EWQOS

ENVIRONMENTAL & WATER QUALITY OPERATIONAL STUDIES

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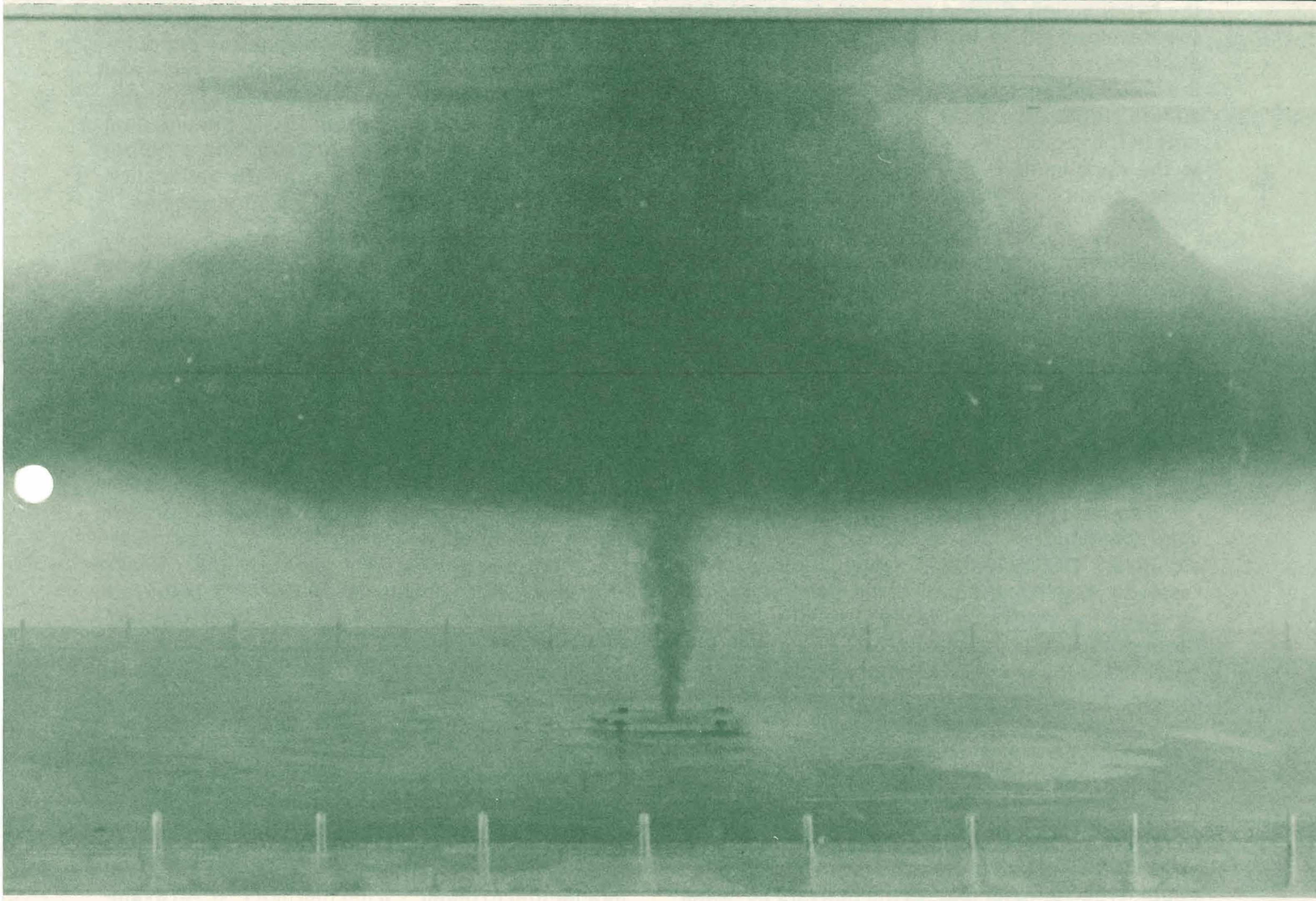


Density stratification in the waters of a reservoir may cause reduced dissolved oxygen (DO) content and anoxic conditions in the deeper waters (hypolimnion) even though the surface waters (epilimnion) may be saturated with DO because the stratification restricts the vertical transport of DO. The DO depletion results in poor water quality in the hypolimnion and may also impact downstream water quality if hypolimnetic releases are required.

