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Executive Summary Report

THERMAL POLLUTION MATHEMATICAL MODEL

(Volume One of Seven Volumes)

THERMAL POLLUTION MODEL PACKAGE VERIFICATION AND TRANSFER

Volume I

by

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15. Abstract

Two three-dimensional time-dependent models, one free surface, the other rigid lid, have been verified at Anclote Anchorage and Lake Keowee respectively. The first site is a coastal site in northern Florida; the other is a man-made lake in South Carolina. These models describe the dispersion of heated discharges from power plants under the action of ambient conditions. A one-dimensional horizontally-averaged model was also developed and verified at Lake Keowee. The data base consisted of archival in-situ measurements and data collected during field missions. The field missions were conducted during winter and summer conditions at each site. Each mission consisted of four infrared scanner flights with supporting ground truth and in-situ measurements. At Anclote special care was taken to characterize the complete tidal cycle.

The three-dimensional model results compared with IR data for thermal plumes on an average within 1°C root mean square difference. The one-dimensional model performed satisfactorily in simulating the 1971-1979 period. The results have been reported in three separate reports, one for each model. Corresponding user's manuals have also been prepared. This report provides a summary of tasks performed.

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PREFACE

The thermal pollution group at the University of Miami has developed a set of three-dimensional predictive mathematical models under NASA-KSC sponsorship. These models were developed and calibrated at several lake and coastal sites. In 1978 a two year effort was initiated to verify these models at Anclote River, Florida, and Lake Keowee, South Carolina. This effort was sponsored by EPA-RTP and NASA-KSC. During this period, a one-dimensional model was also developed for long term heat budget studies of lakes. The models have been verified and the codes transferred to EPA-RTP together with user's manuals. The models can be used for thermal pollution impact studies and power plant siting decisions.

ABSTRACT

Two three-dimensional time-dependent models, one free surface, the other rigid lid, have been verified at Anclote Anchorage and Lake Keowee respectively. The first site is a coastal site in northern Florida; the other is a man-made lake in South Carolina. These models describe the dispersion of heated discharges from power plants under the action of ambient conditions.

A one-dimensional horizontally-averaged model was also developed and verified at Lake Keowee. The data base consisted of archival in-situ measurements and data collected during field missions. The field missions were conducted during winter and summer conditions at each site. Each mission consisted of four infrared scanner flights with supporting ground truth and in-situ measurements. At Anclote special care was taken to characterize the complete tidal cycle.

The three-dimensional model results compared with IR data for thermal plumes on an average within 1°C root mean square difference. The one-dimensional model performed satisfactorily in simulating the 1971-1979 period.

The results have been reported in three separate reports, one for each model. Corresponding user's manuals have also been prepared. This report provides a summary of tasks performed.

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SECTION 1

INTRODUCTION

BACKGROUND

Two thirds of the energy input to power plants is rejected by the cooling system to the surrounding environment. This can cause disturbances to the receiving ecology. A summary of these ecological effects is available in papers compiled in the proceedings of conferences on Waste Heat Management and Utilization (1, 2).

Discharges can be through open systems into lakes, rivers and coastal areas or through closed systems such as cooling towers. However, both systems ultimately transfer the heat to the atmosphere. Open systems have aquatic plumes. Closed systems have atmospheric plumes. References 1 and 2 contain numerous papers on these topics.

In order to anticipate the effects of thermal pollution, predictive modeling is necessary. These models can be physical or mathematical. Physical models have problems of geometric and turbulent scaling and costs of customized site specific construction associated with them. Mathematical models can be more general. A summary of mathematical models for surface discharges to the aquatic environment is presented by Dunn and Policastro (3).

THE UNIVERSITY OF MIAMI MODEL PACKAGE

The thermal pollution group at the University of Miami initiated an effort to develop a three-dimensional numerical model package that could be applied to a wide variety of aquatic discharge situations. The underlining guideline was to obtain a tool that was reasonably general in purpose with a minimum level of site specific assumptions. This effort resulted in two distinct models.

Free Surface Model

This model is a three-dimensional time-dependent model that allows the air/water interface to be free. It is suited for domains where surface wave heights are significant compared to mean water depth, such as estuaries and other coastal regions. This model computes the velocity, temperature and surface height variations with time, given a set of initial conditions and time-dependent boundary conditions. These conditions are available from local meteorological tidal and discharge conditions.

The model is easily adaptable to a new site since domain boundary is input through a marker matrix. The model includes a vertical normalization, thus facilitating application to domains of varying depth.

