Enhanced Freshwater Inflow to the Chesapeake Bay Through Operational Modifications: Feasibility of a Real-time Water Quality Release Model

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Report 87- 8

July 1987

Interstate Commission on the Potomac River Basin
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Acknowledgements

Several individuals contributed to the completion of this work. Robert D. Miller of the Water Supply Division in the Maryland Department of Natural Resources - Water Resources Administration provided both funding and interest. Graduate students Kimberly Gray and John Tobiason in the Environmental Engineering program within the Department of Geography and Environmental Engineering of the Johns Hopkins University participated in helpful discussion.

This report has been prepared by the Interstate Commission on the Potomac River Basin. Funds for this report were provided by the United States Government, the U.S. Environmental Protection Agency, and the signatory bodies of the ICPRB: Maryland, Pennsylvania, Virginia, West Virginia, and the District of Columbia. The opinions expressed are those of the authors and should not be construed as representing the opinions or policies of the United States or any of its agencies, the several states, or of the Commissioners of the Interstate Commission on the Potomac River Basin.

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Executive Summary

The reallocation of reservoir storage in Randolph Jennings Lake could provide water for use in increasing the the fresh water inflow to the Chesapeake Bay during low flow periods. Such a reallocation must not have a large effect on the ability of the project to meet its primary objectives. Knowing that real-time models can enhance the daily operation of reservoirs, the focus of this study is to determine the feasibility of developing a real-time, PC based water quality release model for Randolph Jennings Lake. The model would provide information describing the water quality in the lake to be used in making a daily release decision, and thereby aid in the attainment of the water quality objectives under any reallocation scenario.

The major components of the proposed water quality simulation and release model have been developed through earlier efforts. However, there are additional needs for a real-time model. These are threefold. First is the incorporation of the necessary chemical equilibrium equations and water quality parameters to allow estimation of pH, a parameter around which daily release decisions are made. Second is the reformulation of short-term operating rules with which to meet the water quality objectives and which may be implemented on a PC. The third need is real-time data with which to update the model; the availability of the data must be assessed.

Upon detailed discussion of each of these needs, it is concluded that the development of a real-time, PC based water quality release model is a feasible project. Methods of incorporating the necessary chemistry have been outlined and demonstrated in the literature, operating rules may be formulated to be compatable with PC capabilities, and the necessary data is being collected and maintained.

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Introduction

One alternative for providing higher flows to the Chesapeake Bay from the Potomac River during periods of low flow is the reallocation of storage in Randolph Jennings Lake (Bloomington Lake prior to May 1987) from flood control storage to water storage. Such a reallocation would affect the expected benefits from two of the four authorized project objectives, flood control and enhancement of downstream water quality. For this alternative to be acceptable, the expected benefits may not be significantly degraded. With regard to the benefits derived from flood control, a U.S. Army Corps of Engineers (COE) study (11) has shown that a nine foot (8,800 acre-feet) reallocation could occur with a reduction in flood control benefits of 3% and an eighteen foot (18,800 acre-feet) reallocation could occur with a reduction in flood control benefits of 7%. Other studies suggest that these reductions are even smaller when means are used to reduce the hydrologic uncertainty in the flood hydrographs and when this better information is incorporated into the flood control operating rules (7,8).

With regard to the water quality objectives of the project, the COE study concluded that structural additions to the release tower would be necessary to maintain water quality at its current level. However, through the use of a water quality simulation model and an operating rule which selected reservoir releases such that violations of downstream water quality targets were minimized, it was shown that structural changes are not required to maintain current water quality levels downstream for either of the reallocation volumes (6,8).

It appears that 'informed' operating rules can lead to more efficient use of flood control storage and provide better than expected management of water quality problems. To this point in time, however, the water quality simulation model has only been employed in a long-term framework. This investigation is to determine the feasibility of modifying the existing model and operating rules for real-time use. The intent is to develop a PC based operational tool with which different future release strategies may be examined for the resulting affects on downstream water quality and for the resulting distributions of the water quality constituents within the lake. This knowledge would be used in determining the release for the current day.

