, hypolinetic temperature results in August for scenario b and c were decreased except at station 8 (Figure 11). During the cooler month of October, temperature results for profiles at station 5 and 8 were decreased. Temperature differences were attributed to slower travel times through the system.

REFERENCES

Cole, T. M. and H. H. Hannan. 1990. Dissolved oxygen dynamics. Reservoir Limnology Ecological Perspectives. Kent W. Thornton, Bruce L. Kimmel, and Forrest E. Payne, eds., New York, NY: John Wiley & Sons,Inc.

Cole, T. M. and E. M. Buchak. 1995. CE-QUAL-W2: A numerical two-dimensional, laterally averaged, hydrodynamic and water quality model, version 2.0 User Manual. Instruction Report El- 95-1. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

J. E. Edinger Associates, Inc. 1984. Response temperature calculator. Computer program, IBM-PC. Wayne, PA.

Mobile District. 1958. Walter F. George Lock and Dam Design Memorandum No. 13, Chattahoochee River, Georgia and Alabama. Mobile, AL: U.S. Army Engineer District, Mobile, Corps of Engineers.

Table 1
Final values for coefficients adjusted during temperature calibration at WFG

Coefficient	Value
Horizontal eddy viscosity	1.0 $m^2 s^{-1}$
Minimum vertical eddy viscosity	1.4 x $10^{-7} m^2 s^{-1}$
Horizontal eddy diffusivity	1.0 $m^2 s^{-1}$
Minimum vertical eddy diffusivity	1.4 x $10^{-4} m^2 s^{-1}$
Bottom frictional resistance	70.0 $m^{1/2} s^{-1}$
Fraction of solar radiation absorbed at the water surface	0.45
Light extinction - water	0.40 m^{-1}
Wind sheltering coefficient	1.0