Both pneumatic and hydraulic methods of transferring oxygen to the hypolimnetic region are being investigated as part of the Environmental and Water Quality Operational Studies (EWQOS). The investigation of hydraulic destratification, described in the following article, included physical and mathematical models. The photo above shows a hydraulic model of a vertical jet penetrating the thermocline and the subsequent density interflow.

HYDRAULIC DESTRATIFICATION

J. P. Holland, M. S. Dortch, and D. R. Smith*

When density stratification develops in a reservoir, the hypolimnion may become deficient in oxygen. Although the epilimnetic waters of the reservoir may be saturated with dissolved oxygen (DO), the density gradient separating the epilimnion and hypolimnion inhibits the vertical transport of DO between the two regions. Additionally, penetration of light into the relatively deep hypolimnion is usually minimal, and little (if any) oxygen is produced from photosynthesis. As a result, biochemical processes tend to gradually reduce the DO level in the hypolimnion. Such a reduction could result in the development of anaerobic conditions in the hypolimnion, thereby enhancing the probability of the dissolution of trace metals, release of hydrogen sulfide, depression of the pH, and release of nutrients in the region. The resulting poor water quality in the hypolimnion, in turn, impacts downstream water quality when hypolimnetic releases are required.

Numerous methods have been suggested for transferring oxygen(O_2) to the hypolimnetic region. One method utilizes artificial circulation to destratify the reservoir. Complete or partial destratification is achieved by the continuous mixing of the hypolimnetic waters with the oxygen-rich epilimnetic waters. The elimination of stratification results in DO and temperature distributions that are essentially constant in the vertical direction.

The redistribution of the in situ DO combined with enhanced surface reaeration can result in a significant DO increase in deeper regions of the reservoir. The redistribution of the reservoir thermal structure results in an increased temperature in the lower region of the reservoir, and a complementary decrease in the temperature of the upper region. If this change in the lake thermal structure does not adversely impact the reservoir ecosystem or release objectives, transfer of DO into the lower region by destratification may be a viable option.

Two methods of destratification, pneumatic and hydraulic, have been employed. With pneumatic destratification, compressed air is injected through a submerged diffuser and, as the buoyant air-water plume rises to the surface, mixing results. In hydraulic destratification, mixing is achieved by pumping water from some region in a reservoir to a region of different density. Although both methods have been effective in small lakes, no design guidance exists for large reservoirs. As part of the EWQOS Work Unit IIIB, both destratification techniques are being investigated .The results of the initial efforts on pneumatic destratification were reported in Vol E-80-2, April 1980. A synopsis of the hydraulic destratification investigation is presented herein.

APPROACH

To develop initial design guidance, a systematic parametric laboratory study was conducted with hydraulic models. Initially, various injection orientations were investigated to determine the most efficient injection scheme. The model tests simulated density stratification typically encountered in CE impoundments and pumping rates and reservoir dimensions that could be scaled to prototype dimensions. Subsequently, a dimensional analysis study was conducted to develop a mathematical model that described the destratification response for the most efficient injection scheme.

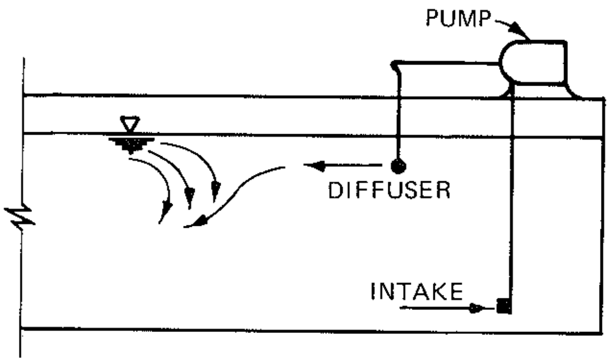
The model tests were conducted by initially stratifying a rectangular model and subsequently destratifying by vertical or horizontal injection into the epilimnion or the hypolimnion (Figure 1). Withdrawal was always horizontally and vertically remote from injection. During each test, constant and equal injection and withdrawal rates were used.

