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14. ABSTRACT

Several examples applications of water quality models were discussed to provide background into the development of a comprehensive mathematical model capable of evaluating water quality conditions in any river-reservoir system. A need exists for a river-reservoir water quality model which can be continuously updated and maintained with the best available concepts. The "Water Quality for River-Reservoir Systems" (WQRRS) model was developed by the Hydrologic Engineering Center (HEC) to meet these needs. The HEC continuously updated the WQRRS based on the advantages of water quality research work brought to their attention.

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US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

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WATER QUALITY EVALUATION OF AQUATIC SYSTEMS[1/]

R. G. WILLEY[2/], Member ASCE

INTRODUCTION

Environmental considerations have concerned water resource planners for many years. In the last 10 years, public interest has caused significantly increased effort towards development of numerical techniques for analysis of water quality conditions in water resource systems. Today, water resource planners in this country and abroad have recognized the need to analyze existing water quality conditions at a project site and evaluate how those conditions are expected to change as proposed projects are imposed on the existing environment. This type of comparison has often been accomplished by first examining observed water quality data (i.e., pre-project conditions) and then using judgment and intuition to evaluate the changes that are expected to occur under project conditions. In the past, this approach has generally provided planners with sufficient information for project evaluation. However, in more recent years, many planners have encountered opposition to the subjectivity of their evaluation of changes expected to occur under project conditions. Also, many planners have experienced the need to evaluate more water quality parameters than were evaluated in past studies. Many important water quality parameters have significant interrelationships which defy

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2/ Research Hydraulic Engineer, The Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California 95616.

evaluation by an intuitive process. Because of the need for a more comprehensive analysis and the need for less subjectivity, a number of mathematical computer program models have been recently developed and applied to numerous environmental conditions with varying degrees of success [1-18].

MODEL DEVELOPMENT

Introduction. Most of the individuals and groups developing water quality computer programs during the last few years have recognized their efforts as being only a first step in an evolutionary development of their respective models. For the evolution of comprehensive state-of-the-art models capable of analysis of water quality conditions in various types of water systems under various physical, hydrological, meteorological and hydraulic characteristics, these models must be continuously applied and modified.

Several example applications of two water quality models will be discussed with an attempt to provide background into the development of a comprehensive model capable of evaluating the water quality conditions in any river-reservoir system.

Trinity River Study. In mid-year 1972, there was an immediate need for a water quality evaluation of existing and proposed project conditions on the Trinity River in Texas. This study involved analysis of both existing and proposed reservoirs, and analysis of existing and modified stream channel conditions. While several river or reservoir water quality models were available, the Ecologic Simulation model for deep impoundments [19] that was developed by Drs. Chen and Orlob was selected. The selection of this model was based on technical critiques [20, 21, 22] and personal discussions with several research investigators in this field and based on a number of other considerations.

It is the opinion of the author and others [23, 24] that the Chen-Orlob reservoir ecologic model was and still is the most comprehensive single program available for analysis of reservoir water quality. Examples of its comprehensiveness are shown in figure 1 and table 1. The selection decision also included knowledge of the availability of an unreleased river ecologic model developed by Mr. William Norton of Water Resources Engineers, Inc., which was already somewhat compatible with the Chen-Orlob reservoir ecologic model.

Dr. Orlob's firm, at that time Water Resources Engineers, was contracted to connect the two existing models into one model capable of analysis of any river and reservoir system, and to calibrate and apply the resultant model to the Trinity River System [25]. An example of a typical type of system that can be analyzed is shown in figure 2.

During the interval when the Trinity River study was in progress and recently thereafter, several other investigators have obtained and used various versions of the Chen-Orlob reservoir ecologic model or the Norton river ecologic model.

Tocks Island Lake Study. The first such study involved a comparison of existing and project conditions at the proposed Tocks Island Lake [1] on the Delaware River. The proposed impoundment is 37 miles long and 155 feet deep at the dam. In this study, the original version of the reservoir model, with minor changes, was used for the analysis. Very little data existed for input and most of the required data was generated based on judgment. No calibration data existed for the region and the required system coefficients were derived from the literature [22]. The model input was changed to accept previously computed reservoir temperature profiles, using the water quality model in conjunction with an existing reservoir temperature model.