Presently, a number of computers exist which can house the water quality simulation model, so the primary items of concern for this feasibility study are as follow:

1. Extension of the simulation model to include the parameters around which the daily release decisions are made,

2. Development of daily release rules which reflect current operational philosophies and do not require specialized and limiting computer software, and

3. Identification of what real-time data is required and its availability.

This report proceeds with a description of the water quality setting in the North Branch Potomac River basin and current water quality operations at Randolph Jennings Lake. This is followed, in Section 2, by a brief outline of the water quality model as it currently exists and a detailed discussion of the additional modeling required for real-time use. Section 3.0 addresses the data requirements, and Section 4.0 summarizes the findings.

1.0 The Water Quality Setting and Water Quality Operations

Randolph Jennings Lake is a multipurpose impoundment located on the boundary between Maryland and West Virginia. A major portion (51,000 acre-feet, 40% of useable storage) of Randolph Jennings Lake is devoted to water quality storage. This storage is used to maintain downstream flowby requirements of a quality conducive to the growth of fish and aquatic life; the river reach below the lake has been designated as a cold-water fishery.

Randolph Jennings Lake is used to average the quality of the North Branch. The water of the North Branch Potomac River is of very poor quality. Major sources of pollution in the basin are acidic coal mine drainage from abandoned deep mines and strip mines. The main characteristics of mine drainage are sulfuric acid, heavy metals, high dissolved solids, and precipitates. In addition, the natural background levels of alkalinity are extremely low in the North Branch basin due to the type of geologic strata. This results in the inability of the streams to buffer even small acidic discharges.

With its physical presence, the reservoir prevents acid slugs from flowing downstream during rainstorms in low flow conditions. Further and much greater control of the quality of the reservoir releases is exercised through a selective withdrawal system, a system which allows the release of water from different elevations within the lake; in a density stratified lake the quality at different levels is markedly different. A schematic of a selective withdrawal tower is shown in Figure 1. The water quality ports, represented by the smaller circles, are located in the upper one hundred feet of the lake. The flood gate, represented by the large circle, is located at the base of the tower and may release a flow of twice the order of magnitude as a water quality port.