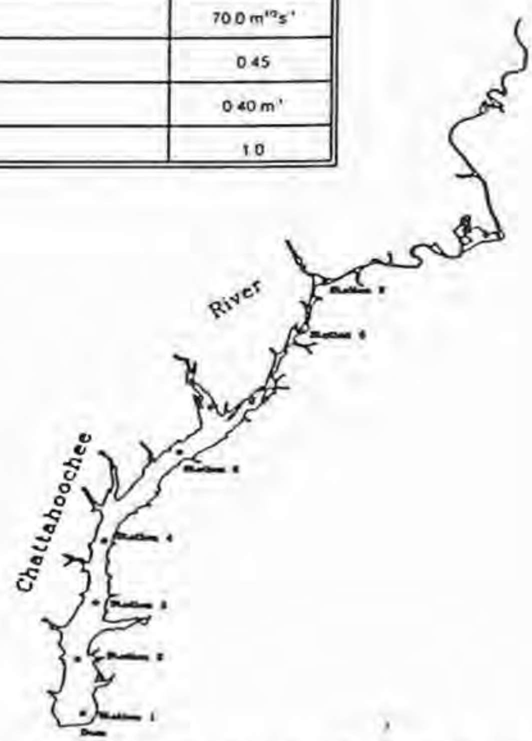


Figure 1. Site Map for Walter F. George

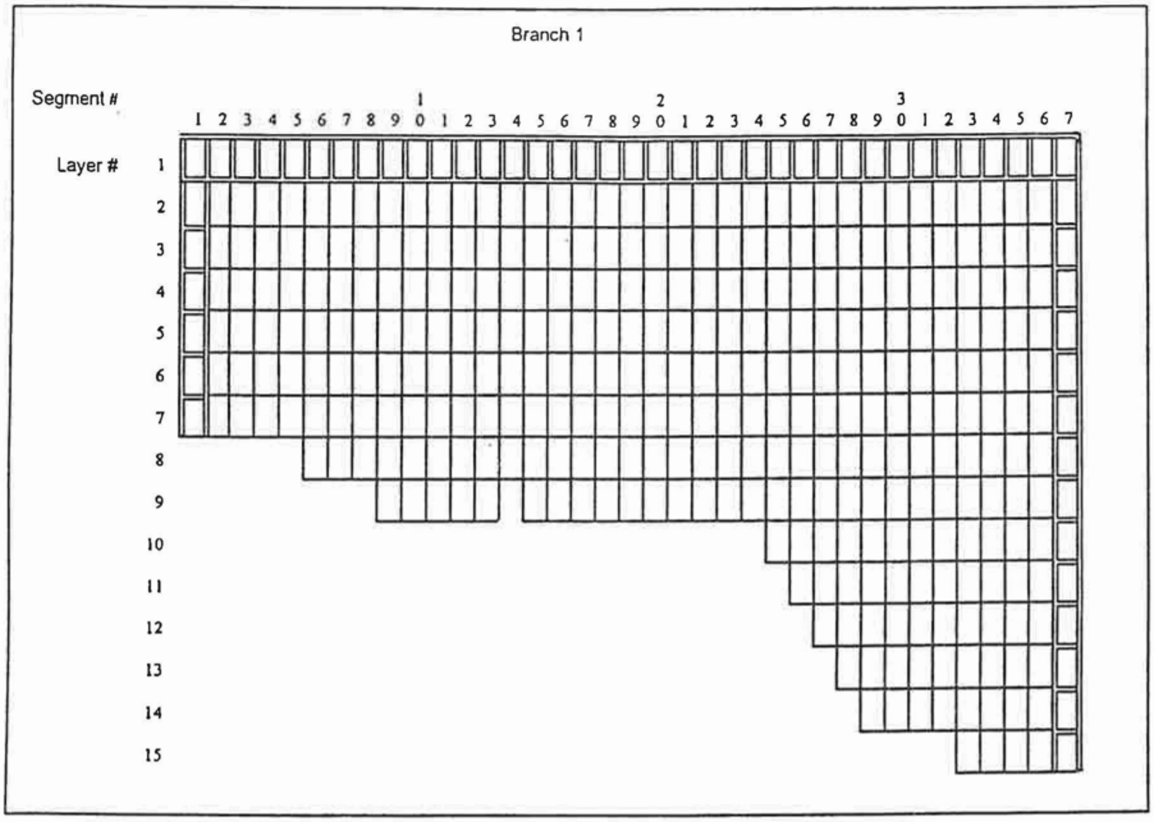