RESULTS

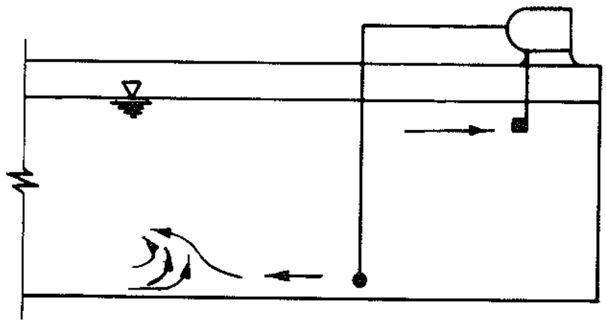
Orientation. Two geometric factors, injection orientation (vertical or horizontal) and diffuser-intake orientation, were considered of prime importance prior to testing. The latter, diffuser-intake orientation, was found to have little effect on the rate of destratification for a given injection orientation. The injection orientation, however, was found to significantly affect the rate of destratification. Vertical injection of jets that penetrate the thermocline was found to be much more efficient in destratifying a body of water than horizontal injection. A typical comparison of epilimnetic injection for the vertical and horizontal schemes is shown in Figure 2.

Vertical jets are inherently more efficient than horizontal injection if the vertical jet has sufficient momentum to penetrate the thermocline. An example of this is indicated in the cover photo of vertical injection in the hypolimnion toward the epilimnion. The initial jet momentum in the hypolimnion produces entrainment of dense hypolimnetic water; the momentum of the rising plume results in penetration of the jet into the epilimnion to a height at which the density is less than the density of the plume. As the

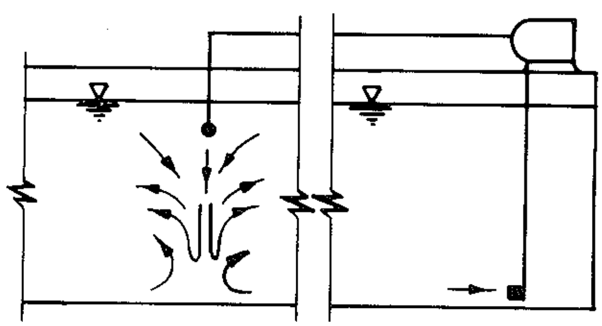
** Smith is a Supervisory Research Hydraulic Engineer and is Chief, Reservoir Water Quality (Physical) Branch, Hydraulic Structures Division, of the WES Hydraulics Laboratory; Holland and Dortch are Research Hydraulic Engineers assigned to the same organization.*



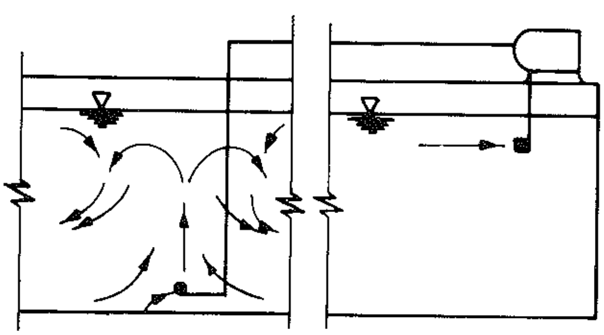
a. Horizontal injection in the epilimnion



b. Horizontal injection in the hypolimnion



c. Vertical injection in the epilimnion



d. Vertical injection in the hypolimnion

Figure 1. Schematic of diffuser-intake orientation

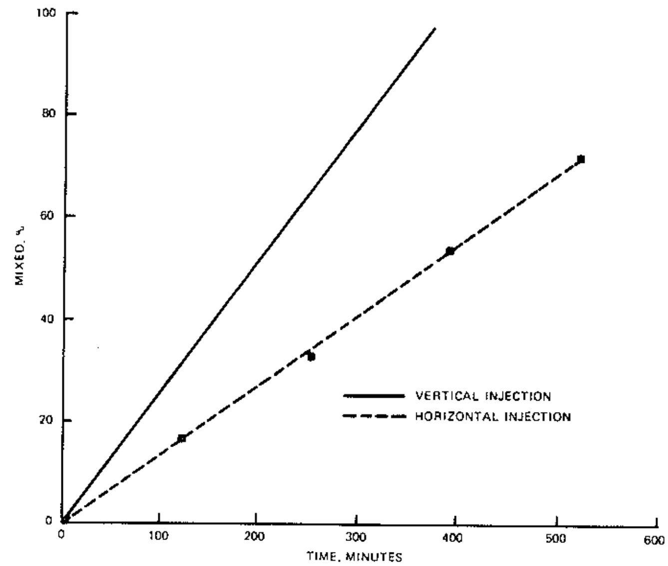


Figure 2. Comparison of mixing accomplished with vertical and horizontal injection of epilimnetic waters into the hypolimnion

plume falls to a level of neutral buoyancy, epilimnetic water is entrained. An analogous dual entrainment process occurs if water is withdrawn from the hypolimnion and vertically injected into the epilimnion toward the hypolimnion. Since horizontal injection results in much less vertical momentum, entrainment is predominantly limited to the zone of injection and is therefore less effective.

