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The model uses a linear programming algorithm to evaluate the "best" system operation among all the reservoirs and nonlinear routing for 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.

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

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TP-104

MODELING WATER RESOURCES SYSTEMS FOR WATER QUALITY*

by

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ABSTRACT

A reservoir system analysis computer model has been recently developed with the capability to simulate up to ten reservoirs, thirty control points and eight water quality parameters. With this model the user can evaluate a "best" system operation analysis for multipurpose reservoir regulation to obtain target water quality conditions at user specified control points.

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INTRODUCTION

The U.S. Army Corps of Engineers is responsible for the operation of hundreds of multiple purpose reservoirs in addition to maintenance of hundreds of miles of non-reservoir projects (e.g., levees and navigation channels). Management of reservoir releases can be analyzed to determine the best operation with any of the numerously available reservoir computer programs (2,3,5,6,7). With river analysis programs, the impact of specified reservoir releases can be evaluated at downstream points of interest.

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The problem with using single project models is the difficulty of coordinating releases among projects which impact on a single location. This is particularly obvious in Figure 1 where the operation of both Reservoirs A and B impact on the amount and quality of water at City A (i.e., control point 3). As the system is expanded further downstream, the computations necessary to provide a best operation of Reservoirs A through D for control point 7 obviously require a comprehensive system approach.

MATHEMATICAL MODEL

"HEC-5Q, Simulation of Flood Control and Conservation Systems (Including Water Quality Analysis)" computer model (4) 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 operational concerns like flood control, hydropower, water supply, and irrigation diversions. Since the computer program users manual (4), and several technical papers (1,8,9) adequately document the details of the model concepts and the input description, only a brief overview is provided below.

Flow Simulation Module

The flow simulation module was developed to assist in planning studies for evaluating proposed reservoirs in a system and to assist in sizing the 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 in selecting the proper reservoir releases throughout the system to minimize flooding as much as possible while maintaining a balance of flood control storage ("balanced pool") among the reservoirs.

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

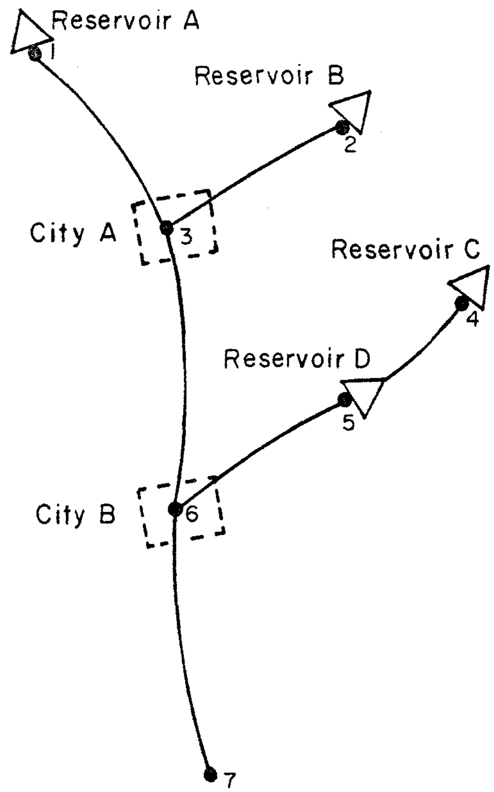

Figure I
TYPICAL RESERVOIR SYSTEM SCHEMATIC

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 better 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.

RESERVOIR SYSTEM DESCRIPTION

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 (390 km) 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, Tehama-Colusa, Corning and Glenn-Colusa Irrigation District Canals are major irrigation diversions.

Oroville Reservoir is located on the Feather River in the Sierra foothills about 100 miles (160 km) 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.

Folsom Reservoir is located on the American River in the Sierra foothills about 30 miles (50 km) 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. This study's lower boundary is located near Hood about 20 miles (30 km) south of Sacramento.