Figure 2. WFG computational grid

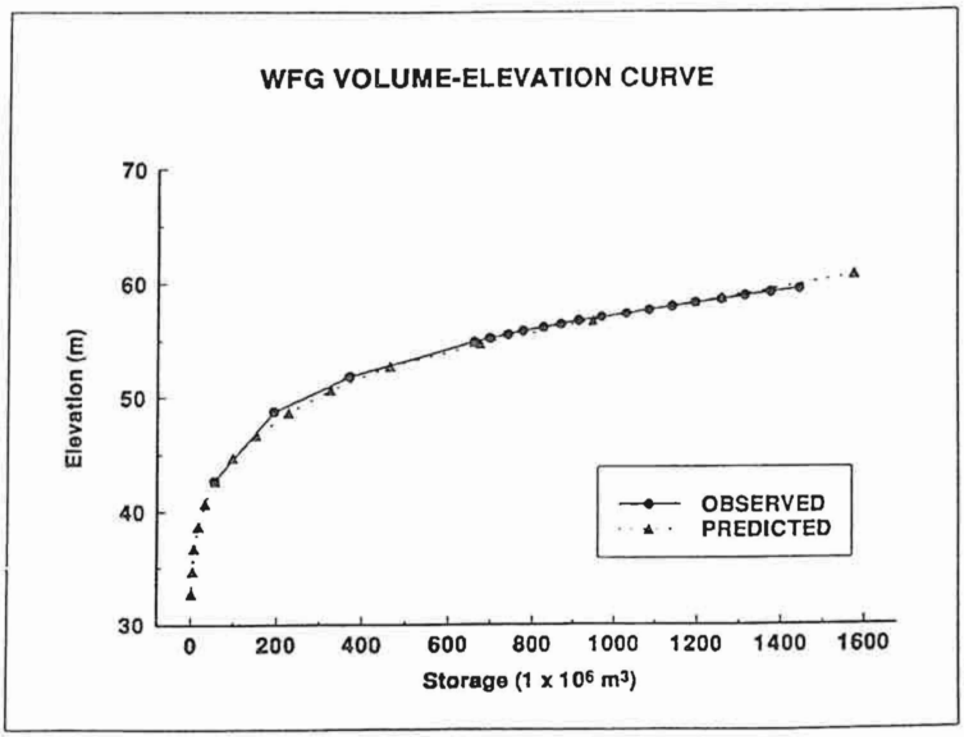
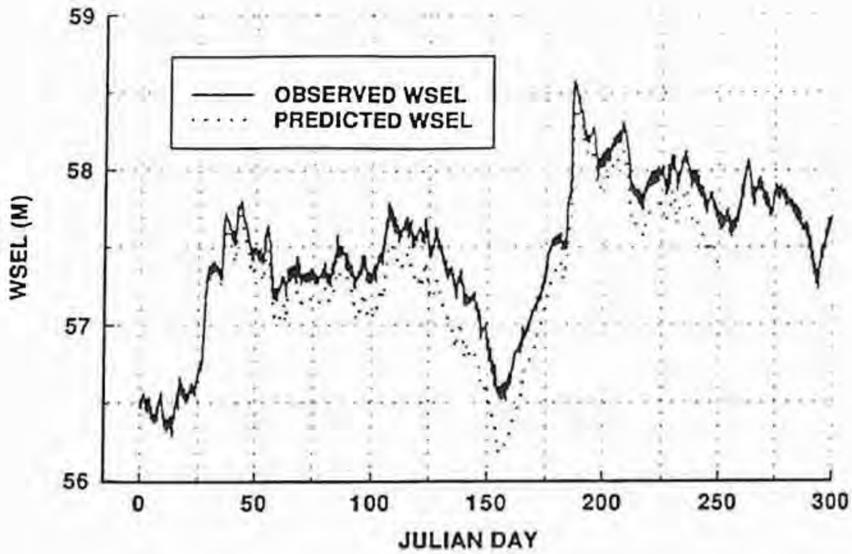
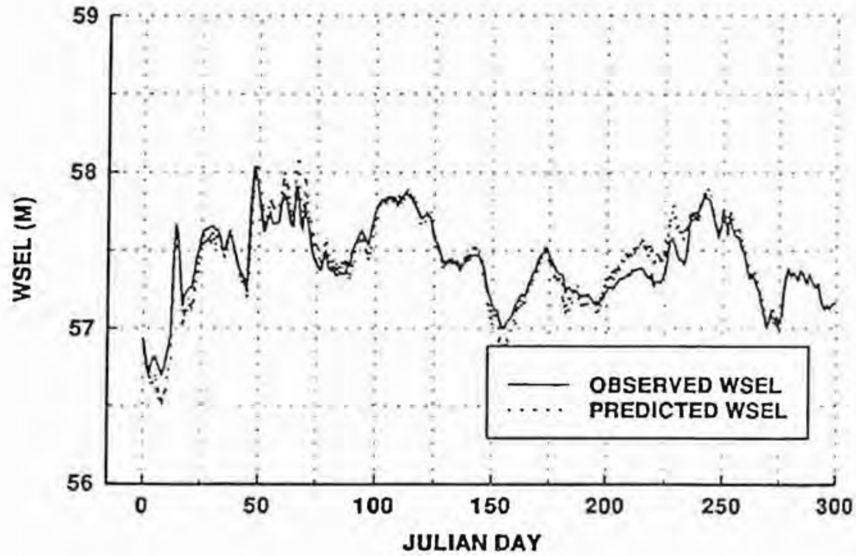