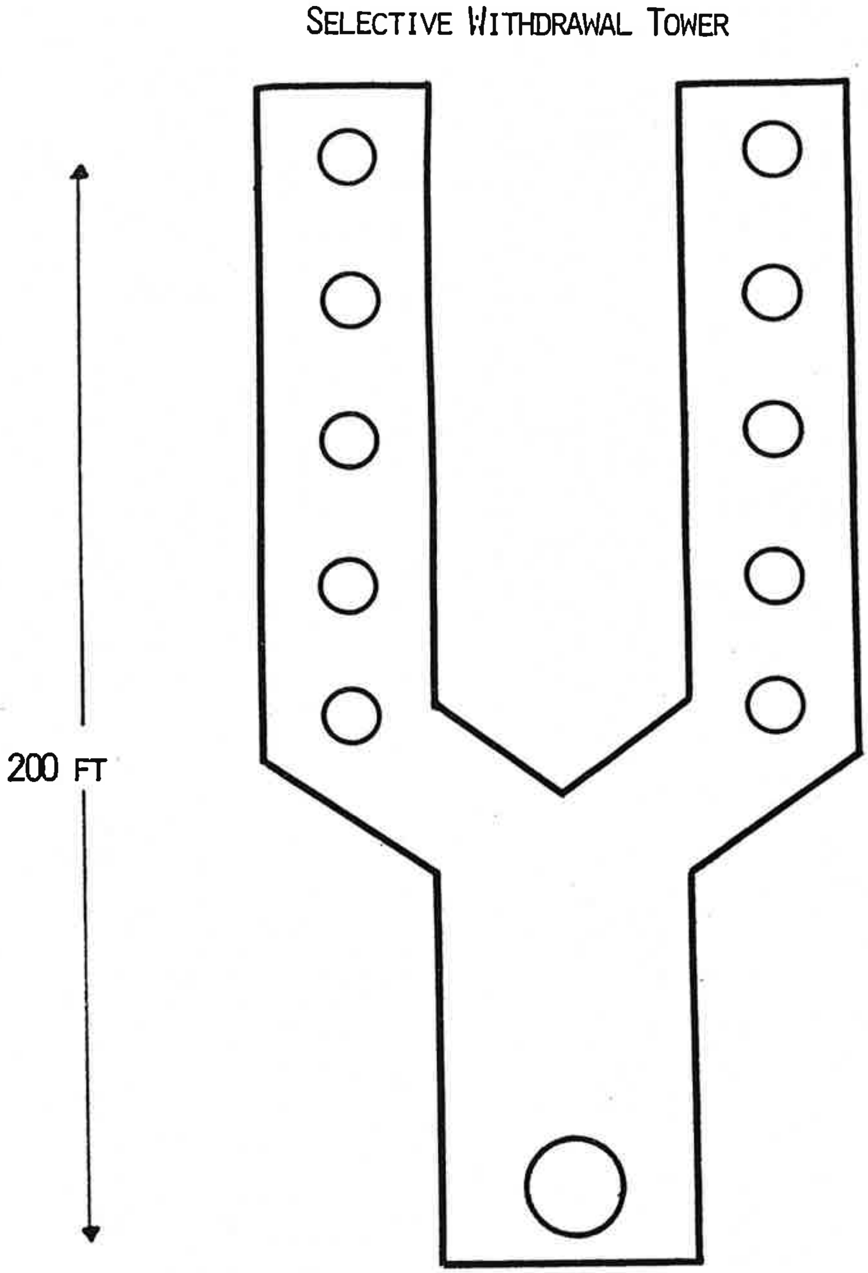

Figure 1. Schematic of Selective Withdrawal System

Reclamation efforts upstream of the lake have actually resulted in slightly better water quality than expected. Consequently, the reservoir releases have been regulated to a pH of 6.0. This coupled with a desirable temperature for trout of 18°C constitute the two primary downstream water quality targets.

2.0 The Water Quality Model

2.1 The Current Model

The water quality simulation model, WESTEX, was developed by the COE at the Waterways Experimental Station. WESTEX is a one dimensional finite-difference model. This implies that the lake is discretized into vertical layers and the conservation of heat and mass equation is used to describe each layer. Therefore, given the current state of the reservoir, the volume and temperature of the inflow, and the magnitude of the heat transfer at the air-water interface, a temperature profile at the withdrawal tower is provided. The model may also be used to predict concentrations of conservative constituents, those which conform to mass conservation laws, given the appropriate inflow concentrations and assuming that mixing is density driven. Such constituents are alkalinity, acidity, total dissolved solids, and conductivity.

A basic assumption of a one dimensional lake model is that vertical variations in temperature and the other constituents dominate horizontal variations. This has been shown to be true with temperature and pH both along the longitudinal axis of Randolph Jennings Lake, see Figure 3 and Figure 4, and in the literature (12).

2.2 Modeling of Additional Constituents

The model described above was previously employed to determine the ability of the system to meet downstream temperature and acidity targets during the period of lake stratification (May through October) under different volume reallocation scenarios. For that analysis it was not the particular measure of acid concentration that was important, but whether increased violations resulted when the reservoir pool was raised the incremental amounts.

For the water quality simulation model to be employed in an operational framework, the measure of acid concentration must be pH, $-\log[H^+]$. Estimation of this parameter may be accomplished by incorporating the chemical equilibrium equations which represent the carbonate system. These equations may be expressed as follows (2,13):

