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14. ABSTRACT
Water managers have been attempting to operate reservoirs in a "best water management strategy" to meet specific project objectives since the first man-made impoundment was constructed. It was realized several years ago, that the U.S. Amy corps of Engineers must have the capability to analyze the operation of large multiple reservoir systems for water quality. The Hydrologic Engineering Center was funded to develop a computer program to meet this need. "HEC-5Q, Simulation of Flood Control and Conservation Systems' computer model has the unique capabilities to accept user-specified water quantity and quality needs system-wide, and to decide how to regulate a 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. A brief history and description of the HEC-5Q model is provided along with citations to related case studies and technical reports.

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Modeling Water-Resource Systems for Water-Quality Management

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Abstract: Water managers have been attempting to operate reservoirs in a "best water management strategy" to meet specific project objectives since the first man-made impoundment was constructed. When it was realized, several years ago, that the U.S. Army Corps of Engineers must have the capability to analyze the operation of large multiple reservoir systems for water quality, the Hydrologic Engineering Center (HEC) was funded to develop a computer program to meet this need. "HEC-5Q, Simulation of Flood Control and Conservation Systems" computer model has the unique capabilities to accept user-specified water quantity and quality needs systemwide, and to decide how to regulate a 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. A brief history and description of the HEC-5Q model is provided along with citations to related case studies and technical reports.

INTRODUCTION

Water managers have been attempting to operate reservoirs to provide a "best water management strategy" to meet specific project objectives since the fist man-made impoundment was constructed. Two things, however, require water managers to occasionally reevaluate a best water management strategy. As time passes, project objectives may change because of changes in an individual owner/operator's needs and desires or, in the case of large public projects, changing public interests. Second, state-of-the-art techniques for impoundment regulation change, and these new techniques may require a reevaluation of operational impacts due to structural or nonstructural modifications.

Several state-of-the-art models (*Hydrocomp* 1976; Hydrologic 1978; and U.S. Army 1982) are available for analyzing water-quality conditions in complex reservoir systems for a given set of operational conditions. Some of these models can suggest operational decisions for proper gate regulations to obtain desirable water-quality conditions at a dam site for a given set of flow conditions.

When it was realized, several years ago, that the U.S. Army Corps of Engineers must have the capability to optimize the operation of large, multiple-reservoir systems for water quality, the Hydrologic Engineering Center (HEC) was funded to develop a computer program to meet this need. The "HEC-5Q, Simulation of Flood Control and Conservation Systems" (HEC 1982, 1986, 1989) computer model that was developed has the unique capabilities to accept user-specified water-quantity and -quality needs throughout a system, and to decide how to regulate the network of reservoirs. The decision criteria are programmed to consider flood control, hydropower, instream flow (municipal, industrial, and irrigation water supply, and fish habitat needs), and water-quality requirements. The model may be used for evaluating water-quality impacts of modified reservoir regulation, modified reservoir discharge designs (e.g., adding a multiple-level intake capability), modified point or nonpoint sources, or variations in hydrological and meteorological conditions.

A brief description of the HEC-5Q concepts will be discussed in the following section. A detailed description of HEC-5Q concepts and input to the model are discussed in the aforementioned computer program descriptions. Although HEC-5Q has been used on U.S. Army Corps of Engineers field applications for more than 15 years, it is continuously being upgraded with new capabilities. The purpose of this paper is to disseminate this unique water-quality modeling technology to a wider audience.

PROGRAM DEVELOPMENT

In 1978, various computer programs available within the Corps for evaluating reservoir system operations for water quantity were screened to obtain the best generalized model on which to append water-quality capability (Hula 1979; HEC 1982; U.S. Army 1975). The "HEC-5 Simulation of Flood Control and Conservation Systems" Computer Program (HEC 1982) 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

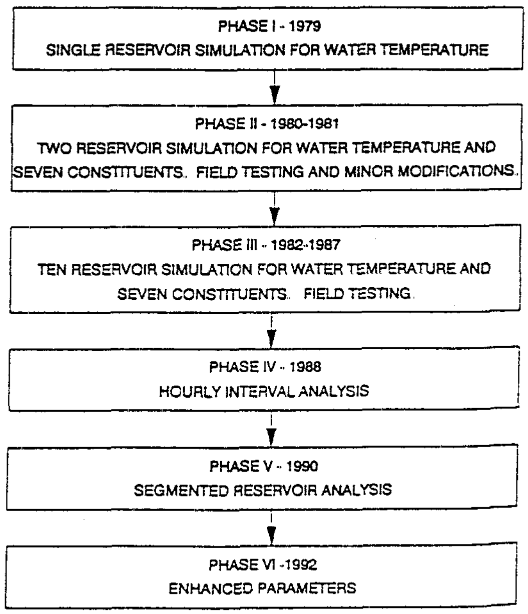

FIG. 1. Phased Development of HEC-5Q

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operation of a reservoir-channel system of a branching network configuration. Any time interval from hourly to monthly can be used. The model has the capability to change from one time step to another in order to provide greater temporal resolution during certain periods, such as floods. Channel routing is provided by any of five hydrologic routing techniques. Reservoir objectives include: (1) Minimizing downstream flooding; (2) evacuating flood-control storage as quickly as possible; (3) providing for low flow requirements and diversions; and (4) meeting 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 automatically performed, using the safe yield concept, and economic computations can be provided for hydropower benefits and flood-damage evaluation.