Figure 3. Walter F. George Reservoir computed versus observed volume elevation curves



a. 1994



b. 1992

Figure 4. Observed and computed water surface elevations for 1994 and 1992

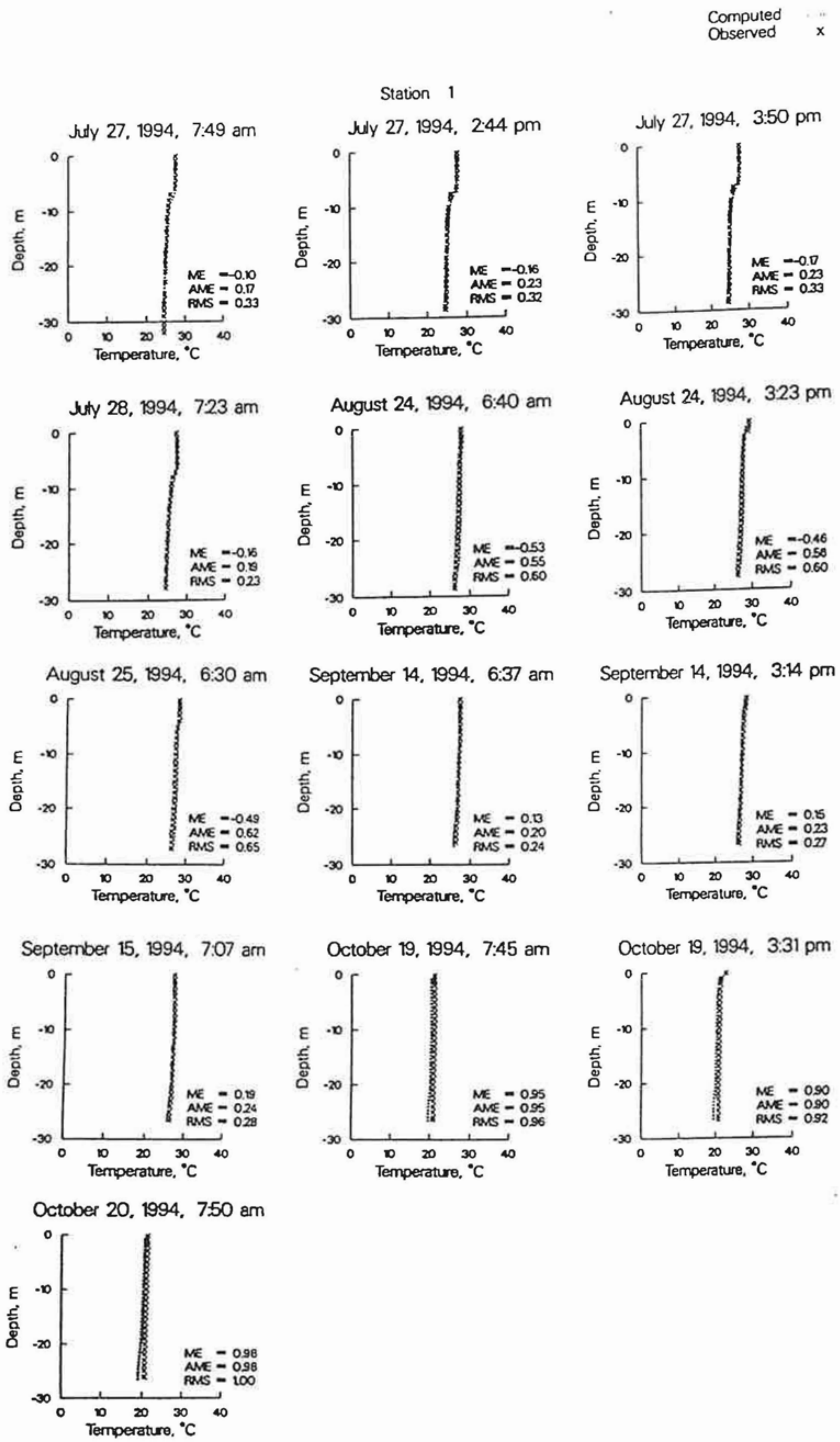


Figure 5. 1994 WFG station 1 Temperature results for July-October

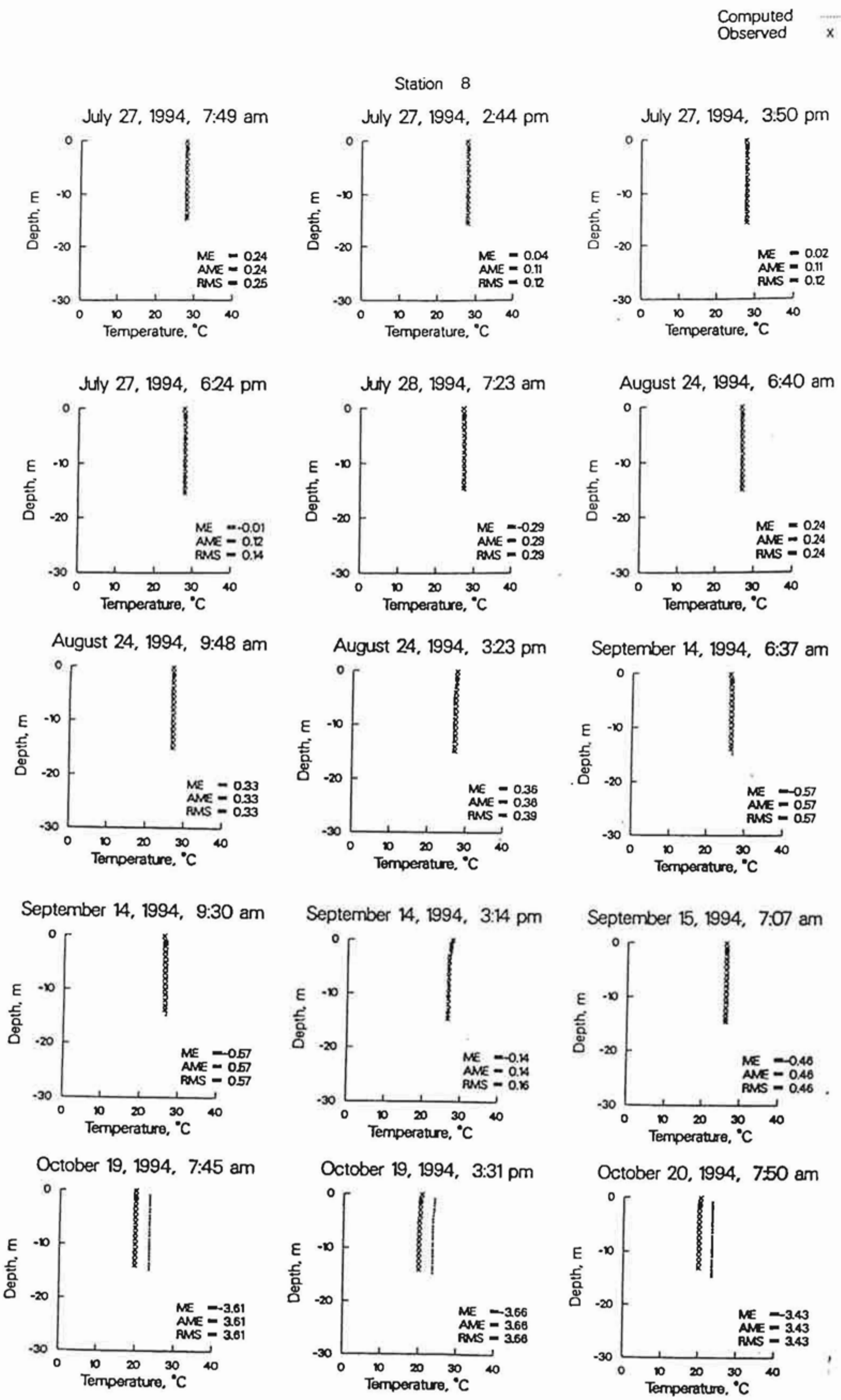


Figure 6. 1994 WFG station 8 Temperature results for July-October