System response. Although vertical injection schemes are relatively efficient, they should not be designed for complete destratification. A typical mixing response with respect to time is indicated in Figure 3. As indicated by the density profiles, immediately after injection is initiated, the mixing process proceeds rapidly. However, with increasing time the mixing rate tends to decrease asymptotically in both the epilimnion and hypolimnion. This effect is especially dominant near the surface and bottom of the reservoir.

These results suggest that either very large pumping rates or prohibitively long time frames may be required to produce a homogeneous reservoir. However, for prototype applications, complete mixing is not a requisite. As indicated in Figure 3, the reservoir can be considered mixed, at least to a first approximation, after approximately 80-percent mixing. Diurnal heat exchange and wind mixing should augment mixing near the surface. The unmixed layer near the bottom boundary would result in only a small volumetric contribution to the withdrawal zone, even for bottom withdrawal. Thus, the lower unmixed region would not compromise released water quality.

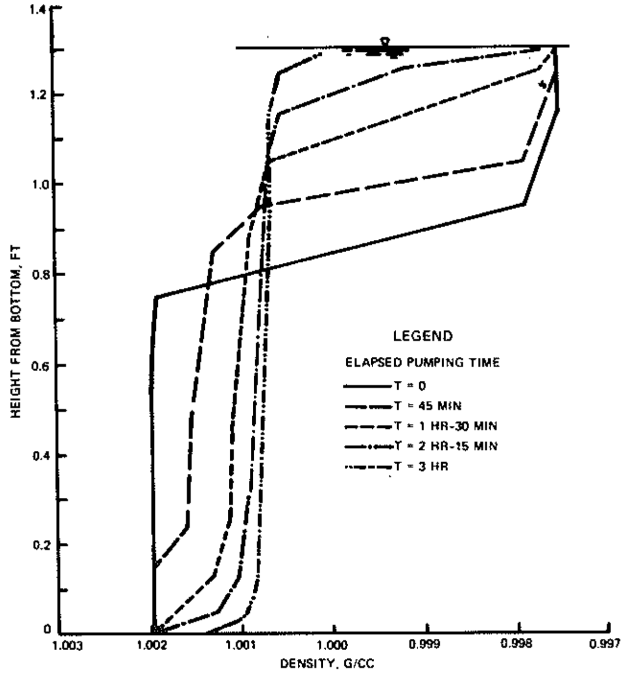


Figure 3. Typical mixing results from artificial destratification

Given these considerations, emphasis was placed on determining the operating conditions required to produce an 80-percent-mixed reservoir.

Predictive equations. The time required for a reservoir to become 80-percent mixed depends upon a large number of variables such as the input power, depth and volume of the reservoir, magnitude of stratification, etc. However, the system response can be characterized by a small number of dimensionless groupings that characterize the dominant hydrodynamical processes.

For vertical injection, only three dimensionless groupings are required: dimensionless time t^* and the respective densimetric Froude numbers of the reservoir (F_{DR}) and jet (F_j). The dimensionless time is equivalent to the fraction of the reservoir volume that has been pumped; F_{DR} describes the effect of the spreading interflow on mixing; and F_j addresses the effect of entrainment induced by the jet momentum. A plot of the relationship between these variables is presented in Figure 4. Regression analysis of this relationship yielded the equation.

$$t^*_{80\%} = 0.00306\,(F_j\,F_{DR})^{-0.54}$$

From the equation, the effects of reservoir and diffuser geometry upon mixing times can be parameterized; pumping requirements to produce an 80-percent-mixed reservoir in a specified time frame can be estimated; and mixing times can be established given diffuser and reservoir geometries and the pumping rate.