In 1979, work was initiated to modify HEC-5 to also evaluate reservoir operations for water-quality control in large reservoir systems. The modifications were identified to be accomplished in the first three phases as shown in Fig. 1. Phase I added the capability to HEC-5 to simulate the water temperature within a single reservoir, and in the downstream river reach. The control of the discharge water temperature was accomplished through multilevel intake structure operation, if available. In September 1979, the single-reservoir water-temperature-control computer program called HEC-5Q was completed.

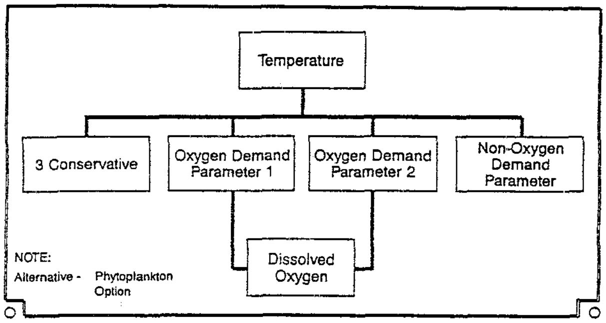

FIG. 2. HEC-5Q Water-Quality Parameters

In 1980, work was initiated to modify the Phase I model to add seven more water-quality parameters and the capability to evaluate either two tandem (i.e., in series) or two parallel (i.e., on two independent tributaries) reservoirs. In September 1980, 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, as shown in Fig. 2, was completed.

Following the phase II development, the model was modified with some small yet significant additions and revisions during 1981. These modifications included flow augmentation, improved model efficiency, and newly developed selective withdrawal routines.

The third phase of development involved increasing the HEC-5Q capability to include up to 10 reservoirs and 30 control points [i.e., often U.S. Geological Survey (USGS) gauging stations] in an arbitrary tandem and parallel configuration. At this point, HEC began detailed testing of the HEC-5Q model on practical applications. The HEC-5Q program was first applied to the Sacramento River system in California, and a report describing how to calibrate and apply the model was published in 1985 and revised in 1987 (HEC 1987). Two other applications with HEC-5Q on the Kanawha River and Monongahela River systems have been completed and reports describing the results were published by Willey (1986a; 1987a).

In 1988, an HEC-5Q application was initiated on the Columbia/Snake River system for the 19 reservoirs shown in Fig. 3. A fourth phase of development of HEC-5Q added a new capability for diurnal analysis (i.e., a computational interval less than daily) of the water-quality parameters. The HEC-5 program already had short-interval water-quantity-analysis capabilities.

During 1991, the Snake River part of the application required evaluation of increased velocities in the long, narrow reservoirs. Phase V added capability to segment reservoirs into compartments in a longitudinal direction. This model expansion has proven to be an important addition to the deep (vertical) reservoir and river segment configurations shown in Fig. 4.

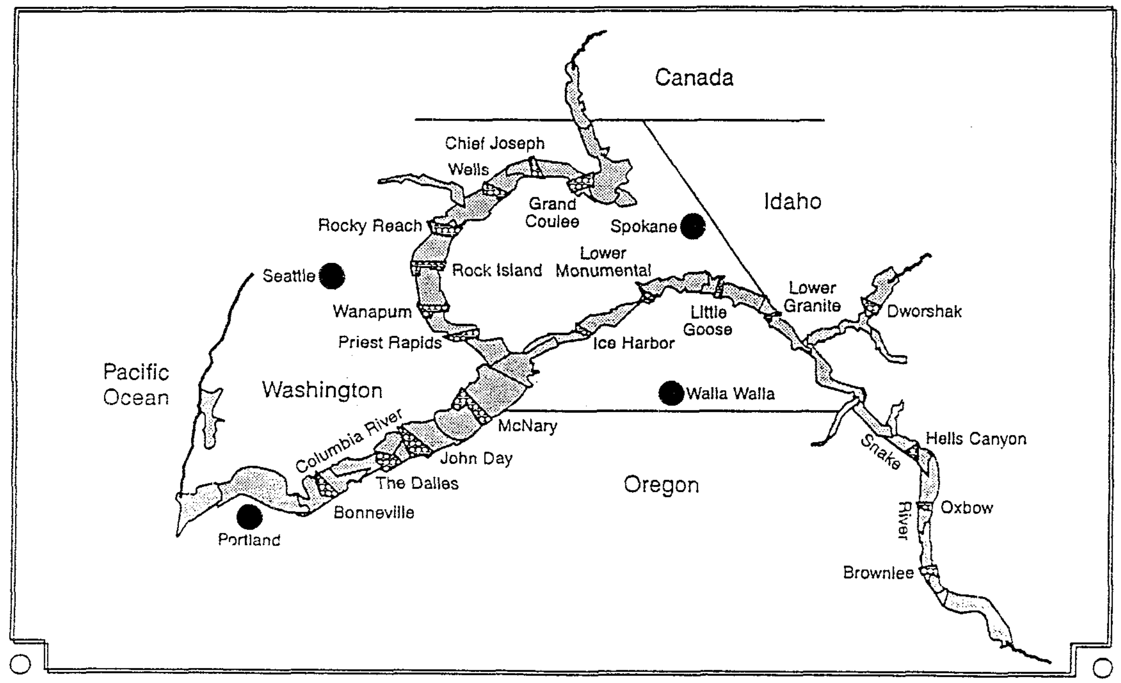

FIG. 3. Lower Columbia and Snake River System

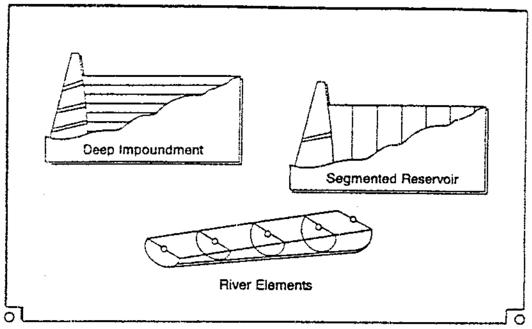

FIG. 4. Water-Quality Computation Segments

The sixth phase of development was initiated in 1992 to add capability to analyze metals, dioxin, and other parameters, shown as follows, including the analysis of chemicals adsorbed on to organic and inorganic particulates.