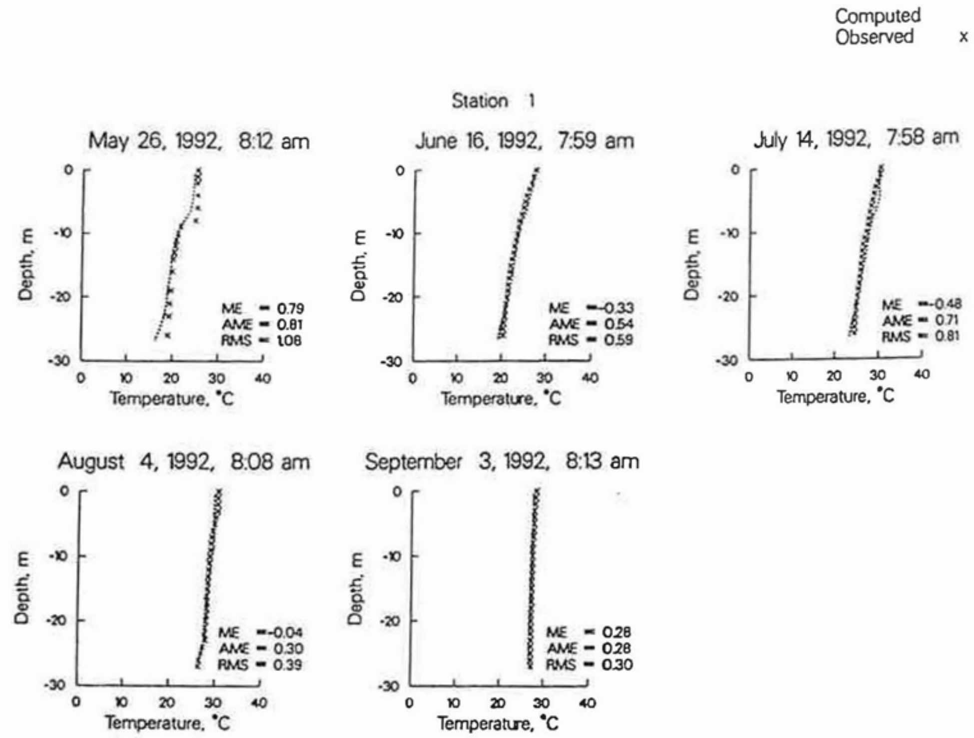


Figure 7. 1992 WFG station 1 Temperature results for May 26-September 3

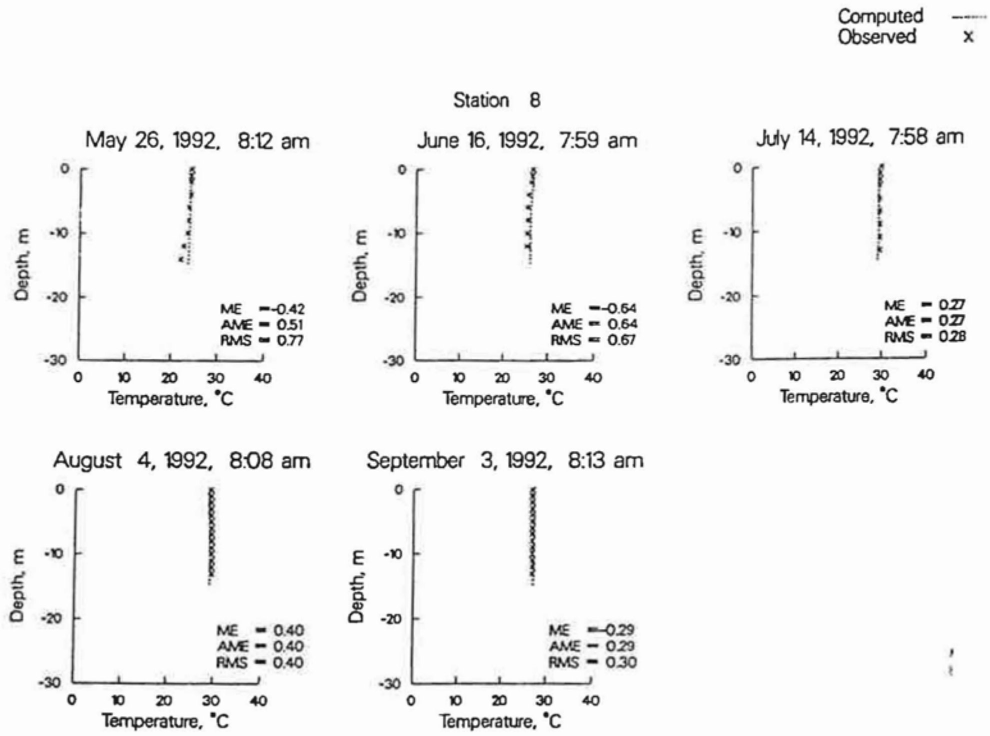


