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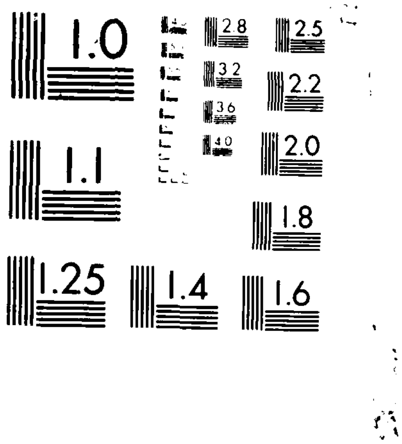

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Modeling and Managing Water Resource Systems for Water Quality

by

R.G. Willey

Technical Paper No. 113

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Modeling and Managing Water Resource Systems for Water Quality*

R. G. Willey 1/

INTRODUCTION

Several state-of-the-art models [2,3,5] are available for analyzing water quality conditions in complex reservoir systems for a given set of operational conditions. Some of these models can even make operational decisions for proper gate regulations to obtain desirable water quality conditions at a dam site for a given set of flow conditions.

HEC-5Q, Simulation of Flood Control and Conservation Systems (Including Water Quality Analysis) [4] computer model has the unique capabilities to accept user-specified water quantity and quality needs system-wide and to decide how to regulate the network of reservoirs. The decision criteria are programmed to consider flood control hydropower, instream flow (municipal, industrial, irrigation, water supply, fish habitat) and water quality requirements.

The HEC-5Q program was first applied to the Sacramento River system in California and a report was published in July 1985 [8]. Two other applications are in progress, the Kanawha and Monongahela River systems have been completed and reports published in July 1986 and November 1986 (draft) respectively. A brief description of the HEC-5Q concepts and these three applications will be discussed below.

MATHEMATICAL MODEL CONCEPTS

HEC-5Q has been developed specifically for evaluating the type of problem shown in Figure 1. The model is capable of evaluating a reservoir system of up to ten reservoirs and up to thirty control points. The model will define a best system operation for water quantity and quality, evaluating such operational concerns as flood control, hydropower, water supply, and irrigation diversions. Since the computer program users manual [4], and several technical papers [1,6,7] adequately document the details of the model concepts and the input description, only a brief overview is provided below.

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Flow Simulation Module

The flow simulation module was developed to assist in planning studies for evaluating proposed reservoirs and to assist in sizing flood control and conservation storage requirements for each project recommended for the system. The program can be used to show the effects of existing and/or proposed reservoirs on flows and damages in a complex reservoir system. The program can also be used to select proper reservoir releases system-wide to minimize flooding yet maintaining a balance of flood control storage ("balanced pool") among the reservoirs.

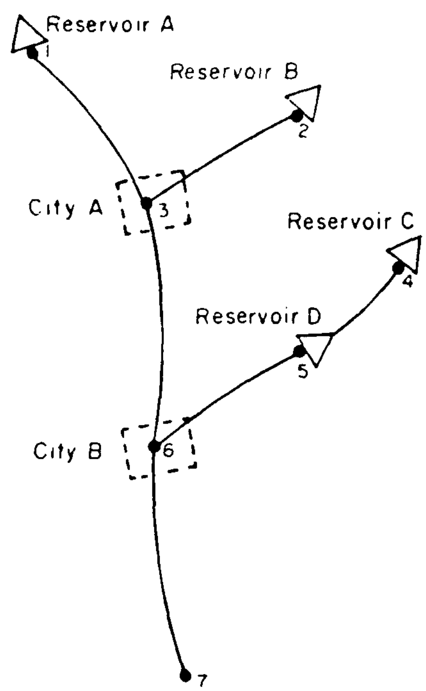

Figure I
TYPICAL RESERVOIR SYSTEM SCHEMATIC

Water Quality Simulation Module

The water quality simulation module is capable of analyzing water temperature and up to three conservative and three non-conservative constituents. If at least one of the nonconservative constituents is an oxygen demanding parameter, dissolved oxygen can also be analyzed.

The water quality simulation module accepts system flows generated by the flow simulation module and computes the distribution of all the water quality constituents in up to ten reservoirs and their associated downstream reaches. The ten reservoirs may be in any arbitrary parallel and tandem configuration.

Gate openings in reservoir multilevel withdrawal structures are selected to meet user-specified water quality objectives at downstream control points. If the objectives cannot be satisfied with the previously computed "balanced pool" flows, the model will compute a modified flow distribution necessary to satisfy all downstream objectives. With these capabilities, the planner may evaluate the effects on water quality of proposed reservoir-stream system modifications and determine how a reservoir intake structure should be operated to achieve desired water quality objectives within the system.

SACRAMENTO RIVER SYSTEM APPLICATION

The Sacramento Valley reservoir system consists of four major reservoirs as shown in Figure 2. Shasta and Keswick Reservoirs are located on the Sacramento River in northern California about 240 miles north of Sacramento. Below Shasta and above Keswick, inter-basin water transfers enter the Sacramento River through Spring Creek. Along the Sacramento River, Cow Creek and Cottonwood Creek are major inflowing tributaries and the Anderson-Cottonwood (ACID), Tehama-Colusa (TC), Corning (C), and Glenn-Colusa (GCID) Irrigation District Canals are major irrigation diversions.

Oroville Reservoir is located on the Feather River in the Sierra foothills about 100 miles north of Sacramento. Major tributaries entering the Feather River include the Yuba and Bear Rivers. Major diversions are located immediately below Oroville Dam from the Thermalito Afterbay. The Feather River flows into the Sacramento River near Verona.