1. Total dissolved solids
2. Nitrate as nitrogen
3. Phosphate as phosphorus
4. Phytoplankton
5. Carbonaceous BOD
6. Ammonia as nitrogen
7. Dissolved oxygen
8. Chlorides
9. Alkalinity as $CACO_3$
10. pH (TIC and CO_2)
11. Dissolved organic chemical #1
12. Dissolved organic chemical #2
13. Heavy metal or radionuclide #1
14. Heavy metal or radionuclide #2
15. Heavy metal or radionuclide #3
16. Dioxin or furan #1
17. Dioxin or furan #2
18. Organic or inorganic particulate #1
19. Organic or inorganic particulate #2
20. Organic or inorganic particulate #3
21. Coliform bacteria

The most recent HEC-5Q application involved water temperature impacts on the McKenzie River fishery. Those results were published by HEC (1994).

MATHEMATICAL MODEL CONCEPTS

HEC-5Q has been developed specifically for evaluating the water-quality impacts of proposed and/or historical discharge operations of large reservoir systems like the type of problem shown in Fig. 3. The model is capable of evaluating a reservoir system with as many as 20 reservoirs and 40 control points. These dimensional limitations only apply to the compiled code as distributed. Parameter statements, in the FORTRAN code, can be easily changed to control these dimensions. The model will define "best water management strategy" for water quantity and quality, addressing operational concerns such as flood control, hydropower, water supply, and irrigation diversions. Since the computer program user's manual (HEC 1982, 1986, 1989) and several technical papers (Duke et al. 1984; Willey 1983, 1986b, 1987b; Willey et al. 1985) adequately document the details of the model concepts and the input description, only a brief overview is provided in the following sections.

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 a system. The program is used to show the effects of existing and/or proposed reservoirs on flows in a complex reservoir system. The program is also used to determine proper reservoir releases systemwide to minimize flooding while maintaining a balance of flood control storage ("balanced pool") among the reservoirs.

Several papers (Bonner 1980; Eichert 1974, 1975, 1979; Eichert et al. 1975; Eichert and Davis 1976; Johnson and Davis 1975; McMahon et al. 1979) have already been written on the detailed technical concepts of the flow simulation module. The remainder of this paper will present the concepts of the water-quality simulation module.

Water-Quality Simulation Module

The water-quality simulation module can be applied at three distinct levels of detail. The first level of detail is capable of analyzing water temperature and up to three conservative and three nonconservative constituents. If at least one of the nonconservative constituents is an oxygen-demanding parameter, dissolved oxygen can also be analyzed. This level of detail is shown in Fig. 2. Temperature adjustment of the reaction rates, and oxygen demand between two of the nonconservative parameters and dissolved oxygen are the only parameter interactions.

The second level of detail is the phytoplankton option. The parameters of Fig. 2 are modified to include the first seven parameters ennumerated earlier and the water temperature. The difference in parameter interactions from those in level one include the effect of nutrients on phytoplankton and the demand of the additional parameters on dissolved oxygen.

The third level of detail is referred to as the enhanced model. Water temperature and the 21 parameters shown earlier can be analyzed with this option. The enhanced model contains more parameter interaction and more comprehensive phytoplankton computations than the other levels of analysis.

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 20 reservoirs and their associated downstream reaches. The 20 reservoirs may be in any arbitrary parallel and tandem configuration. The water-quality simulation module may use flow data from the flow simulation module of hourly, daily, or monthly intervals, depending on the purpose of the analysis. The input data can be divided into time-series and nontime-series data. The time-series data includes weather conditions at one or more stations near the water bodies to be analyzed and the water quantity and quality flowing into the water bodies at all tributary locations. The nontime-series data includes the physical descriptions of the water bodies to be analyzed.

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 using the initially 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 the 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.

Each reservoir is assumed to be a control point, in keeping with the concepts used in the development of the flow simulation module. The water-quality module has a maximum of 40 control points, including the reservoir control points. The additional control points may be placed in the network downstream of each reservoir at points of interest provided the following guidelines are used: (1) The most downstream point in a system must be a control point; and (2) the confluence of

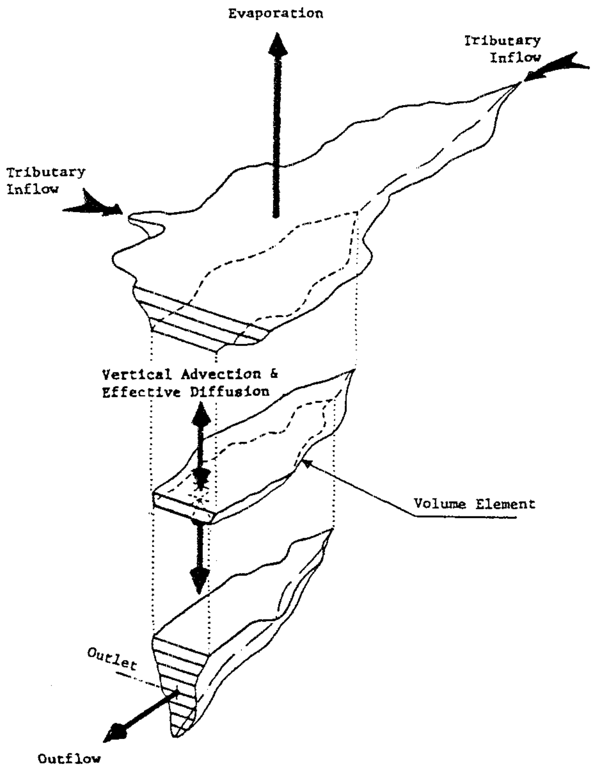

FIG. 5. Geometric Representation of Stratified Reservoir and Mass Transport Mechanism

the two streams, on which parallel reservoirs are located, must be a control point.