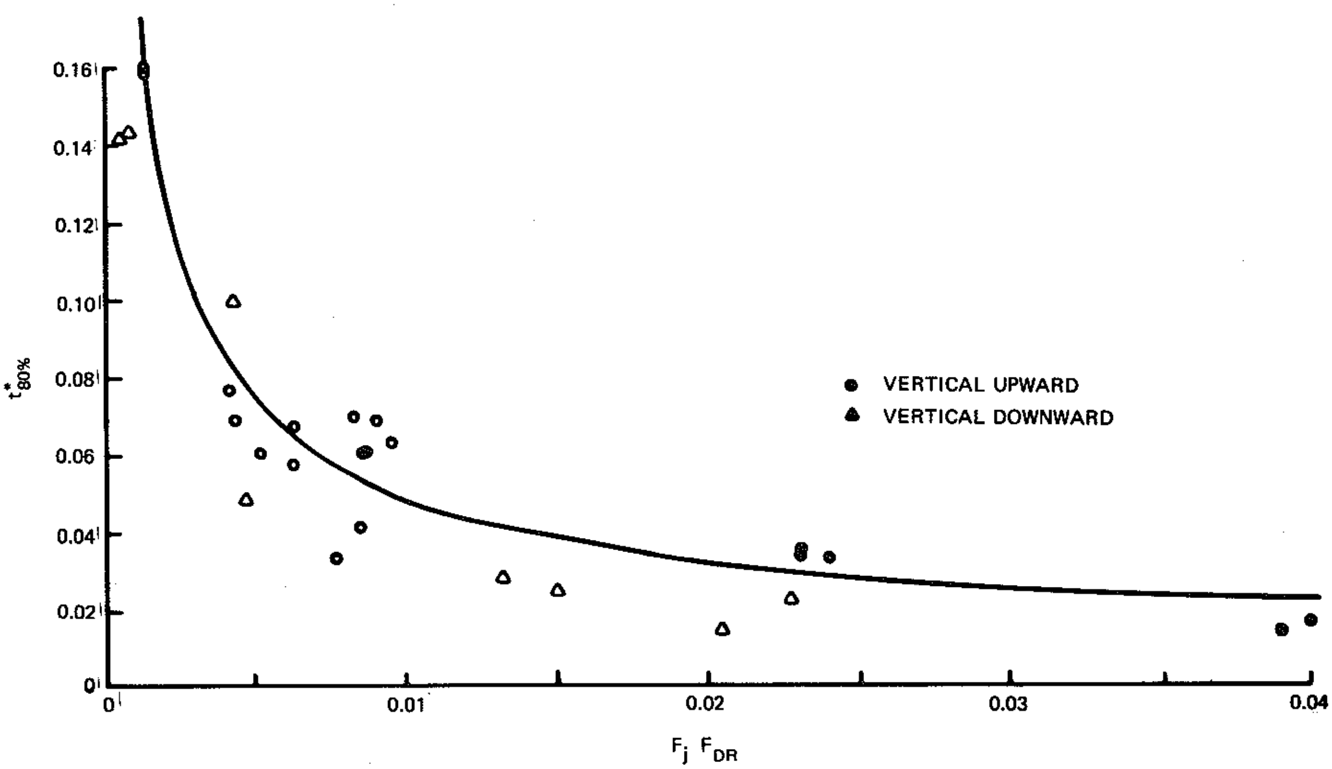


Figure 4. Destratification characteristics of vertical injection

SUMMARY

A parametric laboratory study was conducted to determine the effects of diffuser-intake and injection orientation upon the rate of hydraulic destratification. From analysis of the study results, it was concluded that the rate of destratification was insensitive to diffuser-intake orientation for a given injection orientation. However, the orientation of injection significantly affected the rate of destratification. Vertical injection that penetrated the thermocline was found to be a more efficient mechanism for hydraulic destratification than horizontal injection.

Hydraulic destratification systems shoud be designed to produce an approximately 80-percent-mixed state. Design of a system to produce a homogeneous reservoir would inherently require pumping rates and/or times that are prohibitive. The 80-percent mixed state is essentially equivalent to the fully mixed state except at the vertical reservoir boundaries and can be achieved with realistic pumping rates and times.

A dimensionless description of the hydraulic destratification process was developed. This description correlates normalized mixing time t^* with a dimensionless Froudian product. The latter dimensionless grouping addressed the effects of momentum, buoyancy, and elementary reservoir geometries as they pertain to mixing time. This description may be used in the preliminary stages of hydraulic destratification system design to investigate the feasibility of destratification. Research is being conducted to physically model destratification on a site-specific basis. Upon completion, engineering designs can be developed from laboratory experiments.