Figure 8. 1992 WFG station 8 Temperature results for May 26-September 3

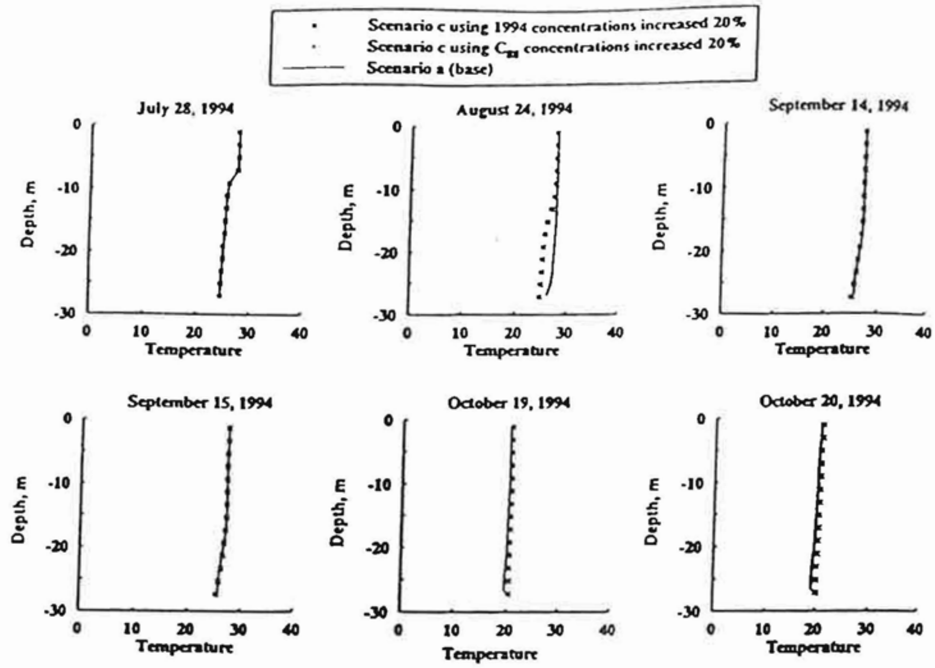


Figure 9. 1994 WFG station 1 Temperature results for July 28-October 20

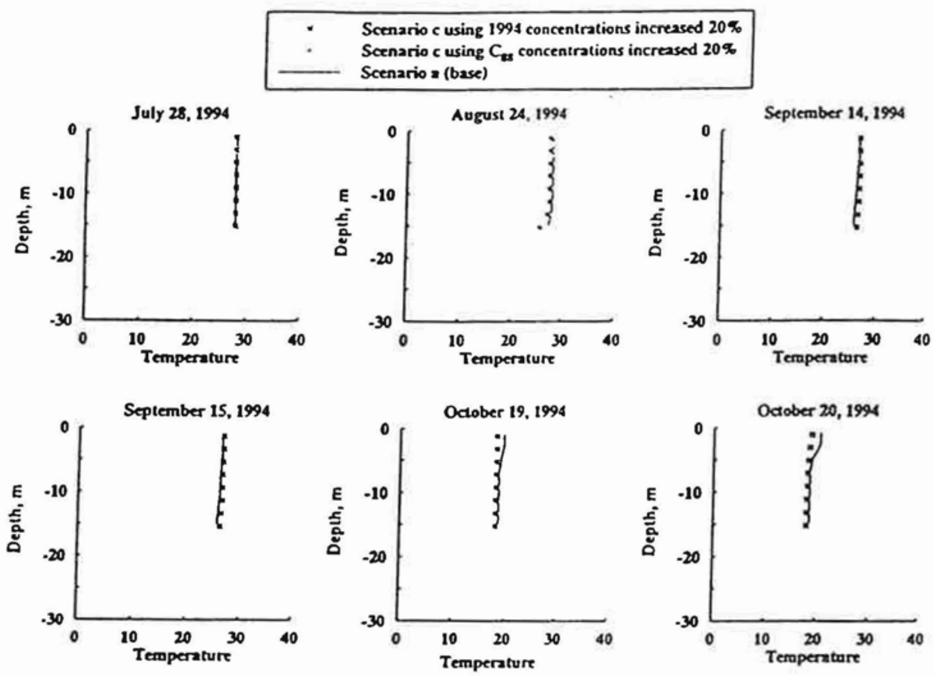