Deep (vertical) reservoirs are represented conceptually by a series of one-dimensional horizontal slices such as those shown in Fig. 5. Each horizontal slice or layered volume element is characterized by a surface area, thickness, and volume. The assemblage of layered volume elements is a geometric representation, in discretized form, of the prototype reservoir. This one-dimensional representation has been shown to adequately represent water-quality conditions in many deep, well-stratified reservoirs by Eiker (1972), Baca et al. (1977), and Water Resources Engineers (1968, 1969).

Within each element, the water is assumed to be fully mixed. This implies that only the vertical gradient is retained during the computation. Each horizontal layer is assumed to be completely homogeneous with all isopleths parallel to the water surface, both laterally and longitudinally. External inflows and withdrawals occur as sources or sinks within each layer. External inflows are instantaneously dispersed and homogeneously mixed throughout each element from the headwaters of the impoundment to the dam. It is not possible, therefore, to examine longitudinal variations in water-quality constituents. These results are therefore most representative of conditions in the deeper regions of the main reservoir body, usually near the dam.

Vertical advection is governed by the location of inflow to, and outflow from, the reservoir. Thus the computation of zones of distribution and withdrawal for inflows and outflows are of considerable significance in the operation of the model. The Waterways Experiment Station (WES) withdrawal method by Bohan and Grace (1973) is used to determine the allocation of outflow. The Debler (1959) inflow allocation method is used for the placement of inflows.

Vertical advection is the net interelement flow and is one of two transport mechanisms used in the module to transport water-quality constituents between elements. The vertical advection is defined as the interelement flows, which result in a continuity of flow for all elements. Effective diffusion is the other transport mechanism used in the module to transport water-quality constituents between elements. The effective diffusion is composed of molecular and turbulent diffusion as well as convective mixing.

Wind- and flow-induced turbulent diffusion and convective mixing are the dominant components of effective diffusion in the epilimnion of most reservoirs. In quiescent, well-stratified reservoirs, molecular diffusion may be a significant component in the metalimnion and hypolimnion. For deep, well-stratified reservoirs with significant inflows to, or withdrawals from, the hypolimnion, flow-induced turbulence in the hypolimnion dominates. For weakly stratified reservoirs, wind-induced or wind- and flow-induced turbulent diffusion will be the dominant component of the effective diffusion throughout the reservoir. One of the two methods may be selected by the user to calculate effective diffusion coefficients. For shallow, weakly stratified reservoirs, the wind-controlled mixing method is appropriate, while the stability method is more appropriate for deeper, well-stratified reservoirs. Both these methods have been shown in numerous applications (Baca et al. 1977; Willey 1986a, 1987a; HEC 1987, 1994) to adequately represent the mixing phenomena for heat and dissolved water-quality constituents when properly applied.

The stream system is conceptually represented as a linear network of segments or volume elements. Each element is characterized by length, width, cross-sectional area, hydraulic radius, Manning's n and a flow and depth relationship (see Fig. 6). Flow rates at stream control points are calculated within the flow simulation module using any one of the several programmed hydrologic routing methods. Within the flow simulation module, incremental local flows (i.e., inflow between adjacent control points) are assumed to be deposited at the downstream control point.

Within the water-quality simulation module, the incremental local flow may be divided into components and placed at different locations within the stream reach (i.e., that portion of the stream bounded by the two control points). A flow balance is used to determine the flow rate at element boundaries. Any flow imbalance (i.e., the difference in the flow at the upstream control point plus all tributary inflows and the flow at the downstream control point) is distributed uniformly to the flows at each element boundary. Once interelement flows are established, the depth, surface width, and cross-section area are computed at each element boundary assuming normal depth (i.e., calculating depth as a function of flow using Manning's equation).

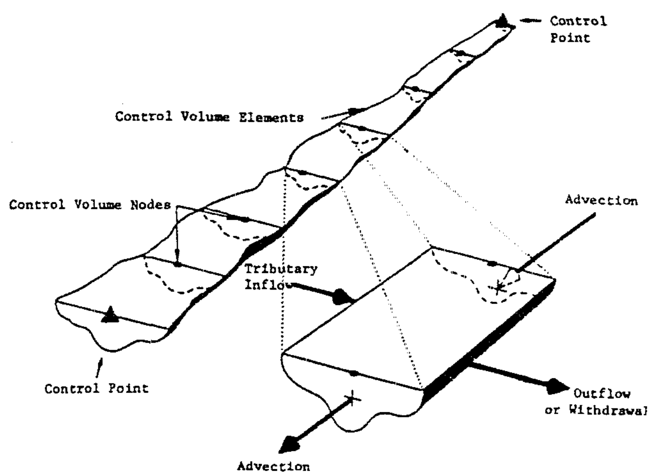

FIG. 6. Geometric Representation of Stream System and Mass Transport Mechanism

The segmented reservoir is a combination of the deep (vertical) reservoir and the stream analysis parts of the model. For a segmented reservoir, the geometric properties of each segment are a function of the deep reservoir's elevation/volume properties but distributed along the longitudinal reservoir axis. In general, the calculations used in the stream are then used in the segmented reservoir except for the outflow operational control in the most downstream segment. That outflow control is the same as in the deep reservoir model. The assumption is that each segment is vertically and laterally mixed, i.e., the longitudinal gradient is simulated.