RESERVOIR SYSTEM ANALYSIS FOR WATER QUALITY

R. G. Willey*

The Corps desires to operate each of its reservoirs according to the best water management procedures available. In general, most Corps reservoirs are already operated in that manner for the facility as it presently exists. EC 1110-2-214 on "Instream Flow Problems and Needs Evaluation" requires Corps offices to define each project's positive and negative effects on the impounded water and on downstream flows including impacts on water quality. This EC also requires each office to define physical and administrative constraints that prevent the present project operation from doing a better job, to discuss structural and nonstructural alternatives to allow for better management results, and to consider how multireservoir system operation could improve existing conditions.

**Willey is a Hydraulic Engineer assigned to The Hydrologic Engineering Center, 609 Second Street, Davis, California 95616.*

STATE-OF-THE-ART

While the Corps is probably achieving the best project operation for water quality control for the existing structural facility, studies must be performed to evaluate possible structural modifications and/or multireservoir systems operations. Evaluation of the water quality benefits due to possible structural modifications can be performed with several existing state-of-the-art one-dimensional computer programs.

Computer programs to evaluate the impact on water quality due to a specific operation of a large system of reservoirs are nonexistent. When it was realized, several years ago, that the Corps must have the capability to analyze the operation of large multireservoir systems for water quality, the EWQOS program funded The Hydrological Engineering Center (HEC) to develop a computer program to meet this need.

PROGRAM DEVELOPMENT

In FY 1978, various computer programs available within the Corps for evaluating reservoir system operations for water quantity were screened to identify the best generalized model for adding water quality capability. Individuals using the SSARR, SUPER, and HEC-5 models were invited to make presentations to a Corps training class on "Water Quality Aspects of Water Control." The speakers were asked to comment on the capability of their model to operate reservoir systems for quantity of flow and to discuss how difficult it would be to expand the model to analyze water quality. In general, expansion of SSARR and SUPER was not recommended. HEC-5 was selected due to its generality, documentation, and level of active support in training and maintenance.

The HEC-5 program is designed to simulate the sequential operation of a reservoir-channel system of a branching network configuration. Any time interval from one hour to one month can be used, and two time intervals can be used within a single simulation. Channel routing is provided by any of five hydrologic routing techniques. Reservoirs as defined within the model operate to (1) minimize downstream flooding; (2) evacuate flood-control storage as quickly as possible; (3) provide for low-flow requirements and diversions; and (4) meet hydropower requirements. Hydropower requirements can be defined for individual projects or for a system of projects. Pumped-storage operation can also be simulated. Sizing for conservation demands or storage can be performed automatically using the safe-yield concept, and economic computations can be provided for hydropower benefits and flood-damage evaluation.

In FY 1979, a scope of work to modify HEC-5 was prepared by an interoffice ad hoc task force. The modifications were identified to be accomplished in three phases as shown in Figure 1. Phase I would add the capability to HEC-5 to control water temperature releases at one reservoir to provide for the best combination of downstream needs at up to three control points, with the control of water temperature accomplished through multilevel intake structure operation. The contract was awarded to Resource Management Associates (RMA). In September 1979, RMA produced a single-reservoir water temperature control program called HEC-5Q (Phase I).

