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Project Summary

Verification and Transfer of Thermal Pollution Model

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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 aver aged 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 (IR) 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 are reported in three separate reports, one for each model. Corresponding user's manuals have also been prepared. This report summarizes all six documents.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Background

Two-thirds of the energy input to power plants is rejected by the cooling system to the surrounding environment. This can disturb the receiving ecology. A summary of these ecological effects is available in papers 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 many papers on these topics.

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 et al.[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 discharges. The underlying guideline was to obtain a tool that was reasonably general with a minimum level of site-specific assumptions. This effort resulted in two models: one, free-surface; the other, rigid-lid.

Free-surface Model

This model is three-dimensional and time-dependent, allowing the air/water interface to be free. It is suited for domains where surface wave heights are significant compared to mean water depth; e.g., 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 that facilitiates 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 have 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; e.g., 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 and Lick[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 Biscayne Bay, Cutler Ridge discharge, and Lake Belews.

The present study verified this model at Lake Keowee in South Carolina.

Details of development and past applications are presented by Lee and Sengupta[5,6,7]. Details of verification of these models are presented in Volumes I and III, summarized by this document.

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, developed as a part of the present study, was calibrated with a data set for Lake Cayuga, NY, and has been verified at Lake Keowee, SC. The model assumed horizontal homogeneity. However, it is unique among 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 buoyancy gradients, and heat transfer by convection from the surface.

Details of the 1-year simulation for Lake Cayuga and the 9-year simulation for Lake Keowee are presented in Volume V, summarized by this document.

Summary of Tasks Performed

The efforts to verify the models and transfer the codes to EPA, described in the six volumes of this report, are summarized below.

Anclote Applications

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

Figure 1. *Anclote Anchorage in Florida.*

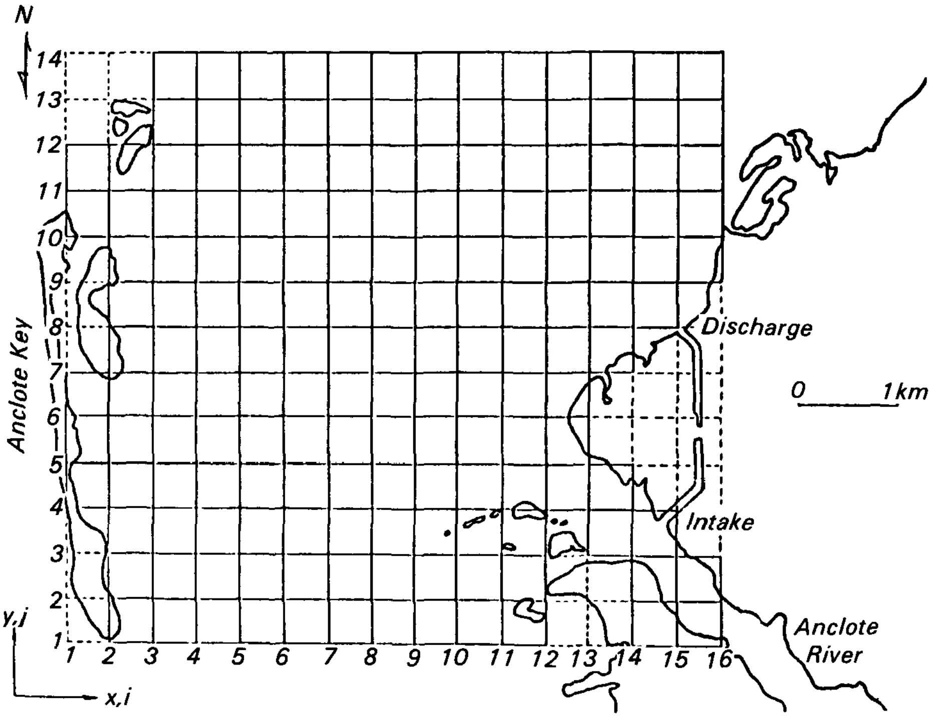

Figure 2. *Grid work for Anclote Anchorage.*

Data Missions

1. Summer
    a. Mission was carried out on June 19 and 20, 1978.
    b. IR flights (ground truth data) were carried out for the 2 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 four 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 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 is 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 at 0853 and ended at 1002 on August 24.
    e. Second IR flight started at 1644 and ended at 1745 on August 24.
    f. Third IR flight started at 0845 and ended at 0953 on 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 2 days.
    c. First IR flight started at 1549 and ended at 1741 on February 27.
    d. Second IR flight started at 0850 and ended at 1002 on February 28.
    e. Third IR flight started at 1514 and ended at 1616 on February 28.

Model Execution

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

Table 1. *Root-Mean-Square Difference Between IR and Predicted Temperatures (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*