$$A_4[H^+] + A_3[H^+] + A_2[H^+] + A_1[H^+] + A_0 = 0$$

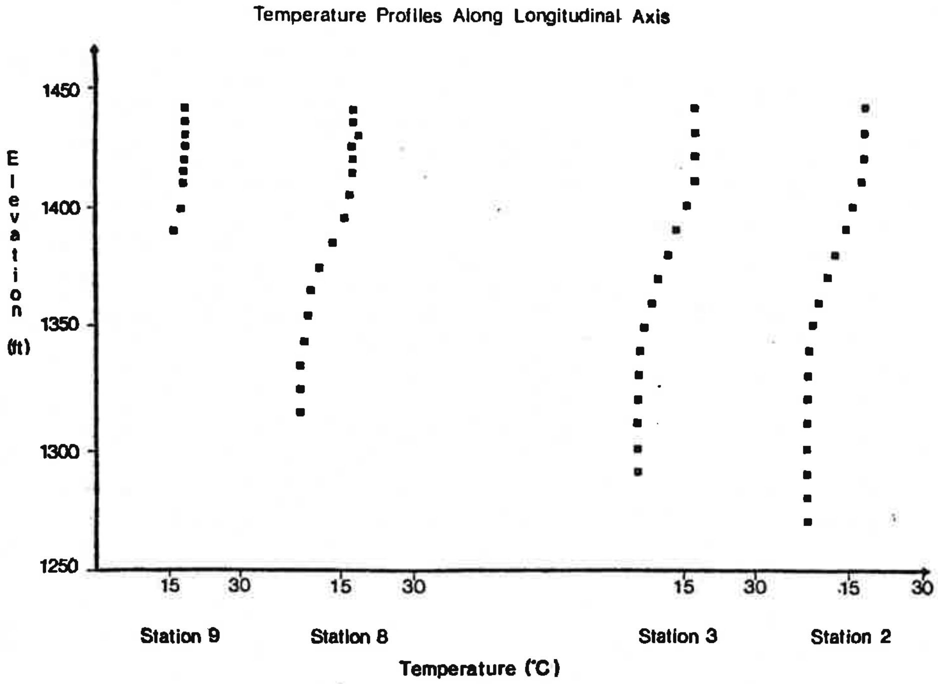

Figure 2

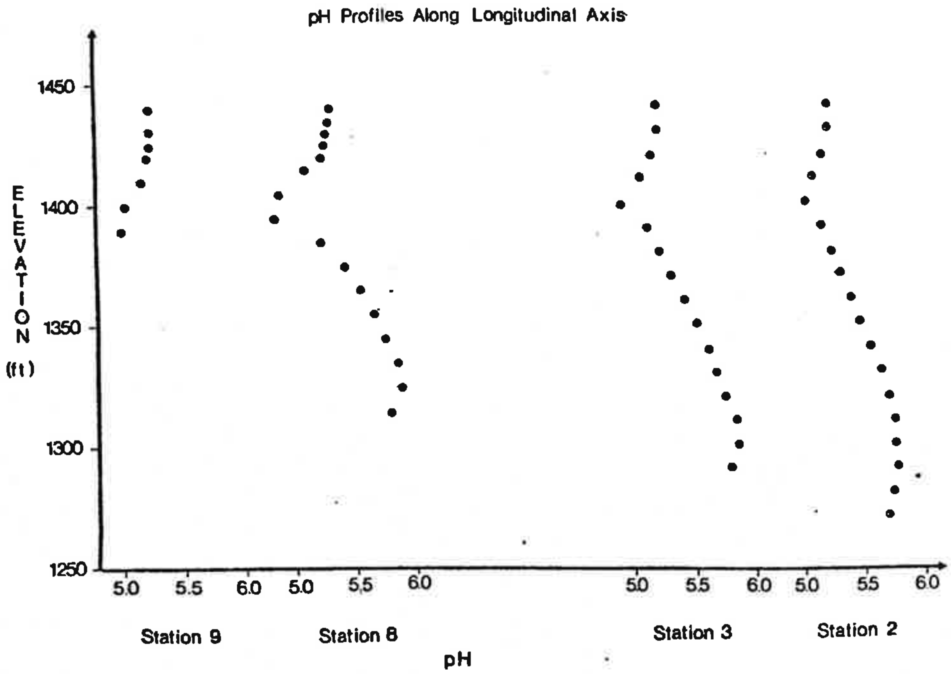

Figure 3

where $A_4 = 1$

$A_3 = [Alk] + K_1$

$A_2 = K_1K_2 - K_1[Acy] - K_w$

$A_1 = -K_1(K_2[Alk] + 2K_2[Acy] + K_w)$

$A_0 = -K_1K_2K_w$

and where K_1 and K_2 are the first and second ionization constants of carbonic acid $[H_2CO_3]$, K_w is the ion product of water and [Alk] and [Acy] are the alkalinity and acidity concentrations.

To solve the fourth order polynomial, the simulation model must account for both CO_2-acidity and alkalinity concentrations. Then the polynomial may be solved using Newton's method of successive approximations of the zero of a function (4).