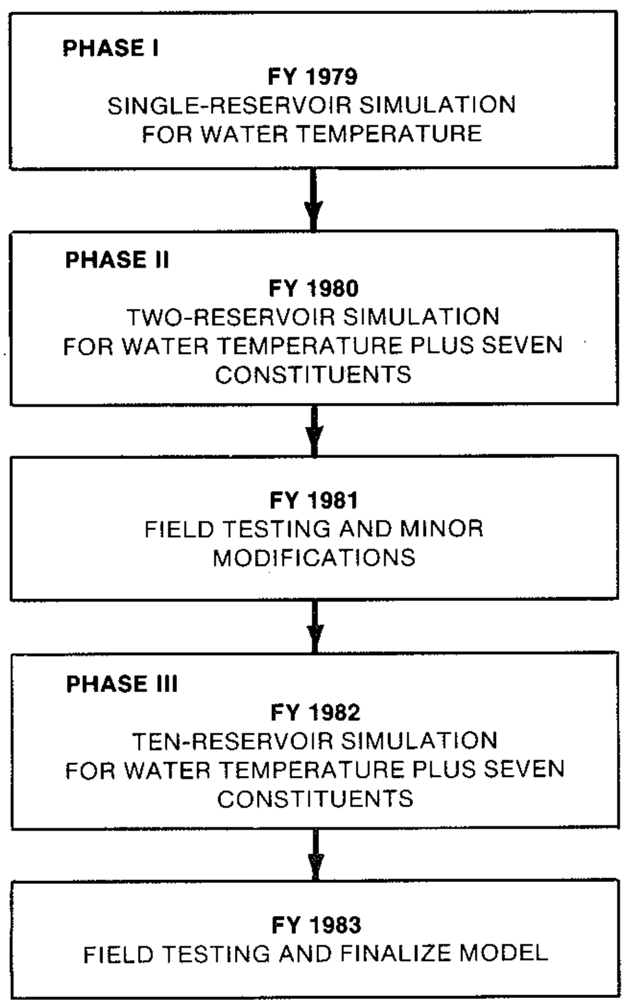


Figure 1. Phased Development of HEC-5Q

In FY 1980, the ad hoc group prepared a new scope of work to modify the Phase I model to add seven more water quality parameters and the capability to evaluate either two tandem reservoirs (i.e., in series) or two parallel reservoirs (i.e., on two independent tributaries). This contract was awarded to Dr. James Duke, an independent contractor in Austin, Texas. In September 1980, Dr. Duke provided the Corps with HEC-5Q (Phase II): a two-reservoir model capable of system operation for three conservative and three nonconservative water quality parameters in addition to dissolved oxygen and water temperature.

The ad hoc group decided to evaluate past accomplishments with in-house testing and to modify the Phase II model with some small but significant additions and revisions during FY 1981. These modifications will include flow augmentation, improved model efficiency, optional calibration mode, recently developed EWQOS selective withdrawal routines, and improved vertical interpolation methods. HEC will test the Phase II model on a practical application and define areas needing refinement in preparation for the Phase III development.

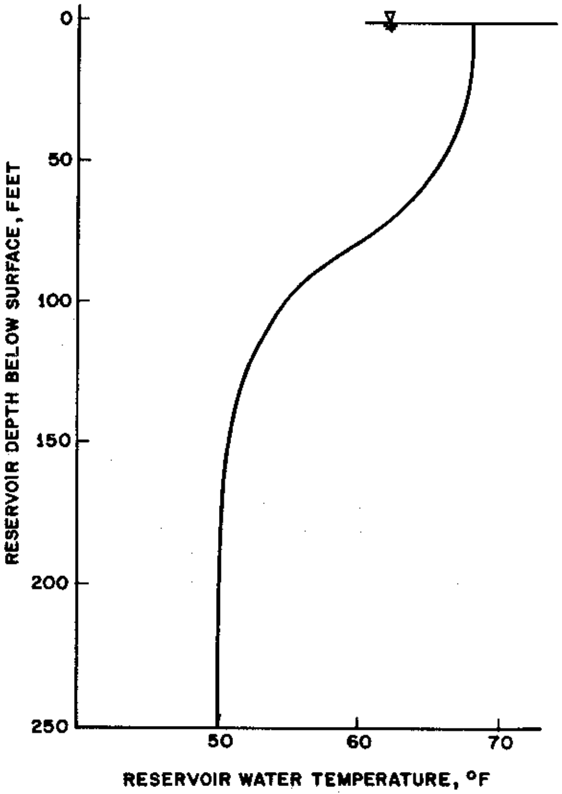
FUTURE DEVELOPMENT

In FY 82, it is anticipated that the ad hoc group will define a Phase III scope of work to modify the HEC-5Q (Phase II) model to provide capability for systems as large as 10 reservoirs. Other refinements defined in FY 81 will be included, but no further water quality expansion is expected.

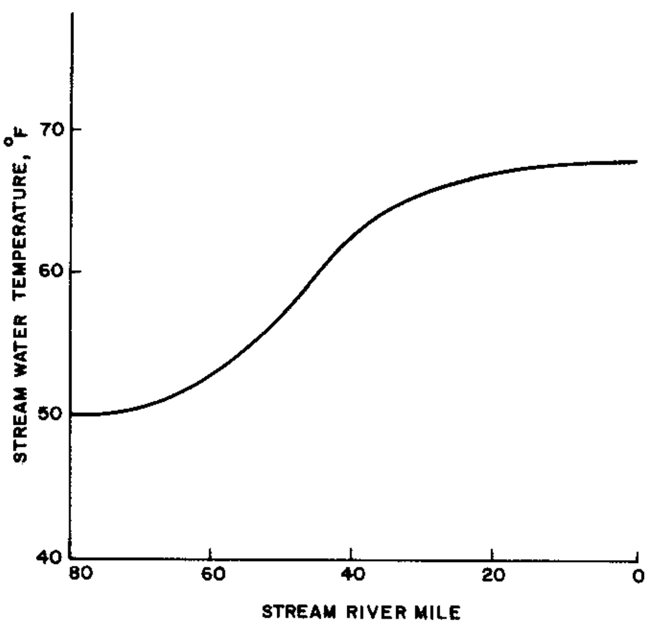
The Phase III model will be tested at HEC on a practical application during FY 1983.