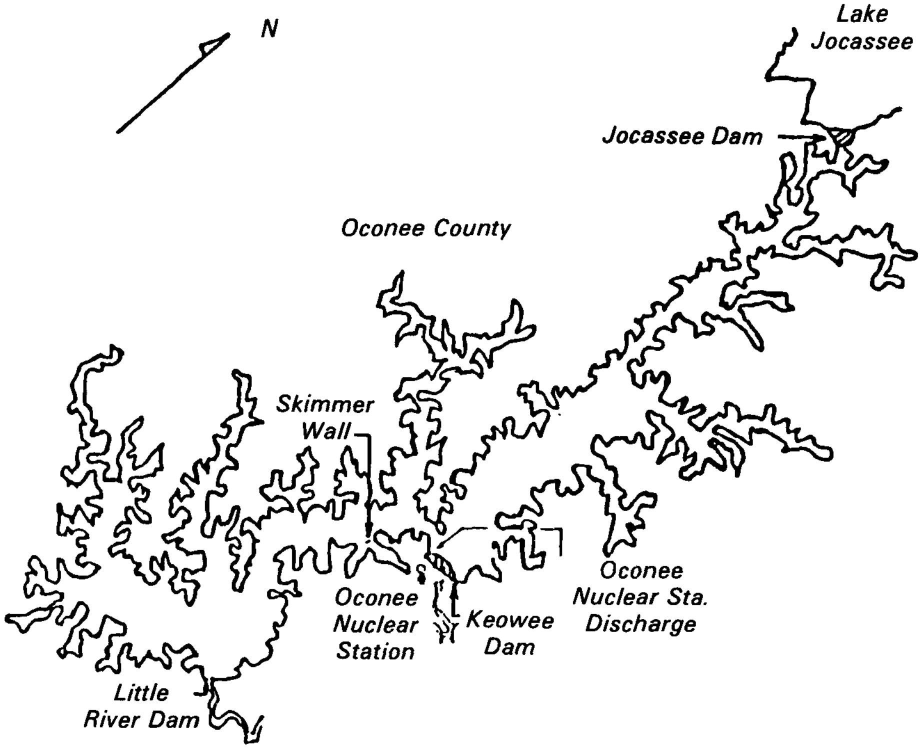

Figure 3. Lake Keowee.

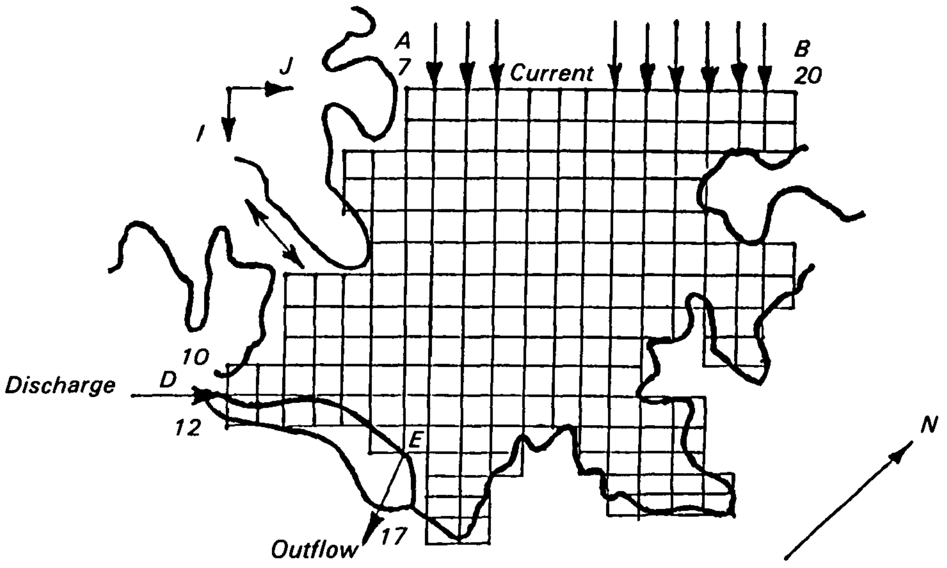

Figure 4. Lake Keowee (region of interest) showing inputs and outputs for three- dimensional model.

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*

2. Summer Verification
   a. Run number: L006, August 24 and 25 verification runs.
   b. Run started at 2400 on August 23 and ended at 2400 on August 25, 1978.
3. Winter Verification
   a. Run number: L007, February 27 and 28 verification runs.
   b. Run started at 2400 on February 26 and stopped at 2400 on February 28.
4. Accuracy of predictions is shown in Table 2.

Conclusions

Conclusions from the application of the three models are summarized below. Detailed conclusions are presented in Volumes I through VI of the full report.

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 hydroelectric 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 about 8-12 hours.
5. The agreement both during the 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 unique to this model.
2. The model predicted the thermal stratification in Lake Keowee over a period of 9 years with no year-to-year degeneration in results. 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 hydroelectric plants over a long term period.

User's Manuals and Codes

1. The program codes have been satisfactorily transferred to EPA's computer system at Research Triangle Park. Accurate transfer has been checked.
2. The user's manuals were prepared as separate volumes to facilitate their use.
3. The ease with which the 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.

Recommendations

Recommendations include:

1. The turbulent closures used for both the free-surface and the rigid-lid models could be changed to include effects of buoyancy 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 Poisson solver for the 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.

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The complete report consists of six volumes, entitled "Verification and Transfer of Thermal Pollution Model:"

- *"Volume I. Verification of Three-Dimensional Free-Surface Model," (Order No. PB 82-238 569; Cost: $13.00, subject to change)*
- *"Volume II. User's Manual for Three-Dimensional Free-Surface Model," (Order No. PB 82-238 577; Cost: $16.00, subject to change)*
- *"Volume III. Verification of Three-Dimensional Rigid-Lid Model," (Order No. PB 82-238 585 Cost: $13.00, subject to change)*
- *"Volume IV. User's Manual for Three-Dimensional Rigid-Lid Model," (Order No. PB 83-116 103; Cost: $16.00, subject to change)*
- *"Volume V. Verification of One-Dimensional Numerical Model," (Order No. PB 82-238 601; Cost: $14.50, subject to change)*
- *"Volume VI. User's Manual for One-Dimensional Numerical Model," (Order No. PB 82-238 619; Cost: $10.00, subject to change)*

The above reports will be available only from:

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