Both the streams and reservoirs are represented by a one-dimensional assemblage of fluid elements linked together by interelement flow and diffusion (stream diffusion is assumed to be small). The equations and details of the concepts are discussed in the following section.

The interelement mass transport and the fundamental principle of conservation of heat are represented by the following differential equation model of the dynamics of temperature within each fluid element.

$$V\frac{\partial T}{\partial t} = \Delta z \cdot Q_z \frac{\partial T}{\partial z} + \Delta z \cdot A_z \cdot D_z \frac{\partial^2 T}{\partial z^2} + Q_l \cdot T_l - Q_o \cdot T + \frac{A_h H}{\rho \cdot c} - T\frac{\partial V}{\partial t} \quad (1)$$

where T = water temperature, in °C; V = volume of the fluid element, in m^3; t = time, in s; z = space coordinate, in m (vertical for the reservoir and horizontal for the stream); Q_z = interelement flow, in m^3/s; A_z = element surface area normal to the direction of low, in m^2; D_z = effective diffusion coefficient, in m^2/s; Q_l = lateral inflow, in m^3/s; T_l = inflow water temperature, in °C; Q_o = lateral outflow, in m^3/s; A_h = element surface area, in m^2; H = external heat sources and sinks, in $J/m^2/s$; ρ = water density, in kg/m^3; and c = specific heat of water, in J/kg/°C.

The external heat sources and sinks, H, are assumed to occur at the air-water interface. The rate of heat transfer per unit of surface area is the sum of the standard heat exchange components, i.e., net short- and long-wave radiation, conduction, back radiation, and evaporation. Complete discussions of the individual terms have been presented by Anderson (1954) and the Tennessee Valley Authority (1972).

The method used in the module to evaluate the net rate of heat transfer at the air-water interface was developed by Edinger and Geyer (1965). Their method utilized the concepts of equilibrium temperature and the coefficient of surface heat exchange. The equilibrium temperature is defined as the water temperature at which the net rate of heat exchange between a water surface and the atmosphere is zero. The coefficient of surface heat exchange is the rate at which the heat transfer process proceeds. The equation describing this relationship is

$$H_n = K_e(T_e - T_s) \quad (2)$$

where H_n = net rate of heat transfer, in $J/m^2/s$; K_e = coefficient of surface heat exchange, in $J/m^2/s/°C$; T_e = equilibrium temperature, in °C; and T_s = surface temperature, in °C.

All heat transfer mechanisms except short-wave solar radiation apply at the water surface. Short-wave radiation penetrates the water surface and may affect water temperatures beneath the surface. The depth of penetration is a function of adsorption and the scattering properties of the water (Hutchinson 1957). This phenomenon is unimportant in the stream routines since elements are assumed to be vertically mixed.

In the deep (vertical) reservoir routines, however, the short-wave solar radiation may penetrate several elements. The amount of heat that reaches each element is determined by

$$I = (1 - \beta)I_0 e^{-kd} \quad (3)$$

where I = light energy at any depth, in $J/m^2/s$; β = fraction of the radiation absorbed in the top foot of depth; I_0 = net light energy at the water surface, in $J/m^2/s$; k = light extinction coefficient, in m^{-1}; and d = depth, in m.

Combining (2) and (3) for the reservoir surface element, the external heat source and sink term, H, become

$$H = K_e(T_e - T_s) - (1 - \beta)I_0 e^{-k\Delta z} \quad (4)$$

where Δz = thickness of a reservoir element, in m. The external heat source, I, for all remaining reservoir elements becomes

$$I = I_z(1 - e^{-k\Delta z}) \quad (5)$$

where I_z = light intensity at the top of the element, in $J/m^2/s$.

Water-quality constituents other than temperature are represented by (1) with the following minor modifications:

1. The definition of the variable T is generalized to represent the concentration of any water-quality constituent.
2. The distributed heat gain/loss term $A_h H/(\rho c)$ is eliminated for conservative constituents; replaced by a first-order kinetic decay formulation, $-K_1 T$, for nonconservative constituents where K_1 is the decay rate (per/day) at 20°C; and replaced by a first-order reaeration term, $K_2(DO^* - DO)$, for dissolved oxygen where K_2 is the reaeration rate, DO^* is the dissolved oxygen saturation concentration (in mg/L) at the ambient temperature, and DO is the existing concentration (in mg/L).

The reservoir reaeration rate is computed as follows:

$$K_2 = (a + bW^2)/z_s \quad (6)$$

where K_2 = reaeration rate (per day) at 20°C; a, b = empirical coefficients derived by curve fit from Kanwisher (1963) to be 0.641 and 0.128, respectively; W = wind speed, in m/s; and z_s = surface element thickness, in m.

The stream reaeration rate is computed using the O'Connor and Dobbins (1958) method or a variety of similar techniques documented in the HEC-5Q program description. All first-order kinetic rates are adjusted for local ambient temperatures using the following multiplicative correction factor, Θ:

$$\Theta = T_{cf}^{(T-20)} \quad (7)$$

where T_{cf} = empirically determined temperature correction factor; and T = water temperature, in °C.

Solution Techniques

Within the reservoir model, a Gaussian reduction scheme is used for solving numerical approximations to the differential equations, which represent the response of the water-quality constituents. Eq. (1) uses a scheme which is forward in time and central in space to describe all the derivatives. The reservoir model solution technique is described in detail in the aforementioned HEC-5Q program descriptions previously referenced.