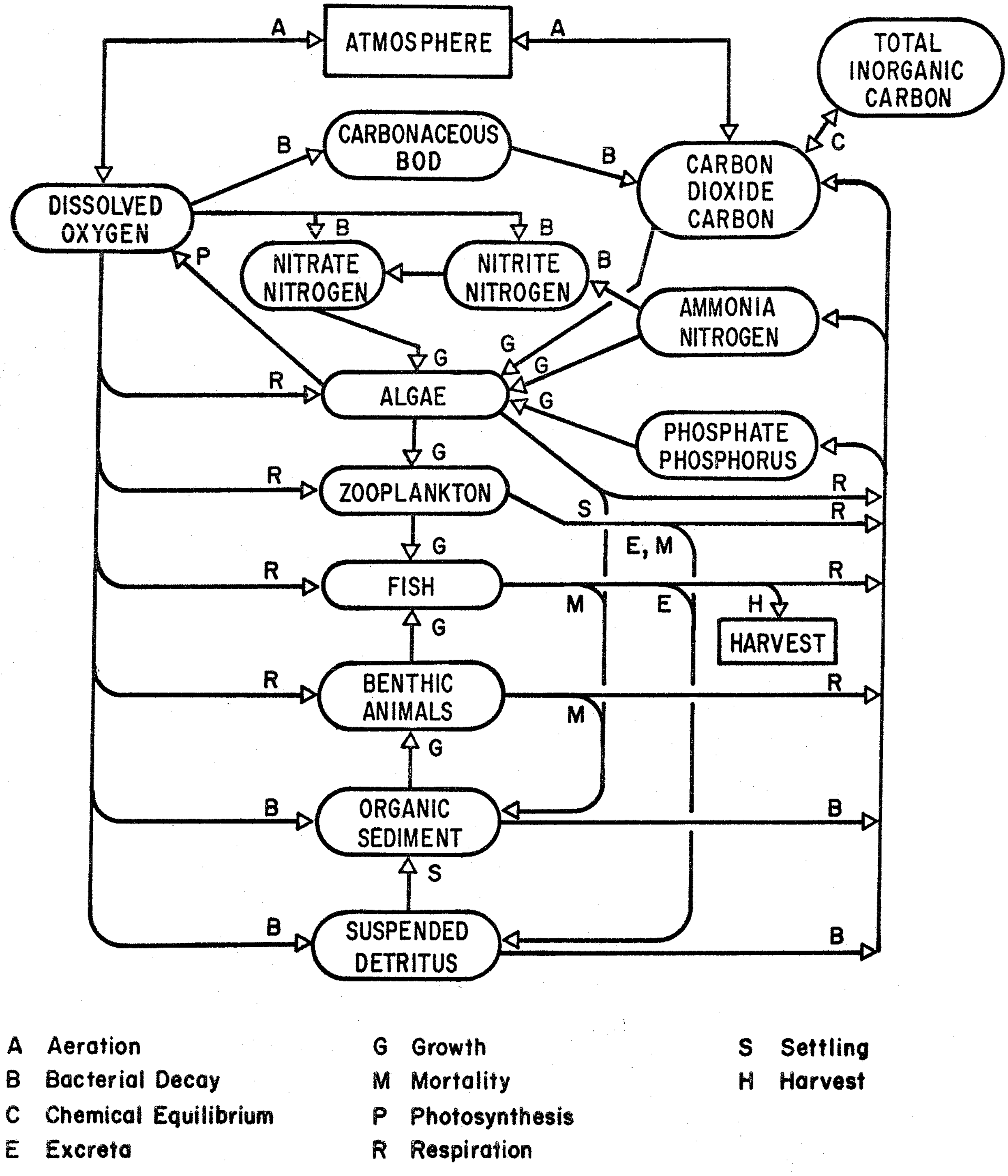

Figure 1

QUALITY AND ECOLOGIC RELATIONSHIPS

CONSTITUENT ↓ DEPENDENT ON →	Temperature	BOD	Fish	Benthic Animals	Zooplankton	Algae	Detritus	Organic Sediment	Phosphate	Total Carbon	Ammonia	Nitrite	Nitrate	Oxygen	Coliforms	Alkalinity and TDS	Light Penetration	Carbon Dioxide	pH
Temperature																	F		
BOD	R													L					
Fish	R,L			F	F			F						L					
Benthic Animals	R,L		C					F						L					
Zooplankton	R,L		C			F								L					
Algae	R,L				C				F		F		F				L	F	
Detritus	R		B		B														
Organic Sediment	R		B	F,B		B	B												
Phosphate			B	B	B	B,C	B	B											
Total Carbon		B	B	B	B	B	B	B						L					
Ammonia	R		B	B	B	B,C	B	B											
Nitrite	R										B			L					
Nitrate						C						B		L					
Oxygen	R,S,A	C	C	C	C	B,C	C	C			C	C							
Coliforms	R																		
Alkalinity & TDS																			
Light Penetration					D	D	D												
Carbon Dioxide	A,S,I					C				I						I,S			I
pH	I									I						I			

LEGEND:

R - Affects rate of decay, respiration, growth and mortality
B - By-product of decay, respiration, growth, mortality and settling of other constituents
C - Consumed by decay, respiration and growth of other constituents
F - Source of energy or nutrients required for growth or other changes
S - Affects saturation
L - Limits growth or decay if out of acceptable range
I - Affects inorganic chemical reaction
A - Affects reaeration rates
D - Decreases by shading