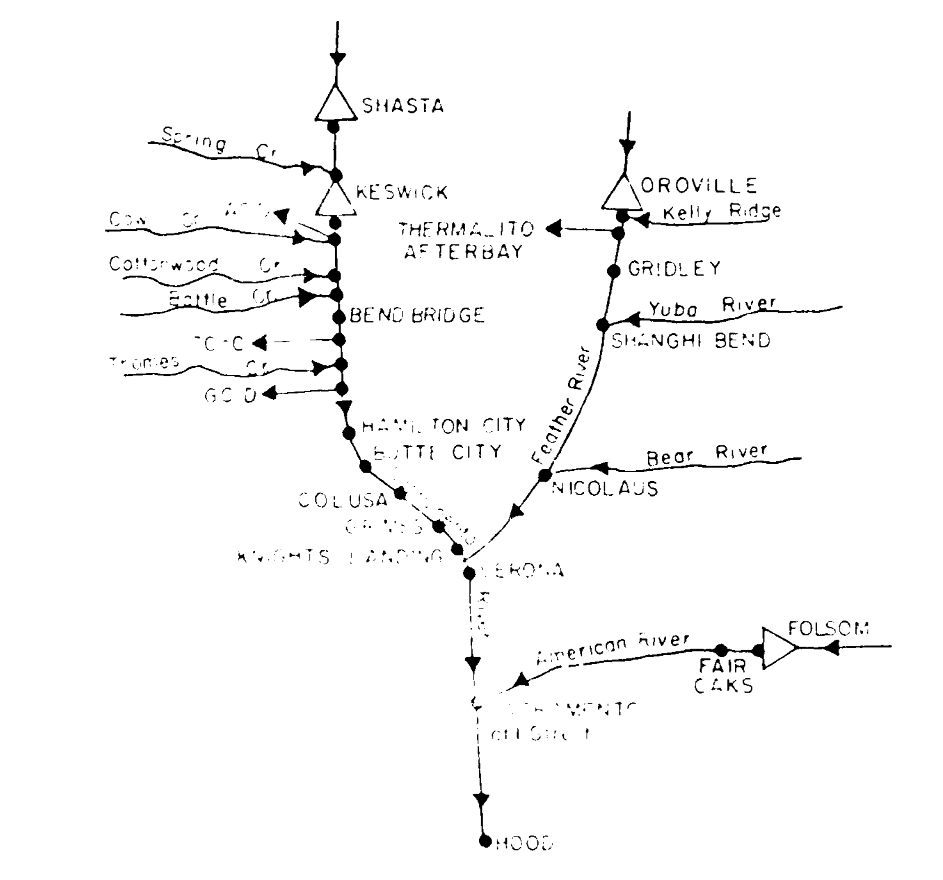

Figure 2
SACRAMENTO VALLEY RESERVOIR SYSTEM SCHEMATIC

Folsom Reservoir is located on the American River in the Sierra foothills about 30 miles east of Sacramento. The American River below Folsom Reservoir is leveed with no major tributaries entering before its confluence with the Sacramento River at Sacramento.

The Sacramento River continues to flow south towards the San Francisco Bay. The lower boundary of this study is located near Hood about 20 miles south of Sacramento.

The application of the HEC-5Q model to the Sacramento Valley reservoir system includes data assembly, model execution and interpretation of results as described below and elsewhere in more detail [8].

Data Assembly

The HEC-5Q model data requirements are similar to those of most comprehensive water quality models. The data to be assembled are categorized into three types: time independent, required time dependent and optional time dependent.

The time independent data include: physical description of the reservoir (i.e., elevation, volume, surface area, discharge capacity, and vertical reservoir segmentation), physical description of the river (i.e., cross sections, channel discharge capacity, and river reach segmentation), control point desired and required flows, model coefficients (i.e., flow routing; reservoir diffusion; physical, chemical and biological reaction rates) and initial conditions for the start of the simulation. The required time dependent data include: evaporation, meteorology, diversions, inflow quantity and quality for all reservoir and river tributaries, discharge quantity from reservoirs (only required to reproduce historical operation), and control point target flow and water quality conditions. The optional time dependent data include: reservoir storages; river flows at other than control points; and reservoir and river water quality profiles. These data are used as checks on the model output in contrast to the previously mentioned data which are required to make the model work.

Sources for the data categorized above are numerous. In general, they include all water-related agencies at the federal, state, local and private levels. Meteorological data are readily available from the U.S. Weather Service, local airports and universities. The primary data source is the NOAA's National Weather Service (NWS) office in Asheville, North Carolina.

Tributary inflows, diversions and reservoir discharges may be readily available from WATSTORE and STORET data systems. WATSTORE is managed by the USGS and contains streamflow data. STORET is managed by the EPA and contains water quality data. These computer data systems can often provide the necessary tributary inflow quantity and quality data.

Model Execution

The model simulation for the Sacramento Valley system used temperature, specific conductance (sometimes called electrical conductivity), alkalinity, carbonaceous biochemical oxygen demand (BOD), ammonia (NH3) and dissolved oxygen (DO). These specific parameters were chosen based on the availability of data in the main channels as well as some limited data for the tributary water quality inputs.

The model can be used for existing and/or proposed reservoirs. If an existing condition is being simulated, usually the objective is to reproduce historical events through model calibration. Selection of the calibration option can significantly decrease computer time by not using the time-consuming linear and non-linear programming algorithms in the model.

Once the model has been calibrated, the objective may be to modify an existing reservoir operation pattern or to evaluate the impact of proposed new reservoirs or channel modifications. This analysis requires the use of linear and non-linear programming algorithms. These algorithms compute the water quality targets at the dam--ones that best meet all the user-specified downstream targets--and decide on the gate operations to meet these computed targets.

The simulation mode discussed above can be used in either of two ways: (1) to evaluate the best water quality possible throughout the system for given reservoir discharges (obtained either externally to the simulation or determined by the HEC-5 flow simulation module); or (2) to evaluate the best water quality operation without prespecified discharge quantities. The former operation is referred to as a balanced pool operation; the latter is a flow augmentation operation.

When using the balanced pool operation, the HEC-5Q program simply evaluates the best vertical level for withdrawal (assuming multiple level intakes are available) at each reservoir to meet all downstream water quality targets for the given reservoir discharge determined by the flow simulation module.