For the stream model, a sparse matrix linear programming algorithm is used to solve a fully implicit backward difference in space, forward difference in time, and finite difference approximation of (1). This approach allows for defining the required reservoir releases using operation research techniques as well as for simulating the effects of those decisions. The stream model solution is also described in detail in the HEC-5Q program descriptions.

Gate Selection

Once a desired reservoir release water quality has been computed, the water-quality simulation module determines: (1)

The reservoir gates from which releases should be made; (2) the water quality of the release; and (3) the mix of flow rates to be discharged from those gates.

Total outflow rates from reservoirs are determined using the flow simulation module. For each reservoir, a port selection algorithm (Poore and Loftis 1983) is used to select one or more of the available gates that should be opened and determine what flow rate should pass through each gate so that the desired release quality is obtained. Each reservoir is assumed to have a minimum capability to release from one gate and may have selective withdrawal capability consisting of one or two wet wells (with as many as eight gates each) and one flood-control outlet.

The port selection routine is a nonlinear programming algorithm with linear constraints. The objective function is quadratic and is directed toward minimizing deviations from the desired reservoir release water quality, subject to gate capacity restrictions.

The HEC-5Q model also provides for releases through an uncontrolled spillway. These releases are not a part of the gate selection algorithm, but the water quality of the spillway releases are considered in the gate selection algorithm.

There are different types of combinations of open ports. When there is only one port available, all of the flow is taken from the single opening and the water-quality index is computed. The water-quality index is a user-defined, dimensionless function interrelating the various water-quality parameters. It is used to optimize the discharge gate operations when multilevel intake capability exists. When there are two or more ports, combinations of any one port in each wet well in conjunction with the flood gate are considered. If the flow alteration option is selected, then the flow is treated as an additional decision variable and the flow for which the water-quality index is maximized is also determined.

For each combination of open ports, a sequence of flow allocation strategies is generated using a gradient method, a gradient projection method, or a Newton projection method, as appropriate. The value of any flow allocation strategy is determined by evaluation of a water-quality index subject to the hydraulic constraints of the system. The computation sequence converges to the optimal allocation strategy for the particular combination of open ports.

To evaluate the water-quality index for a feasible flow allocation strategy, the release concentration for each water quality constituent, R_{cc}, is first computed.

$$R_{cc} = \frac{\sum_{p=1}^{N_p} [\phi_{cp} Q_p]}{\sum_{p=1}^{N_p} Q_p}; \quad cc = 1, N_{cc} \tag{8}$$

where cc = index for constituents; p = index for open ports; N_p = number of open ports; ϕ_{cp} = concentration of constituent cc at port p; Q_p = flow through port p; and N_{cc} = number of constituents under consideration.

TABLE 1. Coefficients in Constituent Suboptimization of Gate Selection Procedure

Curve number (1)	*a* (2)	*b* (3)	*c* (4)	*d* (5)	*e* (6)
1	100	0.0	−0.1	0.0	0.000
2	100	0.0	−2.0	0.0	0.000
3	100	0.0	−10.0	0.0	0.000
4	100	−3.2	−0.7	−0.1	−0.005
5	100	3.2	−0.7	0.1	−0.005

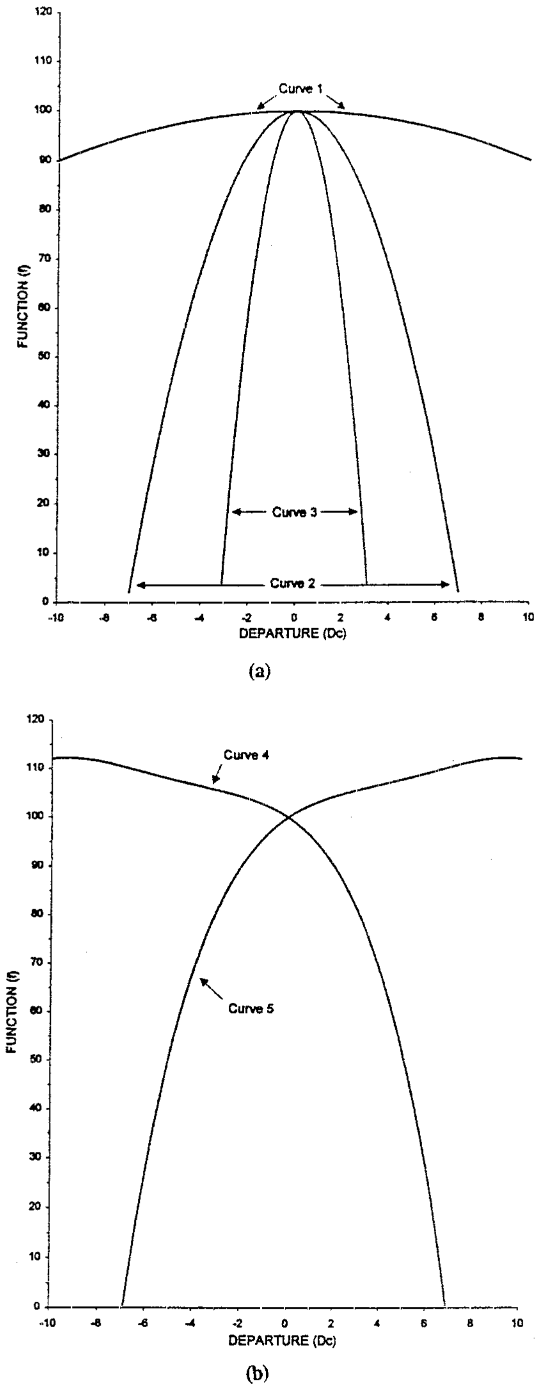

FIG. 7. Graphical Representation of Constituent Suboptimization Function Using Typical Coefficients

The deviation of release qualities from target qualities, D_{cc}, can then be computed

$$D_{cc} = |R_{cc} - T_{cc}|; \quad cc = 1, N_{cc} \tag{9}$$

where T_{cc} = target quality for constituent cc.