TABLE 1

INTERDEPENDENCE OF CONSTITUENTS

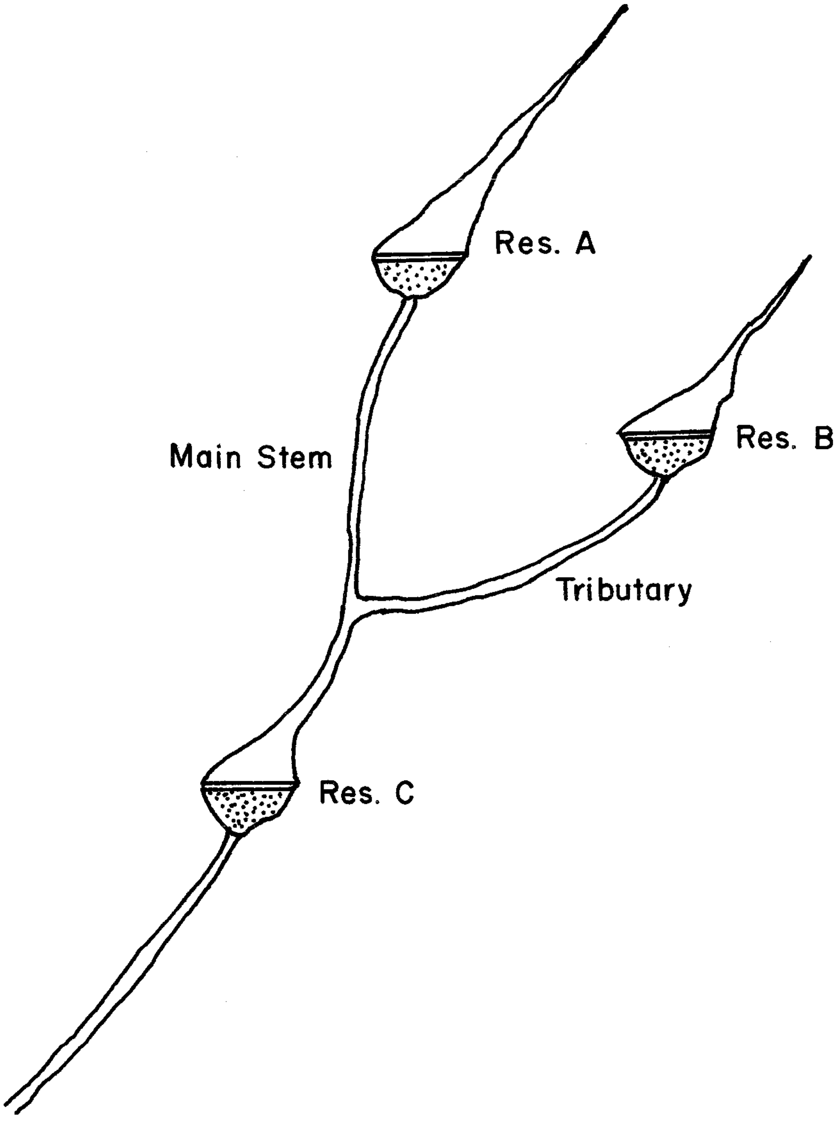

Figure 2
TYPICAL STREAM-RESERVOIR SYSTEM

The contractor's results included a sensitivity analysis of the model's predictive capability for evaluation of the resultant environmental impact under conditions due to several project alternatives.

Lake Koocanusa Study. Next the Lake Koocanusa (Libby Dam) study [2] began with the original version of the reservoir ecologic model, but major modifications were made to allow for evaluation of the best level for making reservoir releases when using the specific multilevel intake withdrawal design planned for Libby Dam. The best level for the reservoir release is defined as the withdrawal level which comes closest to meeting prespecified temperature and dissolved oxygen targets. Other modifications made to this model included calculating water density as a function of total dissolved solids and suspended sediment as well as temperature. Capability to estimate ice cover on the reservoir surface was required since the dam is located in the northern part of Montana. The project impounds a 100-mile long reservoir with a depth of 360 feet at the dam.

Because the study contract period overlapped the construction period, some data was obtained in the impoundment and was eventually used to test the contractor's judgment on calibration of the model. The data was also used for the eventual modification of the system coefficients. Input data on the tributaries to the reservoir was as good as can be expected on the average study.

The model was used to simulate various reservoir intake operational alternatives and constraints on inflow quality in order to evaluate the anticipated water quality condition in the reservoir and in the discharge.

Boise River Study. The Boise River near Boise, Idaho was studied [3] using a significantly modified version of the original river ecologic model.

Several water quality parameters (e.g., benthic algae, suspended sediment, aquatic insects, and toxicity) not included in the original model were added for this application and the model structure was modified to analyze a single-pass segmented branching system in contrast to linking each branch analyzed through tape or disk interface. This version uses an explicit finite difference solution technique.