The flow augmentation operation allows the model to relax the balanced pool concept and to decide how much flow should come from which reservoir and at which vertical level in order to meet downstream water quality targets. Sometimes downstream water quality improvements require significantly increased discharge rates to obtain only small improvements in water quality. This flow augmentation operation is the most time consuming mode of execution.

For the Sacramento River application, the input data set was executed using the calibration option. This option allows the user to define the exact level of the intake structure operated, the normal method used when calibrating the model to observed historical data.

Interpretation of Results

The HEC-5Q execution of the Sacramento Valley reservoir system produced results which were compared to observed water quantity and quality data in the four reservoirs and at all downstream control points. The observed data consisted of discharge rates at most control points as well as water temperature at many of the same locations. Data for other water quality parameters were more limited in availability but were compared where they were applicable. Figures 3-6 show sample graphical results for the reservoirs and at selected locations along the stream network.

These plots satisfactorily demonstrate the capability of HEC-5Q to reasonably reproduce observed reservoir and stream profiles on large systems. The legend on the reservoir temperature graph defines simulated and observed data for various dates. Shasta, Oroville and Folsom Reservoirs have sufficient observed temperature data to be useful for calibration purposes. Sufficient observed data for the other parameters were not available. (Only data for Shasta Reservoir are shown due to space limitations.) Considering the model limitation (at the time of application, but since corrected) of having only one weather station for the entire system, it is the author's opinion that the reproduction is quite good. Perhaps some further refinement could be achieved with additional trials, but the acceptability of the model can be demonstrated with these results.

The legend on the stream plots defines the various observed and simulated water quality parameters for the study period. Simulated constituents 1 and 2 are specific conductance (or EC) and alkalinity. Unlike the simulated data, the observed data points are often more than one day apart. Some caution should be applied to interpretation of the connecting line between observed data points further apart than one or two days.

In general, the calibration of the model is quite good along the Sacramento River for all the observed parameters down to Hamilton City, inclusive. (Only data for Hamilton City are shown due to space limitations.) Butte City and Colusa measured temperatures show that significant warming of this reach of the Sacramento River takes place, at least during the Spring (April and May 1956). This temperature increase, in addition to the lack of sufficient simulated quantity of flow at Butte City and Colusa (compared to accurate simulation of flow at Bend Bridge), suggests that the undefined return flows on the Sacramento River between Hamilton City and Knights Landing are significant and need to be evaluated.

The Feather River below Oroville and the American River below Folsom lack sufficient water quality data to provide adequate information for calibration purposes.