Figure 10. 1994 WFG station 5 Temperature results for July 28-October 20

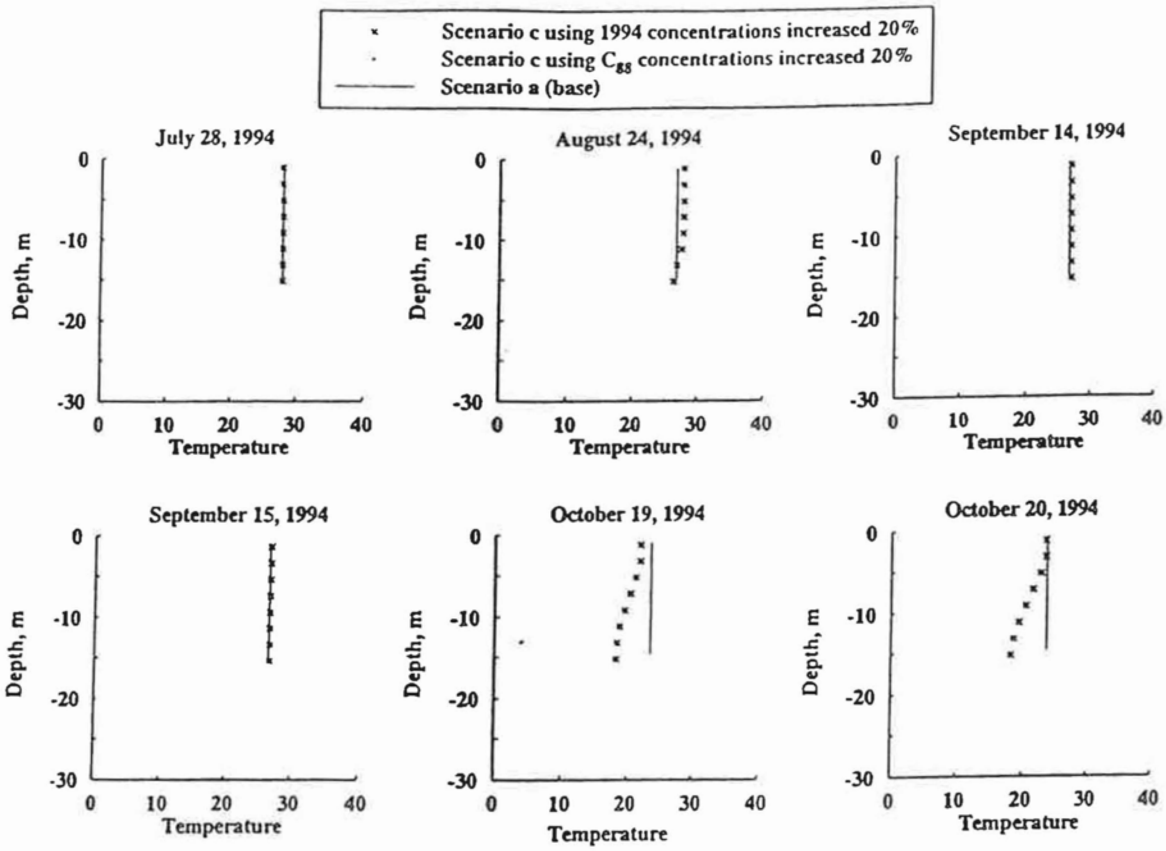


Figure 11. 1994 WFG station 8 Temperature results for July 28-October 20