This model solves the time-dependent equations of motion and energy by explicit numerical schemes. The hydrostatic assumption is used. Turbulence is included through eddy transport coefficient approximations for momentum and heat transfer. The system of equations is coupled by an equation of state.

Versions of this formulation has been calibrated and applied to Biscayne Bay, Cutler Ridge discharge, Hutchinson Island discharge, and Lake Okeechobee. It has been verified as part of the present project at Anclote River discharge.

Rigid-lid Model

This is a time-dependent three-dimensional model where a rigid surface that allows slip is imposed. The surface elevation is no longer a parameter; an artificial lid pressure is introduced. This model is suitable for domains where surface wave height is small compared to depth, such as inland natural or man-made cooling lakes. This model computes the time-dependent velocity and temperature fields given a set of initial and time-dependent boundary conditions. This model has the same computational features as the free-surface model that allows relatively simple adaptation to different sites.

The formulation is the divergence of Navier-Stokes approach proposed by Sengupta (4). It combines the vertically integrated momentum equations to derive an elliptic equation for surface pressure. This equation is solved iteratively. The velocities and temperatures are obtained by using explicit finite difference schemes. The hydrostatic approximation is used together with the eddy transport coefficient hypothesis. An equation of state couples the temperature and the momentum equations.

Versions of this formulation have been calibrated and applied to 1) Biscayne Bay, 2) Cutler Ridge discharge, and 3) Lake Belews.

In the present study, this model has been verified at Lake Keowee in South Carolina.

Details of development and past applications are presented by Lee and Sengupta (5, 6, 7). The details of verification of these models are presented by Lee et al. (8, 9). The corresponding user's manuals are also prepared by Lee et al. (10, 11).

One-dimensional Model

While three-dimensional models are ideal for predicting detailed behavior of plumes, they are prohibitively costly for long term simulation.

Since long term heat budgets can be a measure of overall impact of thermal pollution, simpler models are necessary.

The one-dimensional model that has been developed as a part of the present study was calibrated with a data set for Lake Cayuga, New York, and has been verified at Lake Keowee, South Carolina. The model assumed horizontal homogeneity. However, it is unique amongst other models in that it includes effects of area change with depth together with mechanisms such as radiative penetration through the surface, nonlinear, interaction between wind and bouyancy gradients, and heat transfer by convection from the surface.

Details of the one-year simulation for Lake Cayuga and nine-year simulation for Lake Keowee are presented by Lee et al. (12). The user's manual is also provided by Lee et al. (13).

SECTION 2

CONCLUSIONS

The summary of conclusions from the application of the three models are presented below. The detailed conclusions are presented in References 8 through 13.

FREE-SURFACE MODEL

1. The model has simulated the behavior of a heated discharge into an ambient basin where drastic depth changes are occurring within acceptable computational cost.

2. The model has accommodated significant changes in ocean currents as a function of tidal forcing and produced stable, accurate solutions over several tidal cycles.

3. The model performs equally well over summer and winter conditions and significantly different atmospheric conditions.

4. Comparisons of model-predicted surface isotherms with measured infrared surface temperatures indicate agreement to approximately 1°C root mean square deviation.

5. The effects of inaccuracies in specification of initial conditions are negligible after half a tidal cycle for a shallow basin such as Anclote Anchorage.

6. Adequate data for execution of the model can be obtained from routine measurements ongoing at most power plants.

RIGID-LID MODEL

1. The model has simulated the hydrothermal behavior of the thermal discharge to Lake Keowee within acceptable computational cost in spite of relatively small grid spacings.

2. Significant changes in the plume caused by other inputs and outputs to Lake Keowee, such as Jocassee-pumped storage discharge and Oconee hydroelectrical plant, have been simulated accurately.

3. It has been demonstrated that short term behavior of a plume over a few days can be modeled satisfactorily by considering the mixing

only in the epilimnion.

4. The effects of inaccuracies in specifications of initial conditions become insignificant after approximately 8 to 12 hours.

5. The agreement both during summer and winter simulations between infrared measurements of surface temperature and model simulations was around 1°C root mean square deviation.

6. The data base needed to execute the model is readily available from routine measurements at most power plants.

ONE-DIMENSIONAL MODEL

1. This model provides better results at mid depths compared to other existing one-dimensional stratification models for lakes. This is attributed to the inclusion of effects owing to area change with depth which is somewhat unique to this model.

2. The model predicted the thermal stratification in Lake Keowee over a period of nine years with no year to year degeneration in results.