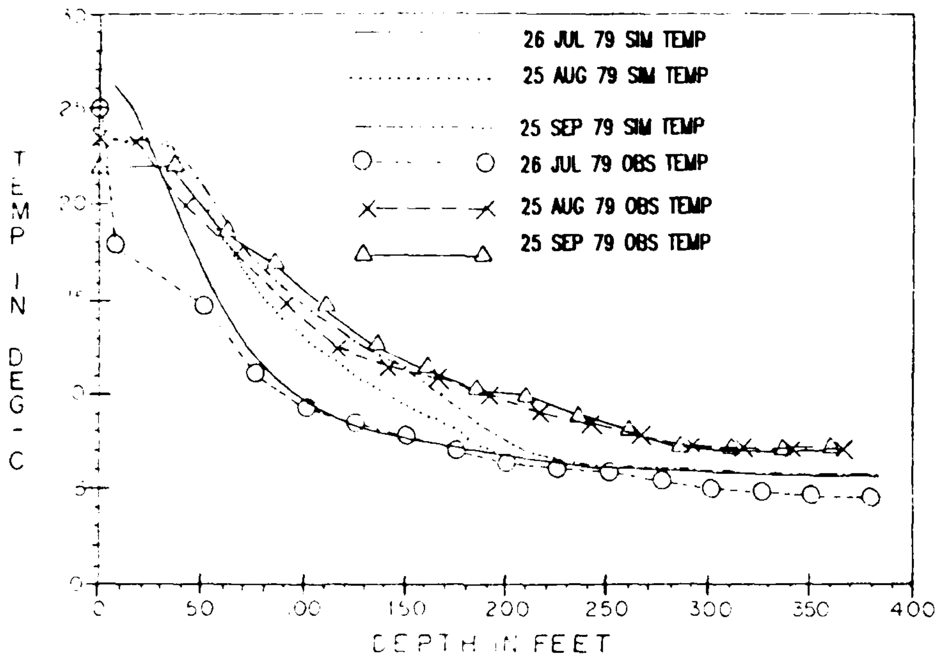

Figure 3

SHASTA RESERVOIR TEMPERATURE PROFILES

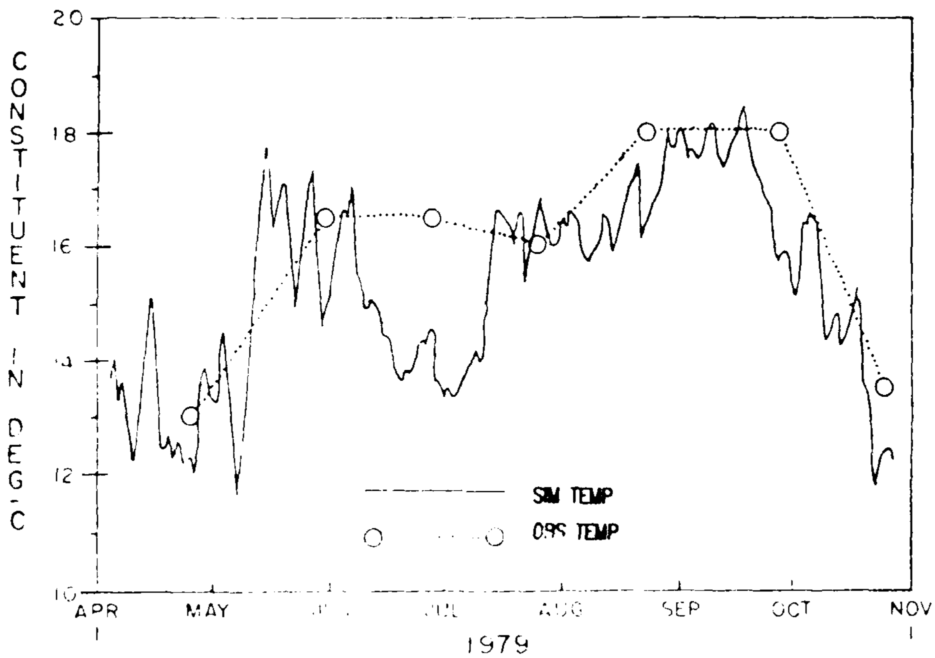

Figure 4

SACRAMENTO RIVER AT HAMILTON CITY – WATER TEMPERATURE

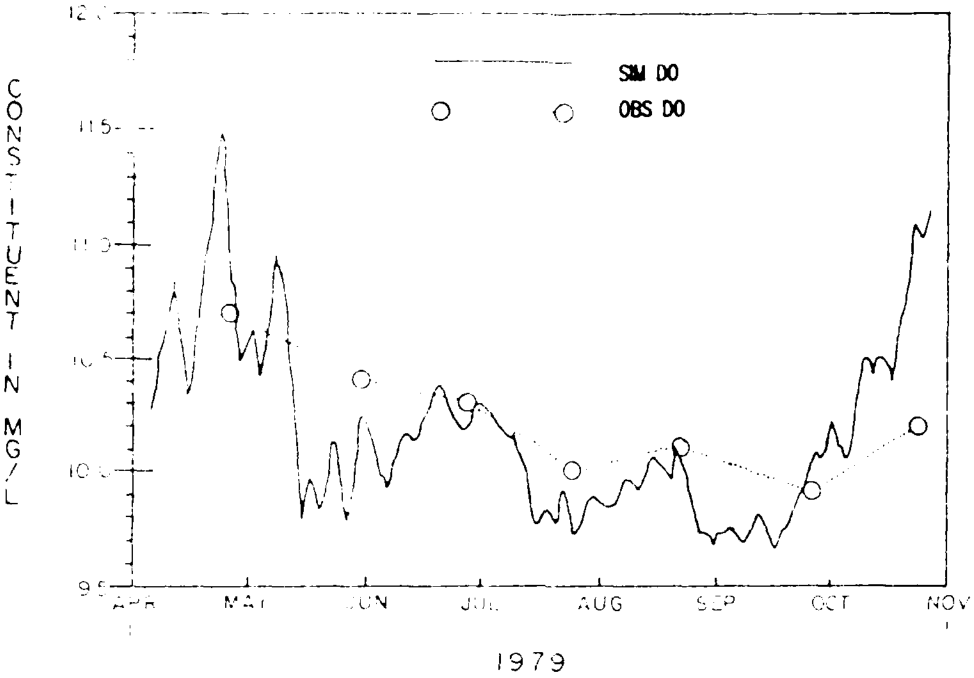

Figure 5

SACRAMENTO RIVER AT HAMILTON CITY-DISSOLVED OXYGEN

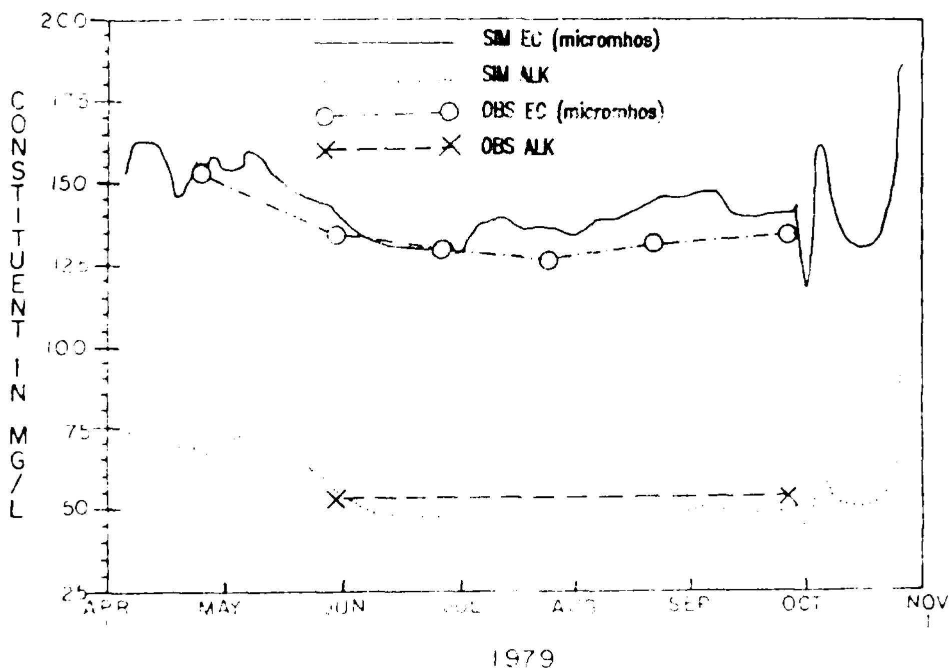

Figure 6

SACRAMENTO RIVER AT HAMILTON CITY - SPECIFIC

CO..UCTANCE (EC) & ALKALINITY

Since the Sacramento River below Sacramento is the combined product of all three river systems, the inaccuracies already discussed are also apparent at this location. Careful interpretation and evaluation of all these results lead the author to encourage the continued application of this model to help develop understanding of the workings and operation of any stream system.

KANAWHA RIVER SYSTEM APPLICATION

The Kanawha River system consists of three major reservoirs as shown in Figure 7. Bluestone Lake Dam on the New River is located about 107 miles south of Charleston, West Virginia. The Greenbrier River, a significant tributary, drains into the New River immediately below Bluestone Lake Dam and above Hinton, West Virginia--the site of significant amounts of observed flow and water quality data. The Summersville Lake Dam on the Gauley River flows into the New River at Kanawha Falls, about 40 miles above Charleston. The Sutton Lake Dam on the Elk River flows into the Kanawha River at Charleston. The New River is renamed the Kanawha River at Kanawha Falls.