Results of this modeling effort were used to evaluate waste load allocations for local communities. Other anticipated uses include studying the water quality impact on the receiving water when changes in urban storm drainage, agricultural return flows, and upstream reservoir releases are considered.

Lincoln Lake Study. After several minor modifications were made, the original version of the reservoir model was used to study another proposed impoundment, Lincoln Lake in Illinois [4]. Lincoln Lake, only 90 feet deep, is one of the shallowest impoundments studied with this model. The modifications included calculation of density as a function of the total dissolved solids as well as temperature.

A significant proportion of this study concentrated on sensitivity studies. Effects of changing nutrient concentrations in the inflow and depth of light penetration in the impoundment were evaluated, because of the limited input data available for these variables. Sensitivity studies also included evaluation of the impact of the magnitude of peak inflows, use of a flood control service gate instead of the multilevel intake structure for all downstream releases, decreased upstream phosphate concentrations due to improved waste treatment and analysis of the impact of algal photosynthesis and respiration.

The major objective of the contract was to determine probable biological conditions expected in Lincoln Lake under several alternative modes of operation.

Mississippi River Study. The Mississippi River near St. Louis was studied [5] using a significantly modified version of the original river ecologic model. The modifications included adding the same water quality parameters and segmented branching structure used in the Boise River model but maintaining the implicit solution technique used in the original model. Capability was added to allow the user to use natural channel geometry instead of the trapezoidal channel geometry used on previous studies.

The modified model will be used to evaluate the impact on water quality of various future water resource alternatives. One of the primary study objectives was to evaluate the resultant water quality impact on the receiving water due to urban storm drainage practices.

After calibrating the Mississippi River model, an actual interface was accomplished between the results of an urban storm model [26] and the results of the river ecologic model [5]. This study used a steady-flow modeling approach and the results show an upper envelope or maximum expected curve for river concentrations of specific parameters versus river mile.