3. The model can be used to predict the approximate stratification in a lake with thermal discharges and other inputs and outputs such as pumped storage and hydroelectrical plants over a long term period.

USER'S MANUALS AND CODES

1. The program codes have been satisfactorily transferred to the EPA computer system at Research Triangle Park. Checks for accurate transfer have been made.

2. The user's manuals have also been prepared as separate volumes to facilitate use.

3. The ease with which staff at Research Triangle Park executed the programs using very brief instructions suggests that other users will find the programs easy to use by following the user's manuals.

SECTION 3

RECOMMENDATIONS

The detailed recommendations are summarized in References 8 through 13. A brief summary of recommendations is presented here.

1. The turbulent closures used for both the free-surface and the rigid-lid models could be changed to include effects of bouyancy through a Richardson number formulation. Higher order closures could also be included. Though there is no guarantee that this would improve predictions, it would include more of the mechanisms of turbulent transport.

2. The surface heat transfer conditions in the three-dimensional models could be improved where more data is available to separate individual components of heat transfer rather than using the surface heat transfer coefficient formulation.

3. The programs could be improved to facilitate use of variable horizontal grids. This would provide increasing spatial resolution near the discharge.

4. For the rigid-lid model, when a useable direct Poission solver for irregular domain, Neumann problem becomes available, it should be included in the model to solve the surface pressure equation. This would make the rigid-lid model significantly more efficient. It would reduce the computation time for solving the surface pressure field, which, at present, is the most time consuming part of the program.

5. Tests could be conducted with the models to determine sensitivity to open-boundary conditions when the domain is not completely surrounded by solid shorelines.

6. The one-dimensional model could be modified to simulate multiple domains connected by input/output terms. This would decrease the inaccuracies resulting from assuming horizontal homogeneity in multiple basin domains.

7. All the codes could be modified to become quasi-interactive to allow for easier execution by the user.

SECTION 4

SUMMARY OF TASKS PERFORMED

The detailed description of the efforts undertaken to verify the models and transfer the codes to EPA is presented by Lee et al. (8-13). A brief summary is presented below.

ANCLOTE APPLICATIONS

The map of the site is shown in Figure 1. The grid used for the model is shown in Figure 2.

Data Missions

1. Summer
   - a. Mission was carried out from June 19 to 20, 1978.
   - b. IR flights, ground truth data were carried out for the two days.
   - c. First IR flight started at EST 1733 and ended at 1852 on June 19 (low-low tide).
   - d. Second IR flight started at EST 0630 and ended at 0753 on June 20 (low tide).
   - e. Third IR flight started at EST 1103 and ended at 1234 on June 20 (high-high tide).
   - f. Fourth IR flight started at EST 1450 and ended at 1558 on June 20 (max ebb tide).
2. Winter
   - a. Mission was carried out from January 30 to February 1, 1979.
   - b. IR flights, ground truth data were carried out for these days.
   - c. First IR flight started at EST 1030 and ended at 1204 on January 30 (flood tide).
   - d. Second IR flight started at EST 1635 and ended at 1817 on January 30 (ebb tide).

e. Third IR flight started at EST 1503 and ended at 1649 on February 1 (high tide).

Model Execution

1. Preliminary Runs
    a. Simulation started at 1730 June 18, 1978.
    b. Total simulation time lasted for 51 hours or 4 tidal cycles.
    c. Current calculation began with zero velocity at 1730 June 18, 1978.
    d. Temperature calculation began with ambient temperature at 27° C.
    e. Temperature at discharge point specified to be sinusoidal of 24 hour period.
2. Verification for Summer
    a. Calculated current with measured current data.
    b. Calculated temperature compared with IR data at four (4) tidal stages.
    c. Comparison in terms of isotherm plots and derivation of calculated temperature from IR scanned temperature.
3. Verification for Winter
    a. Current calculation executed for north-south phase shift calibration.
    b. Calculated current found to be in agreement with measured current at similar tidal stages.
4. Accuracy of Predictions are shown in Table 1.

KEOWEE APPLICATION

Figure 3 describes the site of Lake Keowee station. The grid for the rigid-lid model applied to this site is shown in Figure 4.

Data Missions

1. Summer
    a. Mission was carried out from August 22 to 25, 1978.

   b. August 22/23: ground truth, plume, velocity and drogue data.

   c. August 24/25: ground truth, plume, velocity and drogue data.

   d. First IR flight started 0853 hours and ended 1002 hours August 24.

   e. Second IR flight started 1644 hours and ended 1745 hours August 24.

   f. Third IR flight started 0845 hours and ended 0953 hours August 25.