PRODUCT AVAILABILITY

The HEC-5Q (Phase I) model is available for single-reservoir water temperature applications. The water quantity routines will define a best system regulation by looking at all reservoirs in a large system. The model will decide which reservoirs should discharge and at what rate of discharge to best meet downstream control-point needs and to maintain a balanced system of reservoirs. Once the best system regulation is defined for water quantity, then the quality routines can be applied to any single reservoir to evaluate how to operate an existing or proposed multilevel intake structure to best meet all downstream target temperature controls. Figure 2 shows example results for both the reservoir and the stream. The reservoir temperature profile at the top and the stream temperature profile



a. Reservoir temperature profile



b. Stream temperature profile

Figure 2. Example HEC-5Q (Phase I) model results

at the bottom are typical of the kind of results produced at and below many reservoirs during the summer months.

The HEC-5Q (Phase II) model is available and when tested will supersede the Phase I model. The Phase II model has the capability to evaluate eight water quality parameters including water temperature in any two-reservoir system. Like the Phase I model, any large reservoir system can be regulated for a best operation of quantity and then any two reservoirs selected for water quality regulation.

TRAINING COURSE

A 10-day training course entitled "Application of Water Quality and Ecological Models" will be presented in Arlington, Texas, beginning 4 May 1981 and will be managed by EL staff members. The course was designed and will be presented by researchers who have been actively involved in EWQOS.

The course will provide the "how to" required to evaluate and use water quality models. It will be oriented toward hands-on experience in workshops that will demonstrate the interdisciplinary nature of water quality modeling. The EL staff, with numerous lecturers from both the public and private sectors, will address topics ranging from basic concepts to state-of-the-art techniques in modeling. There will be a review of the information necessary for many types of models: sources of raw data; data interpretation and manipulation in preparation for modeling; and basic relationships between the physical, chemical, and biological realms addressed in modeling.

In addition to a review of currently available riverine and reservoir water quality models, where strengths and weaknesses will be presented and discussed, a few models will be presented in greater detail. CE-QUAL-R1 is a one-dimensional reservoir water quality model that has served as a focal point for information from several EWQOS task areas. Two full days will be devoted to CE-QUAL-R1. The two-dimensional reservoir water quality model LARM will likewise be discussed in detail. Both one- and two-dimensional steady-state riverine models will be presented and discussed. For each model, the assumptions, data preparation for modeling, and interpretation of results will be heavily stressed.

Although the course to be conducted this year is filled, it is currently scheduled to be offered twice in FY 82. Thirty-two is the maximum number of students in each section and interested CE employees should contact their Training Officer. If additional information about the course is desired, contact Dr. Jerry Mahloch, EWQOS Program Manager, at FTS 542-3635 (commercial 601/634-3635) or Mr. Joseph Norton, FTS 542-3719 (commercial 601/634-3719).

EWQOS REPORTS

Leidy, G. R., and Ploskey, G. R. 1980. "Simulation Modeling of Zooplankton and Benthos in Reservoirs: Documentation and Development of Model Constructs," Technical Report E-80-4, prepared by the U. S. Fish and Wildlife Service, National Reservoir Research Program, for the U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi.

Smith, M. H., and Doiron, P. L. 1980. "Management of Water Quality Data Within the Corps of Engineers, 1979," Miscellaneous Paper E-80-2, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi.

NOTE: Copies of the above reports will be furnished to individual requestors as long as supplies last. Since it is only feasible to print a limited number of copies, requests for single rather than multiple copies by a single office will be appreciated. Please address all requests to the Waterways Experiment Station, ATTN: Ms. D. P. Booth. When supplies are exhausted, copies will be obtainable from the National Technical Information Service, 5285 Port Royale Road, Springfield, VA 22161.

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Fred R. Brown

FRED R. BROWN
Engineer
Acting Director

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION
CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180