RECENT ADVANCES

Reservoir Routines. The US Army Corps of Engineers' Waterways Experiment Station (WES) at Vicksburg, Mississippi has contributed significantly to the state-of-the-art in reservoir hydrodynamics through laboratory flume analysis and physical (hydraulic) modeling studies. WES research has led to the development of an empirical equation to predict the reservoir withdrawal pattern as a function of the reservoir water density profile and the physical conditions of the reservoir and the release structure. This research has been documented periodically as improvements in the technique have been developed [27, 28, 29].

More recently WES researchers have been developing a comprehensive understanding of the hydrodynamics of inflow mixing at a tributary inflow point. They have also formulated an empirical method of accounting numerically for this internal mixing.

These two areas of research are presently being incorporated into the Chen-Orlob reservoir ecologic model and will soon be available for use in practical applications of the model.

River Routines. The original version of the river ecologic model was developed for steady-state flow analysis. The model can account for time-variant discharge but does not have capability to hydrologically or hydraulically route the streamflow. Water quality studies are often contemplated for areas where capability for analysis of the hydrodynamics of the actual changes in streamflow would be extremely beneficial. Examples of conditions that suggest the need for hydrodynamic routing occur below hydropower plants and in areas being studied for storm water pollution.

Recognizing an important use of the Norton river ecologic model for evaluation of the impact of urban storm runoff on receiving water quality, the US Army Corps of Engineers' Hydrologic Engineering Center (HEC) has contracted to have dynamic flow routing routines added to the model. The contractor is developing the program logic to provide the user with options for either St. Venant equations, kinematic wave, Muskingum, or Modified-Puls methods of flow routing. Other research is in progress to derive criteria to define the conditions under which one of these methods should be selected over the other methods.

River-Reservoir Systems. The development of final documentation of the model used on the Trinity River study was postponed from the time of completion of the study (August 1973) until a later date to allow time for several model modifications to be made. While the study was in progress, it was obvious that the model input requirements needed to be simplified to accept as much or as little input data as is available. This modification required either a major restructuring of the model or development of a pre-processor to manipulate and in some cases generate the required input data. The latter method has the significant advantage of being used as a data editor.

The HEC has recently completed development of the pre-processor (data editor-generator) and the final program documentation. This documentation, "Water Quality for River-Reservoir Systems" (WQRRS) [30], combines a detailed description of the concepts of the river and reservoir water quality models, an example application problem including input and output, and the input description of the data editor-generator which in turn prepares the input data for both water quality models.

SPECIAL ADAPTATIONS

Lakeport Lake Study. Late in 1973 there was a need for a water quality study on the proposed Lakeport Lake in northern California [6]. This impoundment consisted of two independent inflow tributaries or branches as shown in figure 3. The impoundment will have no significant mixing pool. The intake structure is to be located on the north branch near the dam.

Since the water quality in each branch may be quite different, analysis required simultaneous solution of the two reservoirs. During the major runoff