2. Winter

   a. Mission was carried out on February 27 and 28, 1979.

   b. IR flights, ground truth, plume, velocity and drogue data were carried out for the two days.

   c. First IR flight started 1549 hours and ended 1741 hours February 27.

   d. Second IR flight started 0850 hours and ended 1002 hours February 28.

   e. Third IR flight started 1514 hours and ended 1616 hours February 28.

Model Execution

1. Execution for September 10, 1975 was conducted and results compared with in-situ measurements obtained from Duke Power Company records.

2. Summer Verification

   a. Run number: L006, August 24 and 25 verification runs.

   b. Run started midnight August 23 and ended midnight August 25, 1978.

3. Winter Verification

   a. Run number: L007, February 27 and 28 verification runs.

   b. Run started midnight February 26 and stopped at midnight February 28.

4. Accuracy of Predictions are shown in Table 2.

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Table 1. Root Mean Square Difference Between IR and Predicted Temperature (Anclote Anchorage)

Time	RMS Difference
EST 1030 June 20, 1978	0.36°C
EST 1430 June 20, 1978	0.36°C
EST 1730 June 20, 1978	0.54°C
EST 2030 June 20, 1978	0.36°C
EST 1100 January 30, 1979	0.74°C
EST 1600 January 30, 1979	0.65°C

Table 2. Root Mean Square Difference Between IR and Predicted Temperatures (Lake Keowee)

Time	RMS Difference
Morning, August 24, 1978	0.55°C
Morning, August 25, 1978	0.34°C
Afternoon, February 27, 1979	0.82°C
Morning, February 28, 1979	0.01°C