The subindex S_{cc} for each constituent is then determined by

$$S_{cc} = f(D_{cc}); \quad cc = 1, N_{cc} \tag{10}$$

where the constituent suboptimization function $f(D_{cc})$ takes the fifth-order polynomial form

$$f(D_{cc}) = a + bD_{cc} + cD_{cc}^2 + dD_{cc}^3 + eD_{cc}^4 \tag{11}$$

In selecting these coefficients, $a-e$, the magnitude and importance of the water-quality parameter of interest should be considered. To aid in the coefficient selection process, Table 1 and Fig. 7 are provided.

Curves 1–3, in Table 1 and Figure 7, represent functions where equal weight is given to deviations on either side of the target concentration. Curve 1 would normally be selected for a water-quality parameter such as total dissolved solids (TDS) since wide variations from the target are normally allowed. For a parameter like nitrate where the concentration is small, curve 3 would be an appropriate choice. Curve 2 might be used for temperature and other parameters with concentrations in the range of 5–25.

Curves 4 and 5 represent functions where deviations about the target are not weighted equally. Curve 4 would be selected for a toxic parameter where the lowest concentration possible would be desirable, while curve 5 would be used for a parameter like dissolved oxygen (DO), where a higher concentration is always desired. Almost any shape function desired can be developed for this fifth-order polynomial using readily available curve-fit programs.

Finally, the scalar water-quality index Z, used as the objective function, is determined by

$$Z = \sum_{cc=1}^{N_{cc}} W_{cc} S_{cc} \tag{12}$$

where W_{cc} = weighting factor for constituent cc (the sum of the weighting factors for all constituents must equal one); and S_{cc} = subindex for constituent cc.

If any of the water-quality parameters do not require optimization for reservoir discharge port selection, a required input weighting factor for each parameter can be set to zero. The weighting factor W_{cc}, used in conjunction with the suboptimization function design, allows the user extensive control over the gate operations.

In summary, the problem of determining the optimal allocation of flows to ports for a particular combination of open ports, a specified total flow rate Q, and specified release water-quality targets can be expressed as follows:

$$\max \left[\sum_{cc=1}^{N_{cc}} W_{cc} S_{cc} \right] \tag{13}$$

Subject to

$$\sum_{p=1}^{N_p} Q_p = Q \tag{14}$$

$$\text{and} \quad F_{\min,p} \leq Q_p \leq F_{\max,p}; \quad p = 1, N_p \tag{15}$$

Where $F_{\min,p}$ and $F_{\max,p}$ = minimum and maximum acceptable flow rates through an individual port, respectively.

When an acceptable flow range is specified, the problem is written as

$$\max \left[\sum_{cc=1}^{N_{cc}} W_{cc} S_{cc} \right] \tag{16}$$

Subject to

$$Q_{\text{lower}} \leq \sum_{p=1}^{N_p} Q \leq Q_{\text{upper}} \tag{17}$$

$$\text{and} \quad F_{\min,p} \leq Q_p \leq F_{\max,p}; \quad p = 1, N_p \tag{18}$$

These problems are solved very efficiently by using mathematical optimization techniques that take advantage of the problem structure, namely, a nonlinear objective function with linear constraints.

Flow Alterations

The flow alteration routine is designed to change the reservoir releases, computed by the flow simulation module, to better satisfy the stream control-point water-quality objectives. The routine considers the mass balance for all reservoir releases and all control points affected by those releases. Time-dependent tributary inflows and other time-dependent flows are included. Second-order effects, such as changes to reaeration and external heating due to varying stream surface areas are not included.

The procedure is as follows:

1. The relative mass, ΔM, that needs to be added in the flow at the control point (for those constituents below the target) or reduced in the flow at the control point (for those constituents above the target) is computed using

$$\Delta M = Q_{cp}(C_o - C_{cp}) \tag{19}$$

   where Q_{cp} = flow at the control point, in m^3/s, as determined by the flow simulation module; C_o = target constituent concentration at the control point; and C_{cp} = computed constituent concentration at the control point.
2. The average reservoir release concentration is computed for all reservoirs for which the constituent concentration in the releases is greater than the target concentration at the control point of interest (for those constituents below the target), or for which the constituent concentration in the releases is less than the target at the control point of interest (for those constituents above the target). Thus

$$\bar{C}_R = \left(\sum_{i=1}^{n} Q_{Ri} C_i \right) \Big/ \sum_{i=1}^{n} Q_{Ri} \tag{20}$$

   where $\bar{C}_R$ = average constituent concentration in reservoir releases for only those reservoirs releasing flow with constituent concentrations adequate to dilute the control-point concentration and bring it to the target value; Q_{Ri} = flow release from reservoir I, in m^3/s; C_I = constituent concentration in release from reservoir I; and n = number of reservoirs. The sums are taken only over those reservoirs I that are capable of diluting the control-point constituent concentration that is worse than the target.
3. The total dilution flow requirement is then computed by the following quotient:

$$Q_A = \Delta M / \bar{C}_R \tag{21}$$

   where Q_A = total flow release, in m^3/s, needed to bring the constituent concentration at the control point of interest to the target.
4. The flow Q_A is then apportioned to the reservoirs capable of bringing the control-point constituent concentration to the target in proportion to the flows originally computed for those reservoirs by the flow simulation module.