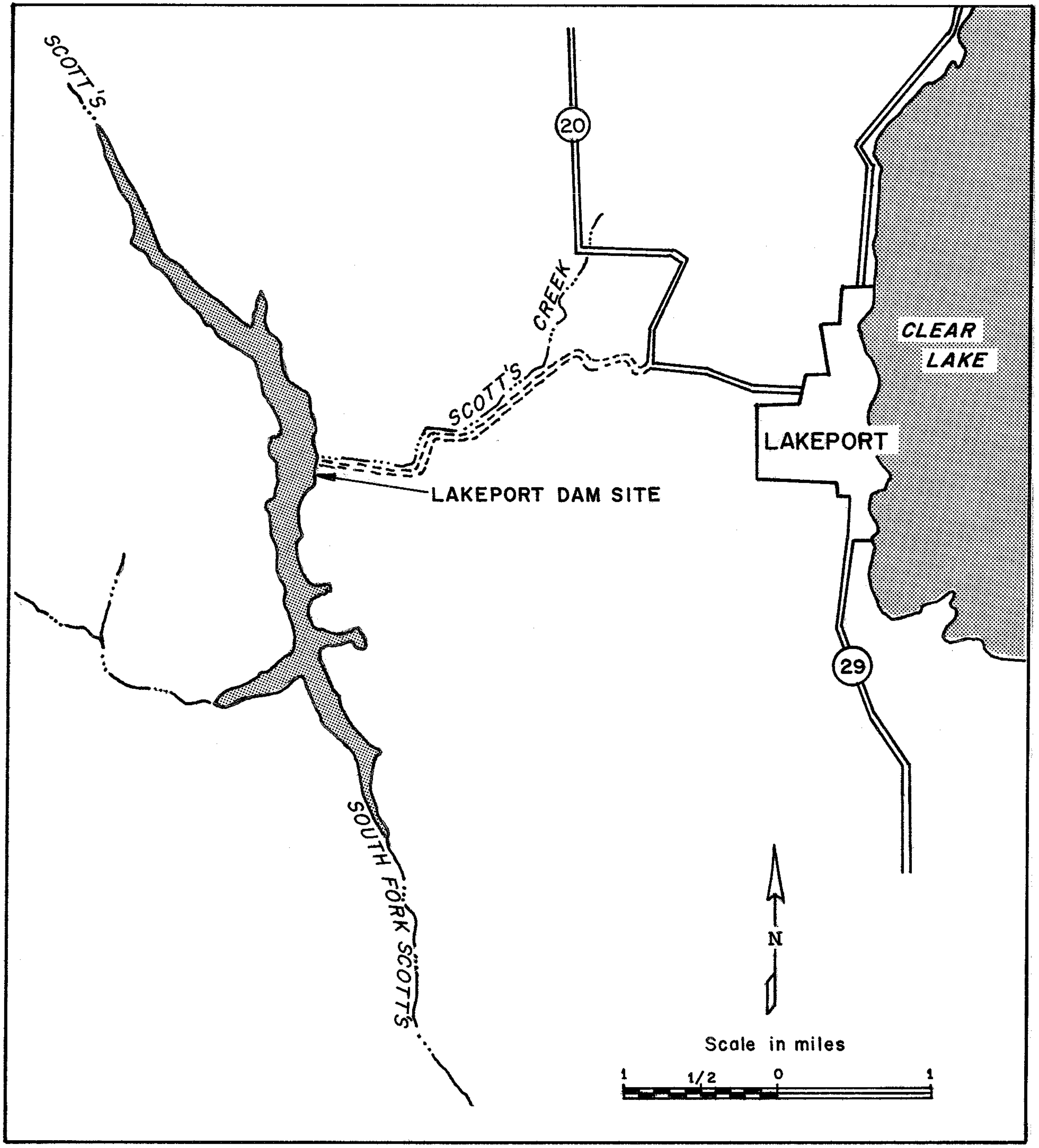

Figure 3

LOCATION OF THE PROPOSED LAKEPORT LAKE

season, the larger inflow in the smaller (based on volume) northern branch causes a resultant interflow to the south branch. The interflow causes water of differing quality at each level of the reservoir to mix. The quality of the mixture at each level can then generate an unstable density profile causing a vertical advective circulation near the intake structure in the north branch.

Another interesting aspect of this study was the need to evaluate the feasibility of using either destratification or reaeration equipment. The model was modified to evaluate the water quality impact of either pumping water from a specified depth to the surface to be aerated and returned to its original depth, or releasing a specified rate of air bubbles from a low level diffuser to either increase oxygen concentrations at the lower levels of the lake or actually causing overturn of the lake. Accounting for known pumping costs of either water or air, the water quality benefits can be examined and compared against the cost incurred.

Optimized Intake Structure Operation. An attempt was recently made to develop guidelines for operating a multilevel reservoir intake structure [31]. The contractor interfaced the Chen-Orlob reservoir ecologic model (i.e., the version used on the Tocks Island study) with a non-linear optimization routine developed at the University of Texas [32] and a water quality index criteria (WQI)[3/] developed by the National Sanitation Foundation [33, 34, 35].

The modified model evaluates various operation procedures, selected at random, in order to optimize the reservoir and the discharge water quality as defined by the WQI. The gate operation was only changed at one week

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[3/] WQI is a single index between zero and one hundred that defines water quality as an additive function of pH, dissolved oxygen, fecal coliform, nitrates, phosphates, temperature, turbidity, total dissolved solids, and five-day biochemical oxygen demand.

intervals, thereby allowing for realistic operation constraints.