The Kanawha River system has been evaluated [9] using HEC-5Q for temperature, specific conductance (or electrical conductance, EC) biochemical oxygen demand (BOD) and dissolved oxygen (DO). Since the necessary input data were available at Hinton (below Bluestone Lake) and analysis of Bluestone Lake was of no interest, only the two lakes, Summersville and Sutton, were analyzed along with the three-river network.

For the purpose of this paper, the modeling procedure used for the Kanawha River system is sufficiently close to that used on the Sacramento River System and therefore not repeated here. The data availability in the main channel was somewhat less than that in the Sacramento River, but is shown in Figures 8 and 9 for a location near the lower boundary selected due to its integrated result from all upstream analysis. Although it has limited observed data for temperature and dissolved oxygen, the results at this location and other locations having observed data are reproduced well within the accuracy necessary to adopt the use of this model. Consequently, the local Corps of Engineers office, for which this model was calibrated, used this model every morning during the 1986 low-flow season to make 5-day operational forecasts on the water quality to be expected at all control points due to specified reservoir operations for water quantity.

MONONGAHELA RIVER SYSTEM APPLICATION

The Monongahela River system consists of three major reservoirs as shown in Figure 10. Stonewall Jackson Lake Dam (presently under construction) is located about 202 miles south of Pittsburgh, Pennsylvania, on the West Fork Monongahela River. Tygart Lake Dam about 152 miles north of Pittsburgh on the Tygart River drains into