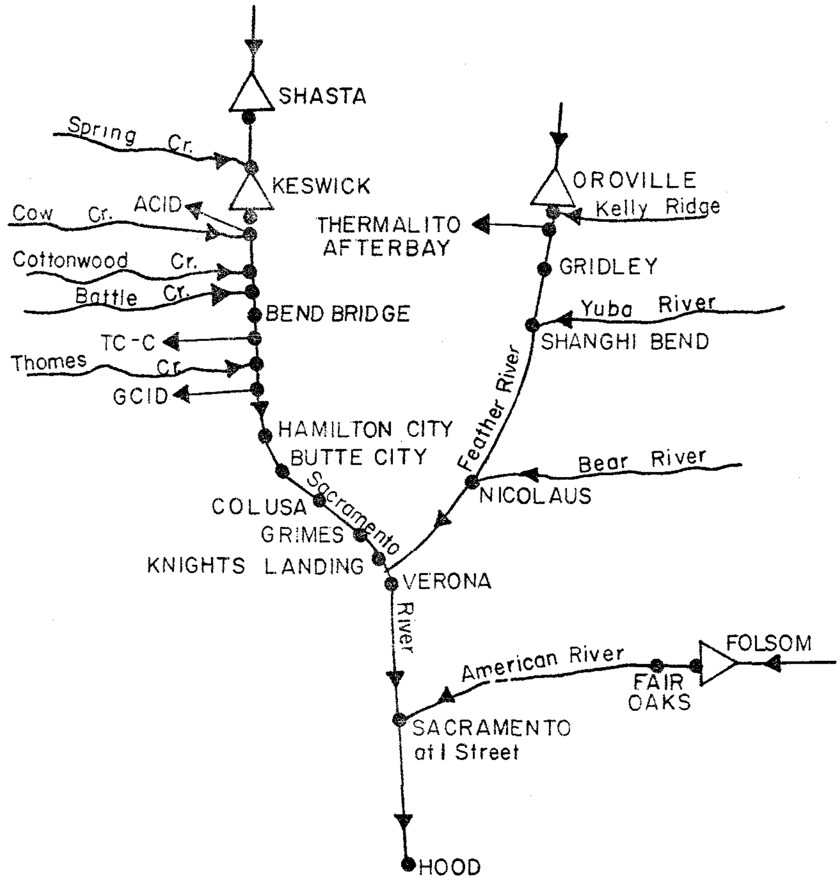

Figure 2
SACRAMENTO VALLEY RESERVOIR SYSTEM SCHEMATIC

APPLICATION PROCEDURE

The application of the HEC-5Q model to the Sacramento Valley reservoir system, or to any other system, includes data assembly, model execution and interpretation of results.

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 vs. volume, surface area and discharge capacity; and vertical reservoir segmentation), physical description of the river (i.e., river mile vs. cross section and 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 reactions 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, and control point target 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 at least limited data.

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 the linear and non-linear programming algorithms.

The simulation mode discussed above can be used either to evaluate the best water quality that can be provided throughout the system for given reservoir discharges (obtained either external to the simulation or determined by the HEC-5 quantity part of the model) or to evaluate the best water quality operation without preconceived discharge quantities. The former operation is referred to as a balanced pool operation and the latter as 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 costly mode of execution.

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

Interpretation of Results

The Sacramento Valley reservoir system was executed and produced results which were compared to observed water quantity and quality data in the four reservoirs and at all downstream control points. The data for comparison purposes consisted of discharge rates at most control points as well as water temperature at many of the same locations. Other water quality parameters are less available but were compared where they were available. Selected portions of the graphical display of these results are shown in Figures 3-6 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 legends at the bottom of the reservoir temperature plots define 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 of having only one weather station for the entire system, it is the authors' 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 at the bottom of the stream profile 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