The resulting model was tested using the data for the proposed Tocks Island Lake. Since there was no observed data, the model has yet to be verified. Verification should be completed at an existing reservoir where the management is willing to operate the project as suggested by the model and compare the results of the reservoir and discharge water quality against the predicted results from the model.

Research in Progress. Several additional major research efforts are presently either in progress or being considered for the WQRRS model. The most comprehensive research in progress with the WQRRS model includes a detailed evaluation of all chemical-biological interrelationships and major modification of the biological food web.

Other major research on the WQRRS model under consideration is the development of capability to analyze anaerobic conditions. While the present model is basically an aerobic model, it has previously been applied, with some minor modifications, to anaerobic reservoirs. These applications definitely demonstrated the need for a more refined analysis when anaerobic conditions are encountered.

GENERALIZED MODEL

Several versions of the Chen-Orlob reservoir ecologic model and the Norton river ecologic model have been previously discussed. While each version has slight differences, in general the models all use the same concepts to describe the reservoir or river hydrodynamics and the interrelationships between the various physical, chemical and biological water quality parameters.

A need exists for a river-reservoir water quality model which is continuously updated and maintained with the best available concepts. The input to the pre-processor should be maintained as constant as possible even when the output from the pre-processor must be modified to interface with modified water quality routines. The documentation should be updated regularly (e.g., every 12 months).

The "Water Quality for River-Reservoir Systems" (WQRRS) model [30] is an initial attempt by HEC to meet these needs. The current program package being distributed includes both the pre-processor and the water quality model originally used on the Trinity River study. This WQRRS model has undergone extensive developmental work to update the program as better techniques have been advanced.

This generalized model includes most of the same concepts as the models used on the Tocks Island Lake [1], Lake Koocanusa [2] and Lincoln Lake [4] studies. The exceptions are basically of two types: (1) specific changes for a particular reservoir intake design, and (2) changes for calculating water density as a function of total dissolved solids and suspended sediment as well as temperature. The first exception cannot be generalized and may possibly require modifications for each specific design. The second exception is presently being added to the WQRRS model by the WES along with the inclusion of the WES withdrawal distribution and inflow mixing functions. These latter modifications will make the reservoir routines of the WQRRS model more advanced than the other versions.

The WQRRS model presently has a different structural concept than that used in the models on the Boise River [3] and Mississippi River [5] studies. The WQRRS package is presently being modified to include the concepts used in these studies with the unique addition of the hydrodynamic routing techniques previously discussed.

The present WQRRS model requires analysis of all 18 water quality parameters even when a particular study may involve fewer parameters. However, modifications are in progress to allow optional "groups of parameters" to be selected for analysis by the user.

The HEC has been distributing the WQRRS model on request and providing assistance to users trying to understand the models' concepts or required input. The program has been tested on UNIVAC 1108, CDC 7600, and Honeywell 600 equipment.

It is not intended to ever include in the WQRRS model, the capability of the models used for the Lakeport Lake Study [6] or the intake structure operation study [31]. These models can be obtained from the HEC if requested for a specific application or research study but will not be distributed in general.

CONCLUSION

The rapidly increasing need for comprehensive water quality computer models has become evident. These models must be capable of analysis of river basins including both river and reservoir elements. Advantages are apparent for system models which are compatible between the river and reservoir routines and capable of interfacing results from each other.

The WQRRS model or other versions also developed by Dr. Orlob, Dr. Chen, and Mr. Norton have been used under various geographical, hydrological, meteorological and physical conditions. The various applications discussed demonstrate the numerous types of potential uses for a generalized water quality model. The need exists for such a model to be readily available, and consistently and continuously maintained.

The ability to maintain a state-of-the-art generalized water quality model requires (1) communication of recent technical advances to model users, (2) application of the generalized model to various project sites and unique conditions, and (3) the willingness to provide assistance to potential users through individual or group training.

The HEC continuously updates the WQRRS generalized water quality model based on the advantages of water quality research work brought to their attention. The documentation for the generalized model is continuously updated and made available on request. Assistance in understanding the model's concepts and the required input data is provided individually and through annual training courses.

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