Figure 1. Anclote Anchoarage location in the state of Florida

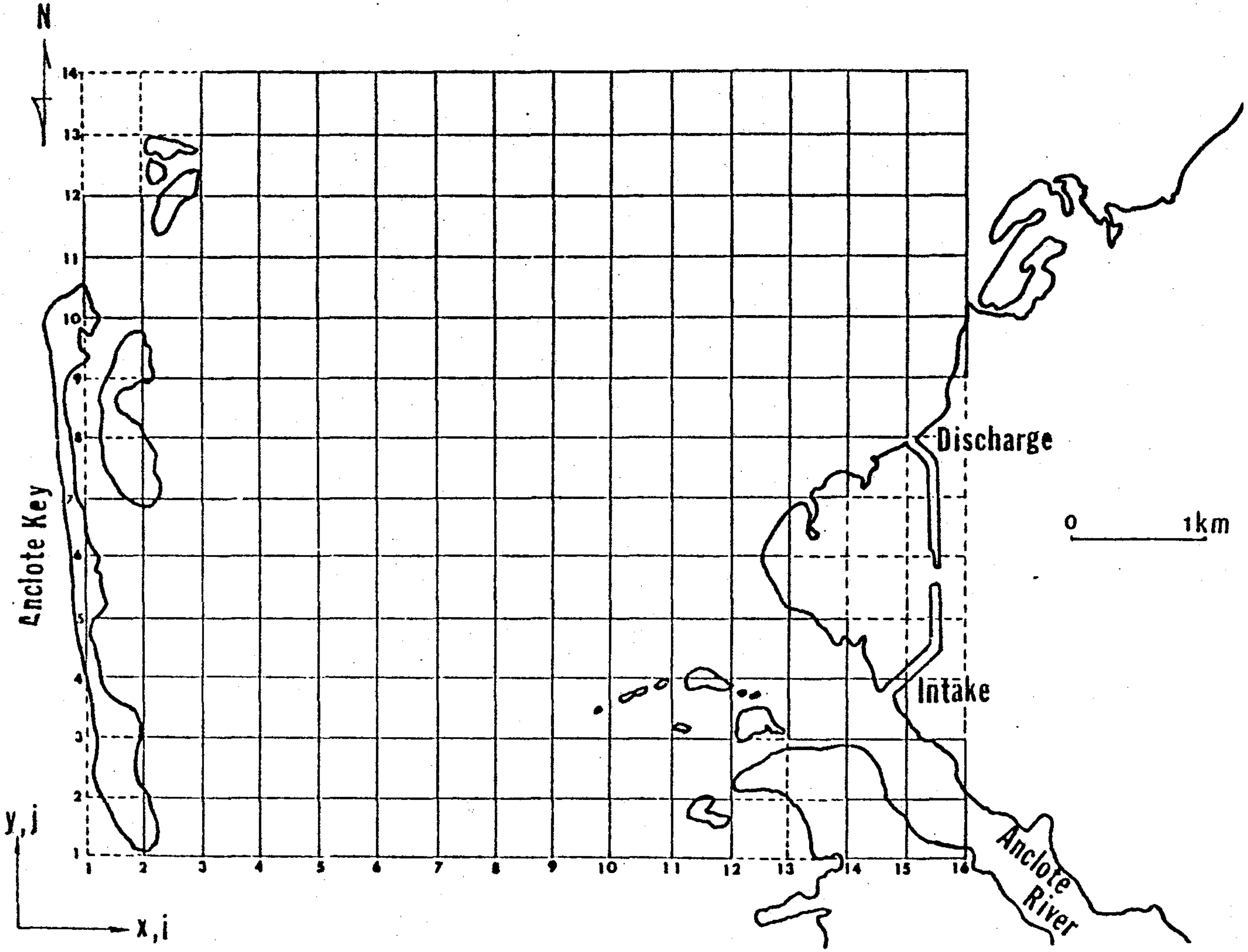

Figure 2. Grid work for Anclote Anchorage

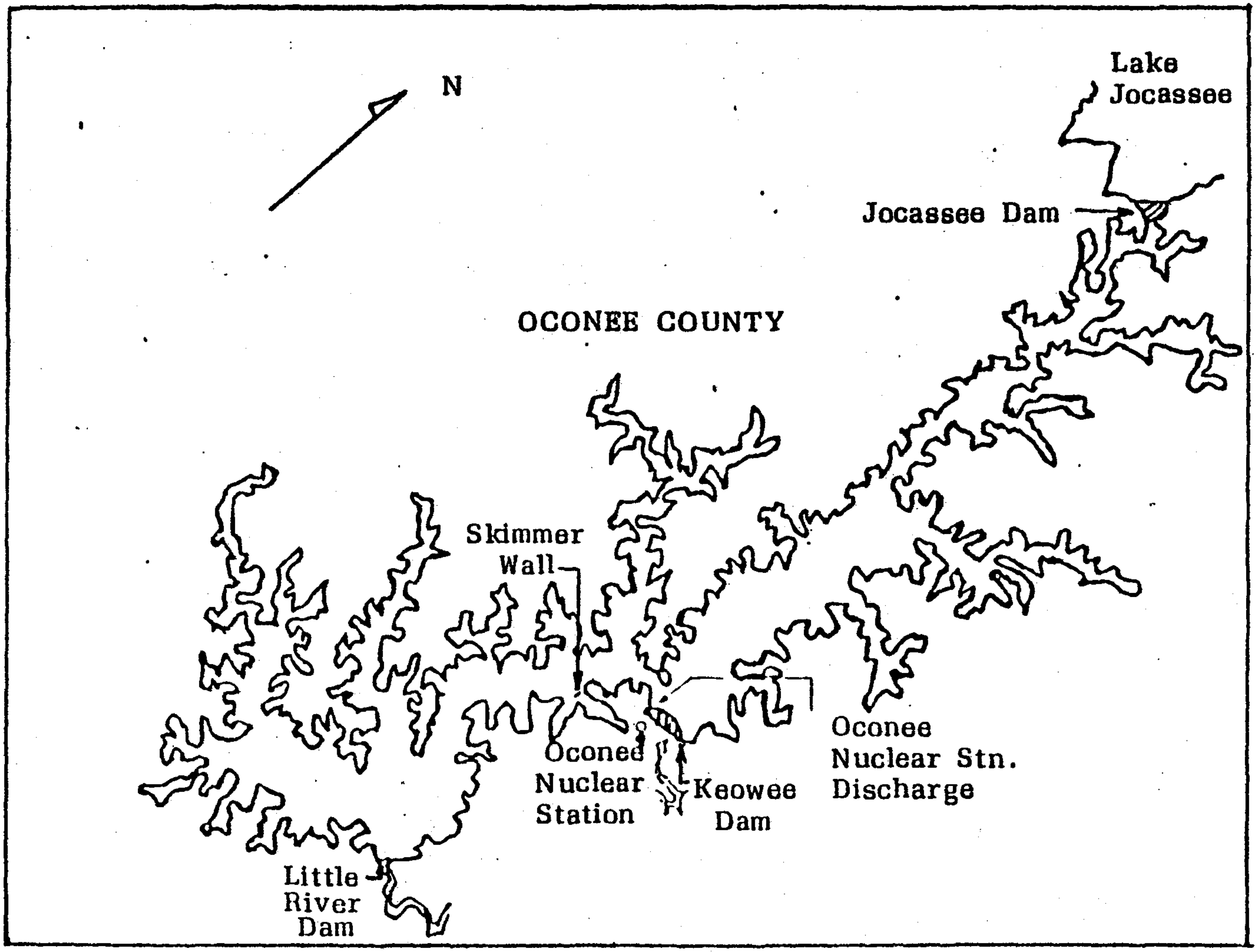