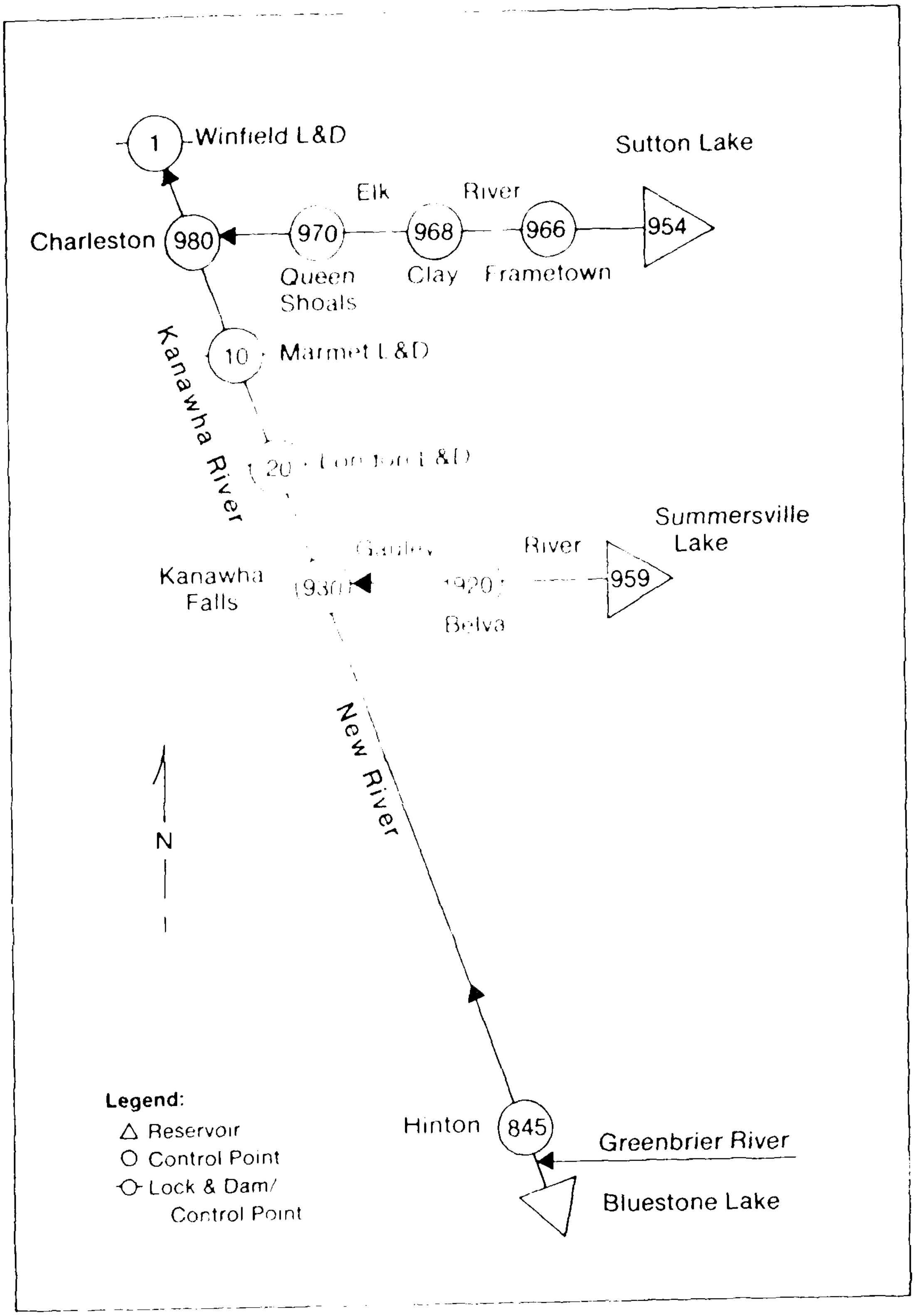

Figure 7

KANAWHA RIVER BASIN SCHEMATIC

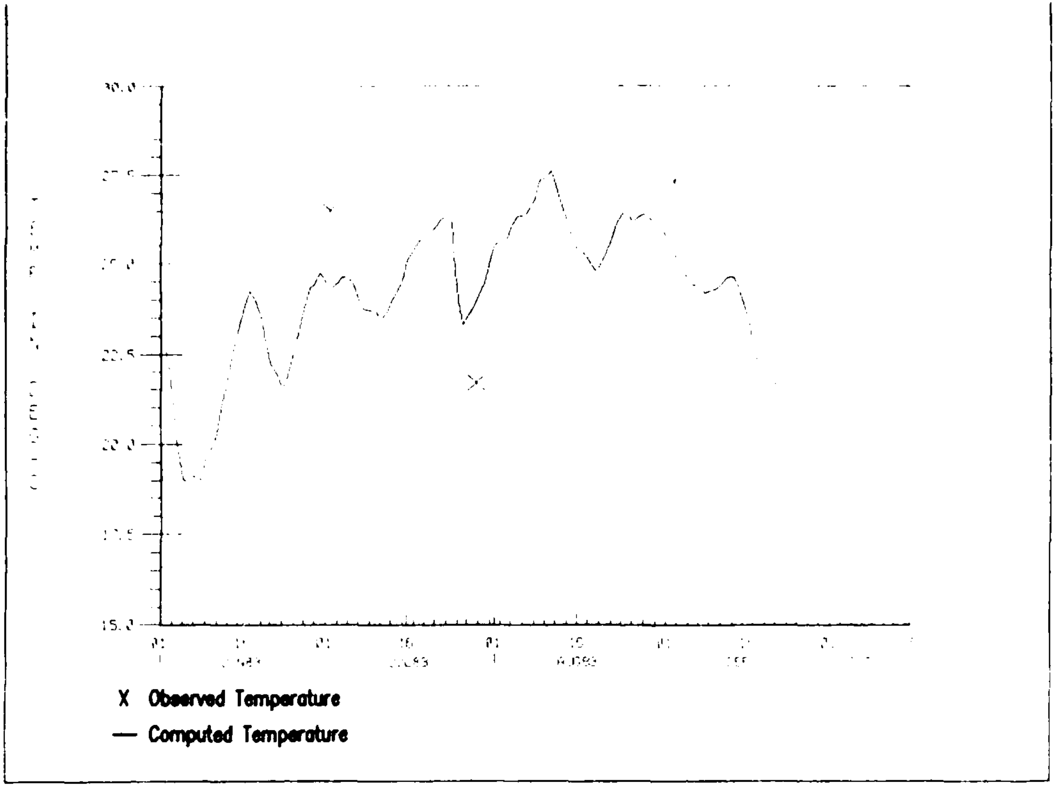

Figure 8

KANAWHA RIVER ABOVE MARMET L&D – WATER TEMPERATURE

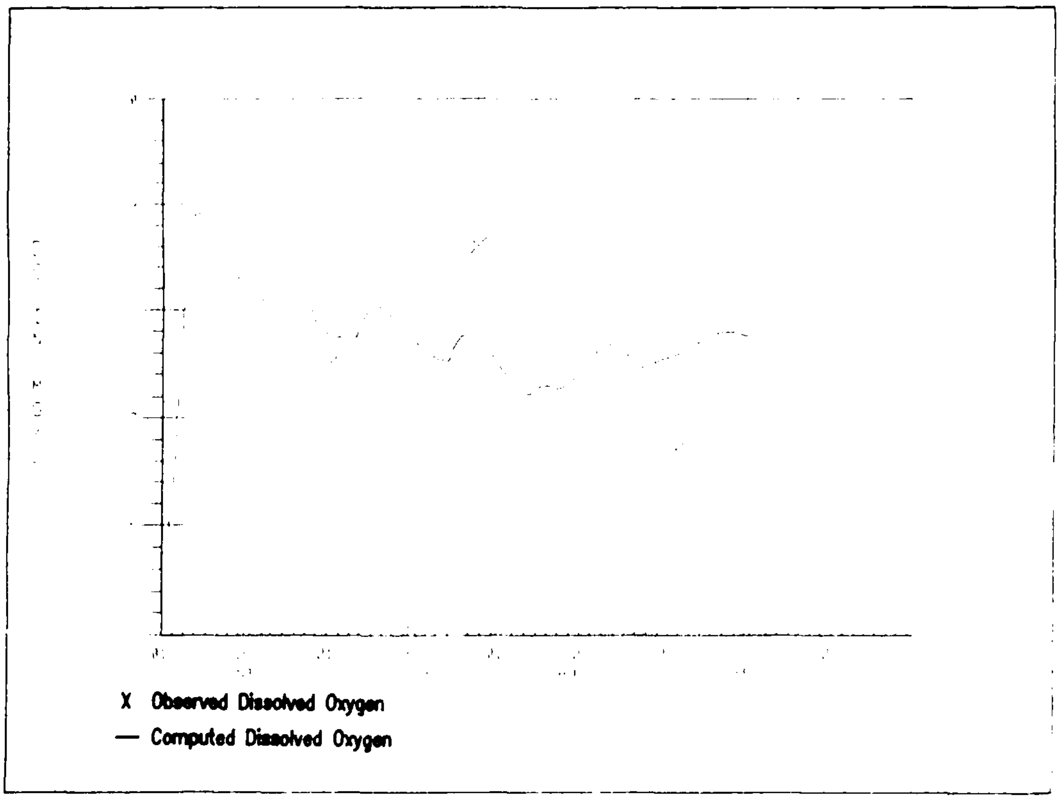

Figure 9

KANAWHA RIVER ABOVE MARMET L&D – DISSOLVED OXYGEN

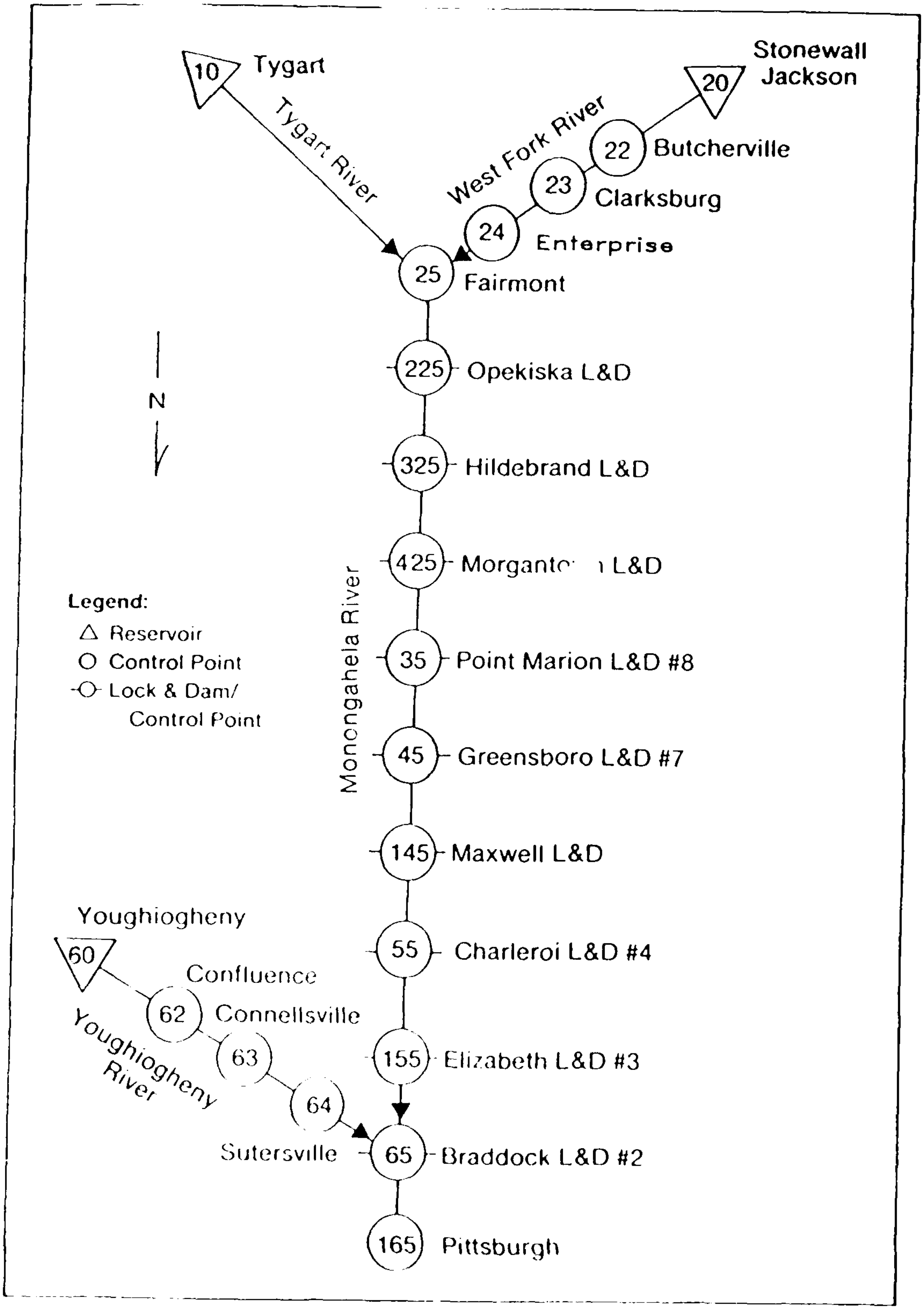

Figure 10

MONONGAHELA RIVER BASIN SCHEMATIC

the Monongahela River at Fairmont, West Virginia (CP25 in Figure 10). Youghiogheny Lake Dam about 85 miles east of Pittsburgh on the Youghiogheny River drains into the Monongahela River at Braddock, West Virginia (CP65). Braddock is about 11 miles south of Pittsburgh.

The Monongahela River system has been evaluated [10] using HEC-5Q for temperature, EC, BOD, and DO. Unlike the Kanawha River Basin study, this study had less interest in the real-time forecasting capability of the model and more interest in being able to assess the water-quality impacts of various operating alternatives for the Stonewall Jackson Reservoir multilevel intake structure.

Preliminary results for temperature and dissolved oxygen are shown in Figures 11 and 12 for a location near the lower boundary. The results are sufficiently accurate to be used for either real-time operations or for development of operation guidelines. Although the final report is still in the review process, the model is virtually certain to be accepted and applied on a routine bases.

Other potential alternative uses of this particular modeling effort include slight modifications of the data set to evaluate hydropower retrofit at the nine navigation dams along the lower Monongahela River up to Fairmont.

SUMMARY

In this paper, the author has provided a brief description of the HEC-5Q computer program for analysis of water quality impacts due to reservoir system operations and a discussion of three applications. The model results are very encouraging. Applications are in progress on the Umpqua River in Oregon for analysis of a proposed reservoir system and the Columbia and Snake River system for hydropower operations.

The model has the capability to evaluate present operations on large integrated reservoir systems such as the Columbia River or similar large systems in other regions of the United States. Once calibrated to historical conditions, alternative regulation can be easily evaluated to meet all project purposes at all points in the system and provide the water managers with input to their operation decisions either in a planning or "real-time" mode.