Thus the flow augmentation requirement can be computed for each control point and for each constituent. The various computed flow rates are then combined by using the coefficients of the linear programming objective function and the deviation of the constituent concentrations from the target concentrations at each respective control point as follows:

$$Q_k = \frac{1}{\sum_{i=1}^{N_{cp}} \sum_{j=1}^{N_{cc}} P_{ij}(C_{ij} - C_{io})} \sum_{i=1}^{N_{cp}} \sum_{j=1}^{N_{cc}} Q_A P_{ij}(C_{ij} - C_{io}) \tag{22}$$

where Q_k = flow release from reservoir k, in m^3/s; N_{cp} = number of control points affected by n reservoirs; N_{cc} = number of constituents; P_{ij} = linear programming objective function coefficient for constituent j at control point I; C_{ij} = computed concentration of constituent j at control point I; and C_{io} = target concentration of constituent I.

Once the Q_k is determined, using (22), the flow simulation module is recalled and the daily computations for flow and water quality are solved again for the final results.

SUMMARY

In this paper, the writers provided a brief description of the HEC-5Q computer program for the analysis of water-quality impacts due to reservoir system operations. The model has been used to evaluate current and proposed operations on large integrated reservoir systems such as the Columbia River and similar large systems in other regions of the United States. Once calibrated to historical conditions, alternative regulations can be easily evaluated considering all project purposes at all points in the system, thus providing the water managers with input to their operation decisions in either a planning or real-time mode.

HEC-5Q is capable of simulating the effects of the operation of as many as 20 reservoirs and the associated stream network of a region. The reservoirs 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 water-quality constituents, including an option for dissolved oxygen. Other levels of detail can be used to evaluate up to 22 water-quality parameters.

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. If necessary, flows may be altered to ensure that downstream water-quality objectives are met. As currently formulated, the model does not use foresight or forecasting in an attempt to ensure that a global optimum solution that meets water-quality objectives is found. The model selects the best solution for systemwide reservoir operation within this limitation.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A_h = element surface area, in m^2;
A_z = element surface area normal to the direction of flow, in m^2;
a = empirical coefficient derived by curve fit to be 0.641;
b = empirical coefficient derived by curve fit to be 0.128;
C_{cp} = computed constituent concentration at the control point;
C_i = constituent concentration in release from reservoir i;
C_{ij} = computed concentration of constituent j at control point i;
C_{io} = target concentration of constituent i;
C_o = target constituent concentration at the control point;
$\bar{C}_R$ = average constituent concentration in reservoir releases;
c = specific heat of water, in J/kg/°C;
cc = index for constituents;
D_{cc} = deviation of release water quality from target water quality;
DO = existing dissolved oxygen concentration, in mg/L;
DO^* = dissolved oxygen saturation concentration, in mg/L at the ambient temperature;
D_z = effective diffusion coefficient, in m^2/s;
d = depth, in m;
$F_{\max,p}$ = maximum acceptable flow rate, in m^3/s through an individual port p;
$F_{\min,p}$ = minimum acceptable flow rate, in m^3/s through an individual port p;
H = external heat sources and sinks, in kcal/m^2/s;
H_n = net rate of heat transfer, in J/m^2/s;
I = light energy at any depth, in J/m^2/s;
I_o = net light energy at the water surface, in J/m^2/s;
I_z = light intensity at the top of the element in J/m^2/s;
K_1 = decay rate (per/day) at 20°C;
K_2 = reaeration rate (per day) at 20°C;
K_e = coefficient of surface heat exchange, in J/m^2/s/°C;
k = light extinction coefficient, in m^{-1};
N_{cc} = number of constituents under consideration;
N_{cp} = number of control points affected by both reservoirs;
N_p = number of open ports;
n = number of reservoirs;
P_{ij} = linear programming objective function coefficient for constituent j at control point I;
p = index for open ports;
Q = total flow release, in m^3/s;
Q_A = total flow release, in m^3/s, needed to bring the constituent concentration at the control point to the target;
Q_{cp} = flow at the control point, in m^3/s, as determined by the flow simulation module;
Q_I = lateral inflow, in m^3/s;
Q_k = flow release from reservoir k, in m^3/s;
Q_{lower} = lower limit of flow, in m^3/s;
Q_o = lateral outflow, in m^3/s;
Q_p = flow through port p, in m^3/s;
Q_{Ri} = flow release from reservoir i in m^3/s;
Q_{upper} = upper limit of flow, in m^3/s;
Q_z = interelement flow, in m^3/s;
R_{cc} = release water-quality concentration for constituent cc;
S_{cc} = subindex for constituent cc;
T = water temperature, in °C;
T_{cc} = target quality for constituent cc;
T_{cf} = empirically determined temperature correction factor;
T_e = equilibrium temperature, in °C;
T_i = inflow water temperature, in °C;
T_s = surface temperature, in °C;
t = time, in s;
V = volume of the fluid element, in m^3;
W = wind speed, in m/s;
W_{cc} = weighting factor for constituent cc;
Z = water-quality index;
z = space coordinate, in m (vertical for the reservoir and horizontal for the stream);
z_s = surface element thickness, in m;
β = fraction of the radiation absorbed in the top foot of depth;
ΔM = additional mass needed to obtain the target constituent concentration at a control point;
Δz = thickness of a reservoir element, in m;
Θ = a multiplicative correction factor;
ρ = water density, in kg/m^3; and
ϕ_{cp} = concentration of constituent cc at port p.

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