Figure 3. Lake Koewee

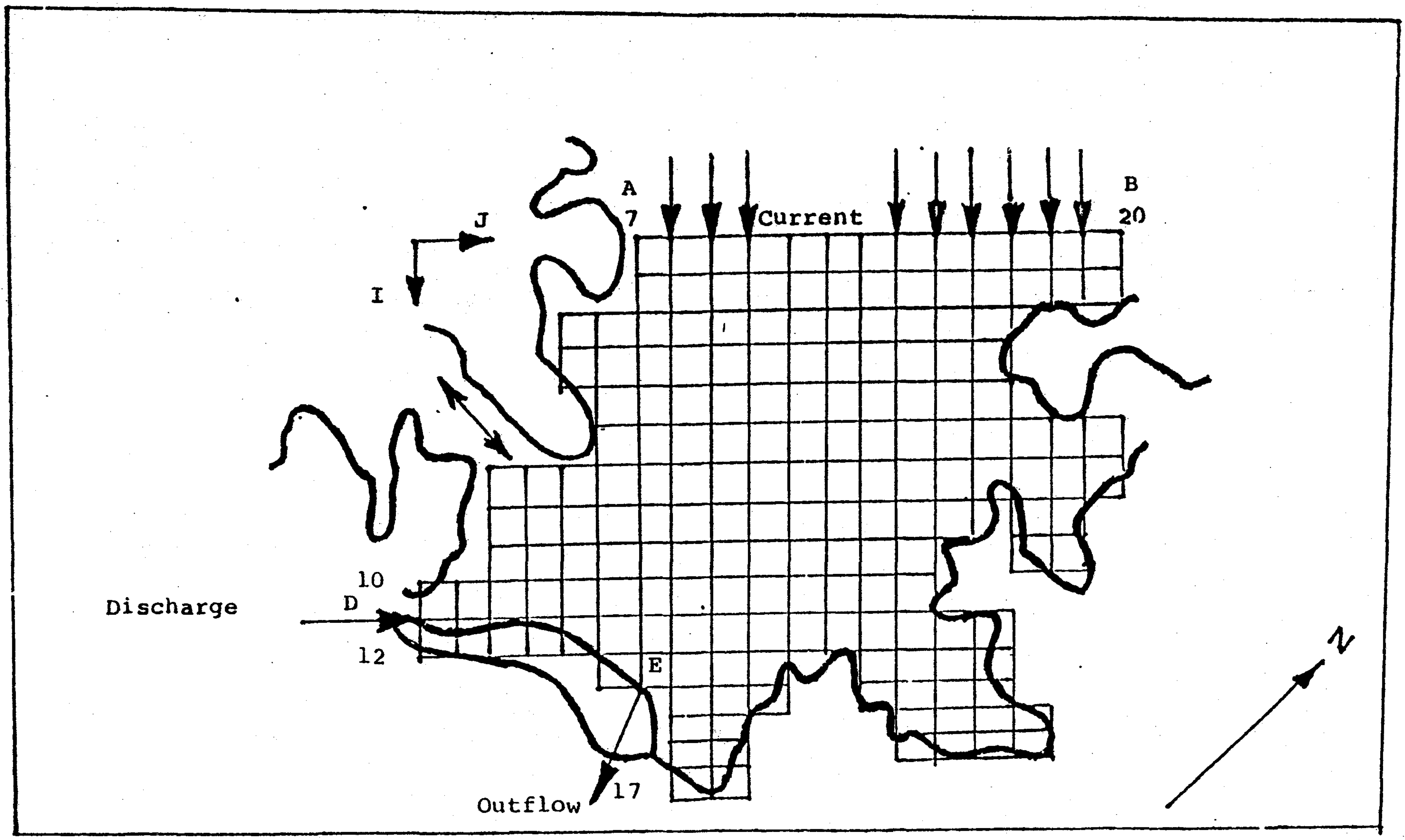

Figure 4. Lake Keowee (region of interest) showing inputs and outputs for three-dimensional model