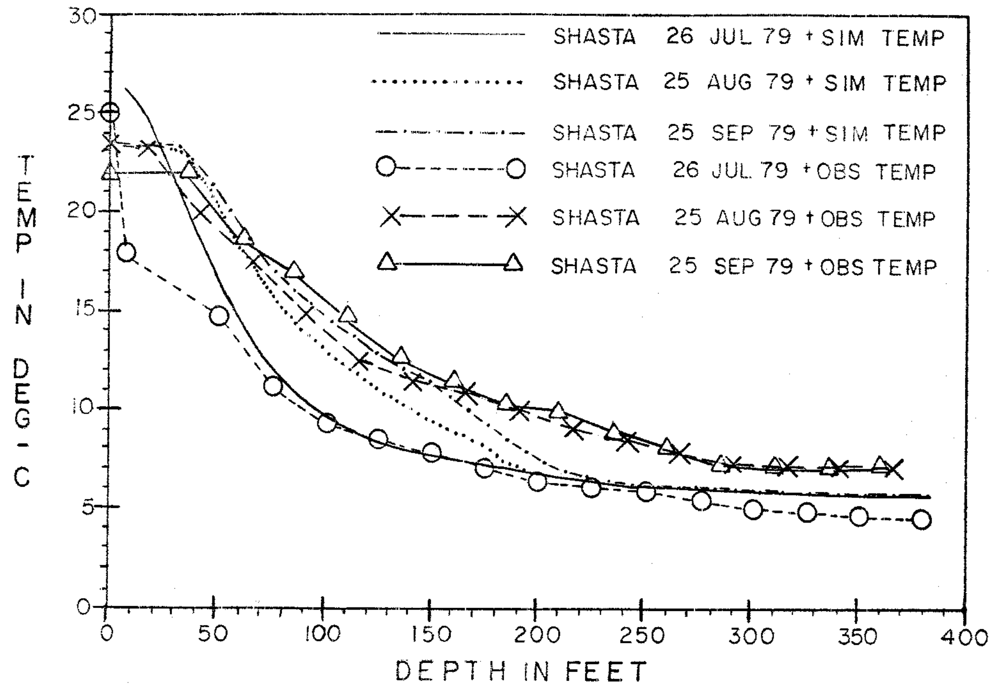

Figure 3

SHASTA RESERVOIR TEMPERATURE PROFILES

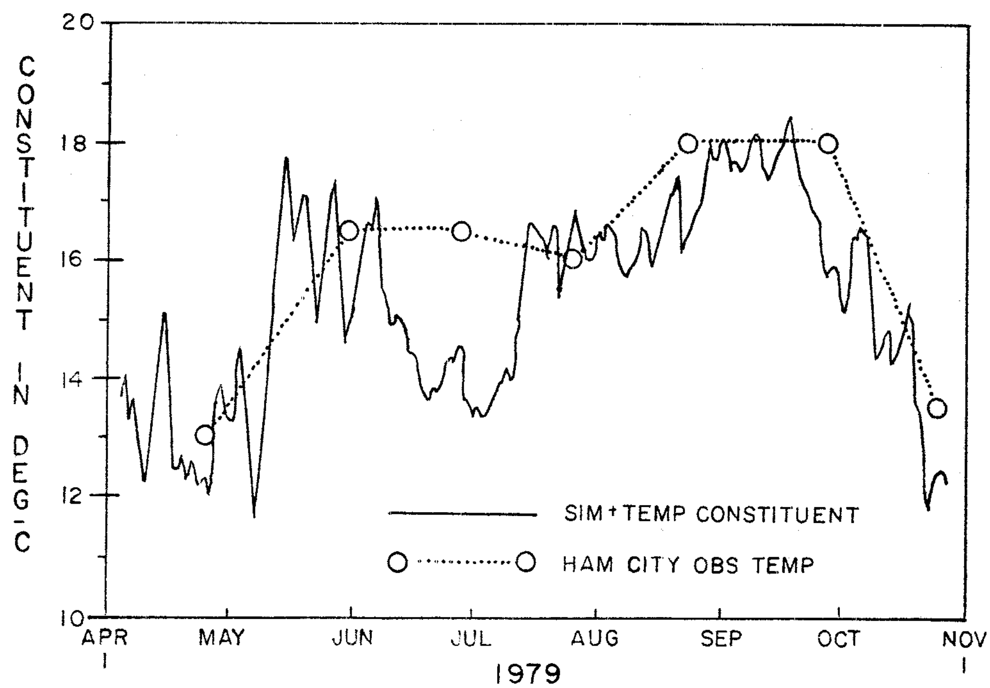

Figure 4

SACRAMENTO RIVER AT HAMILTON CITY - WATER TEMPERATURE

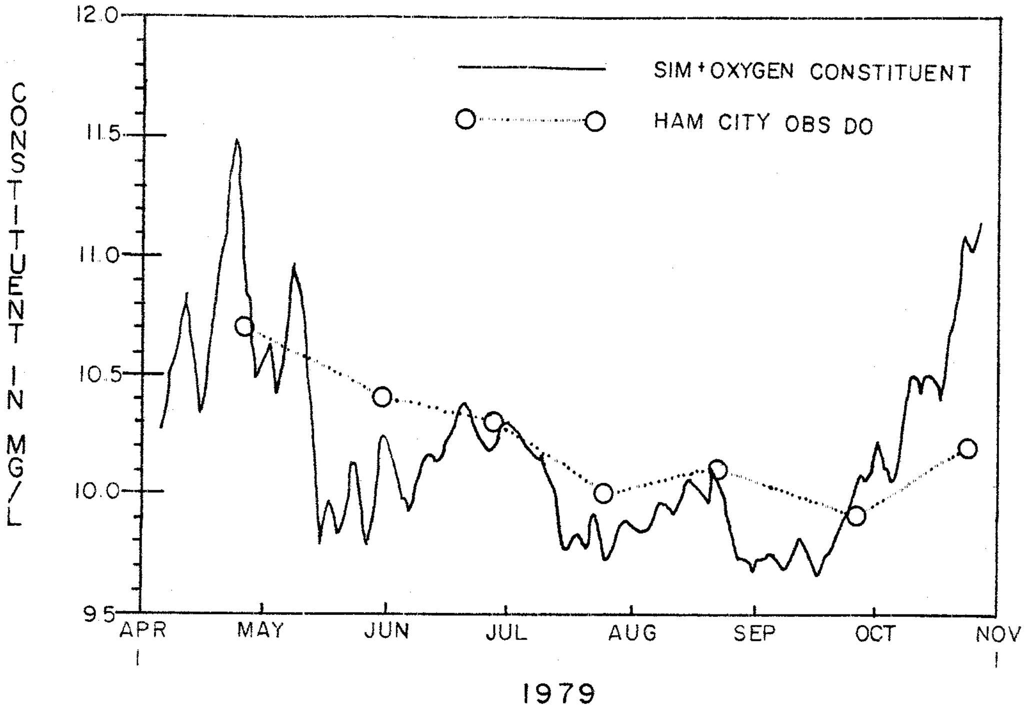

Figure 5

SACRAMENTO RIVER AT HAMILTON CITY-DISSOLVED OXYGEN

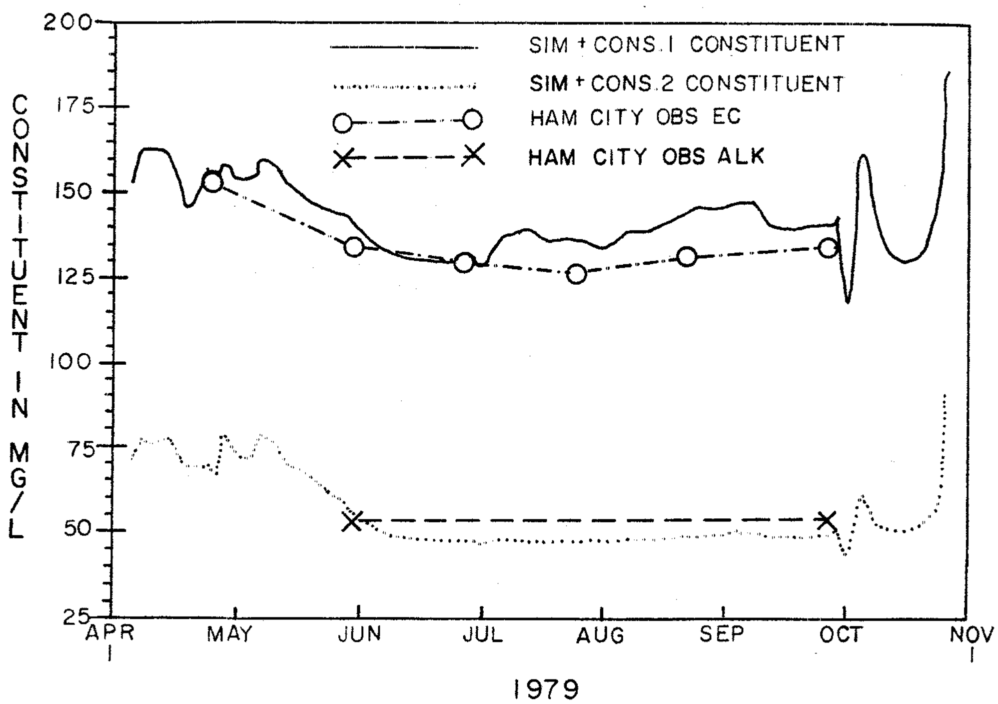

Figure 6

SACRAMENTO RIVER AT HAMILTON CITY - SPECIFIC CONDUCTANCE (EC) & ALKALINITY

significant warming of the reach of the Sacramento River takes place at least during the Spring (April and May 1956). This temperature consideration, 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 sufficiently large 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.

Since the Sacramento River below Sacramento is the combination 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 authors to encourage the continued application of this model to help develop understanding of the workings and operation of any stream system.

SUMMARY

HEC-5Q model is capable of simulating the effects of the operation of as many as ten reservoirs and the stream network of the basin. Each reservoir may be operated to satisfy a number of objectives, including flood control, low flow maintenance, hydropower production, water conservation and water quality control. The water quality portion of the model will simulate temperature and seven other constituents including dissolved oxygen. The model will internally determine the water quality needed from all reservoir releases to meet specified downstream water quality objectives and will determine the gate openings in each reservoir that will yield the appropriate reservoir release water quality.

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