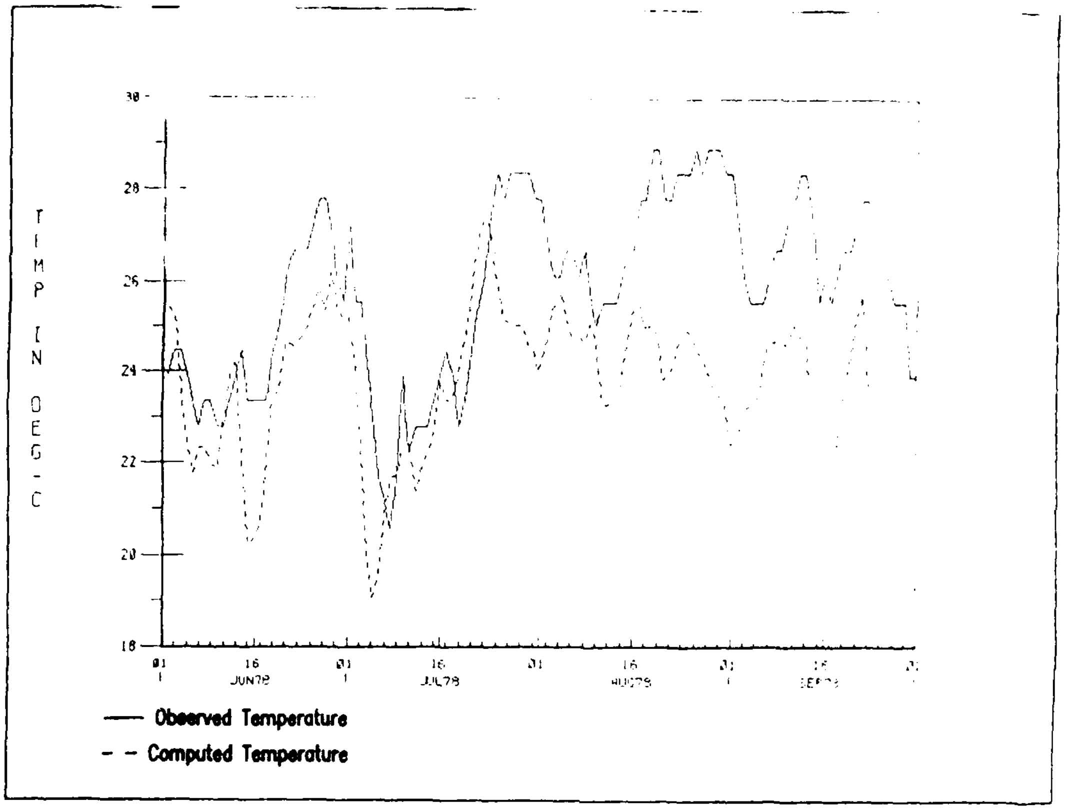

Figure 11

MONONGAHELA RIVER ABOVE PITTSBURGH - WATER TEMPERATURE

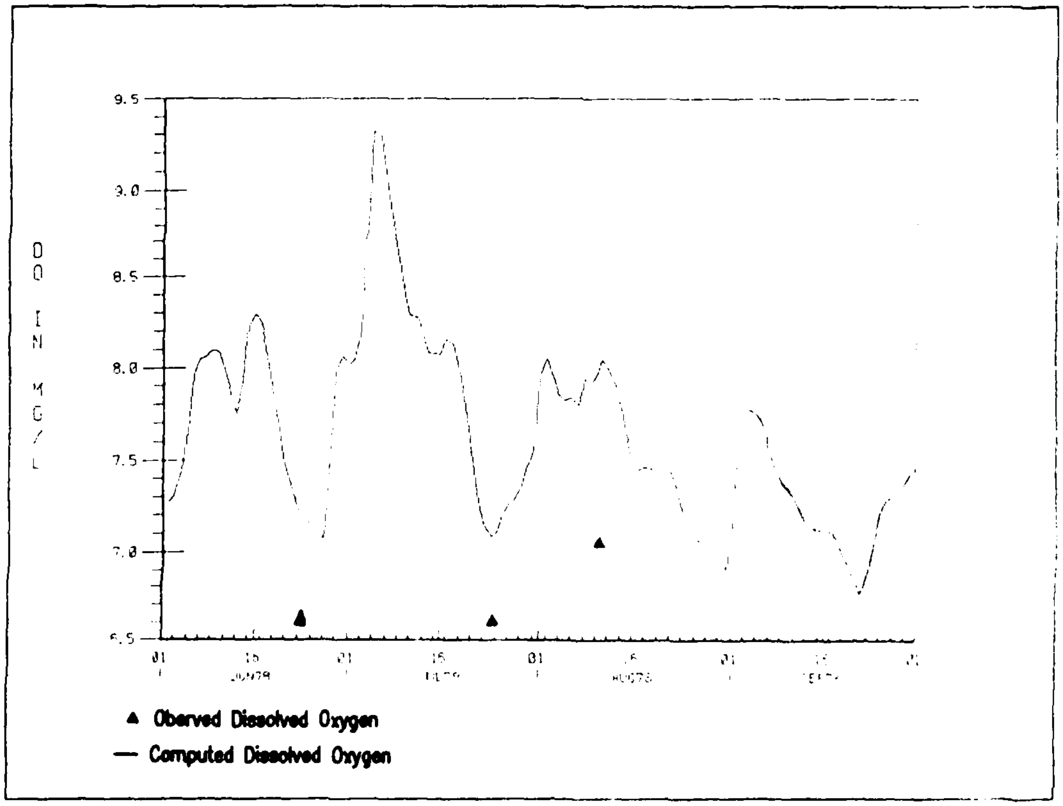

Figure 12

MONONGAHELA RIVER ABOVE PITTSBURGH - DISSOLVED OXYGEN

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Several state-of-the-art models are available for analyzing water quality conditions in complex reservoir systems for a given set of operational conditions. Some of these models can even make operational decisions regarding proper gate regulations to obtain a desirable water quality condition at a dam site for a given set of flow conditions.

HEC-5Q, Simulation of Flood Control and Conservation Systems (Including Water Quality Analysis) computer model, has the unique capabilities to accept

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) user speci[illegible] water quant[illegible] and quality needs system-wide and to decide how to regulate the network of reservoirs. The decision criteria are programmed to consider flood control, hydropower, instream flow (municipal, industrial, irrigation, water supply, fish habitat) and water quality requirements.

The model uses a linear programming algorithm to evaluate the "best" operation of multilevel intakes at each reservoir in the system. The user may select to operate the system for a balanced reservoir pool operation and its associated water quality or to allow for a modified flow distribution between reservoirs to improve the water quality operation.

HEC-5Q has been applied to the 10,000 square mile (26,000 square kilometer) drainage area of the Sacramento River System. The Sacramento system includes two tandem reservoirs, three parallel reservoirs and 400 miles (640 kilometers) of stream channel network.

An application of the Kanawha River System in West Virginia includes using the model for 5-day real-time forecasting of reservoir operations every morning during the low-flow season.

The Monongahela River System application in West Virginia includes using the model to determine the best reservoir operation for a project nearing completion.

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