There are two additional concerns for the modeling of pH in waters affected by acid mine drainage. First, the magnitude of the ionic strength of the water may alter the ionization constants of carbonic acid. If necessary, the effect can be assessed and accounted for using the following equations (9):

$$pK_1' = pK_1 - \frac{0.5\sqrt{I}}{(1 + 1.4\sqrt{I})}$$

$$pK_2' = pK_2 - \frac{2\sqrt{I}}{(1 + 1.4\sqrt{I})}$$

where I is the ionic strength in mg/l and may be estimated as a function of total dissolved solids, S (mg/l),

$$I = S \text{ X } 2.5\text{x}10^{-5}$$

When the concentration of total dissolved solids is not available, it may be estimated as a function of conductivity, C (mhos/cm) (5),

$$S = (4.5\text{x}10^5)(1.02)^{T-25} \text{ X } C$$

These approximations should be sufficient since it is differences of orders of magnitude in ionic strength which have an appreciable affect on the ionization constants.

The second concern is the transfer of CO_2 gas to the atmosphere. This phenomena occurs when the waters are supersaturated with respect to CO_2, a common characteristic for water receiving acid mine drainage (13). Not allowing for this transfer can cause underestimation of pH and, therefore, cause the water quality to appear worse than it is. The transfer occurs across the air-water interface so it need only be accounted for in the top layer of the simulation model. The equations are as follow (1,2):

$$\frac{\Delta[CO_2]}{\Delta t} = K_a \left([CO_2]_s - [CO_2] \right)$$

where K_a is the rearation coefficient, and

$[CO_2]_s$ is the atmospheric saturation concentration of the gas.

In summary, the descriptive equations required to provide estimates of pH at the withdrawal tower may be incorporated into the existing model. Effects of ionic strength and the release of CO^2 to the atmosphere can be incorporated. The estimation of pH requires the modeling of alkalinity and either total dissolved solids or conductivity in addition to CO_2-acidity which is already a component of the simulation model.

2.3 Real-time Release Rules

The existing operating rules were formulated to minimize the violations of downstream water quality targets. That is, the rules determined which release ports should be opened to what extent to provide a reservoir discharge of desirable water quality. The problem is mathematically formulated as a mixed integer linear program and requires special software for solution (a linear programming package with a branch and bound option). This software is not generally supportable on a PC.

Alternatively, solution techniques may be developed which involve enumeration of the possible combinations of open release ports and calculation of the resulting water quality. The degree of enumeration may be reduced using various operational strategies such as releasing as much of the most acidic water (lowest pH) water as possible while maintaining the downstream targets. These strategies would be identified through discussion with COE personnel.

3.0 Data Requirements

3.1 Real-time Flow and Water Quality Data

The following flow and water quality data are required for a short-term operational model:

1. volumetric flow
2. water temperature
3. pH
4. CO_2-acidity
5. alkalinity
6. total dissolved solids or conductivity

This data is required for the inflow to the lake to develop likely forecasts of the water quality of the inflow, and all but the flow data are required at the release tower to provide a starting point for the investigation.

Each of these parameters are routinely measured although with different frequencies at different locations. Automated monitors which produce hourly flow and water quality data records are located at Kitzmiller, Md, Barnum, WV, and Pinto, Md. COE field personnel collect weekly water quality data from the lake and general project vicinity. This is sufficient for forecasting water quality and characterizing the state of the lake.

3.2 Meteorological Data

The simulation model requires meteorological data to estimate the heat exchange at the air-water interface. The equations describing this process are of the following form (3):

$$H_n = -K (T - T_e)$$

where H_n is the net rate of heat exchange across the water surface,

K is the thermal exchange coefficient, a function of wind speed,

T is the air temperature, and

T_e is the equilibrium temperature, a function of air temperature and dew point temperature.

Currently, the location of the closest available data is the NOAA weather station at Elkins, West Virginia. Data from this site has been used in the past.

This data should suffice in part because meteorological data is of less importance in a short-term modeling application. When looking several days or weeks into the future, the heat content and distribution within the lake will not change appreciably. The changes that do occur may be incorporated by updating the model to agree with field data.

The available historical data can be used to generate likely average or extreme future meteorological sequences. It would be useful to begin the collection of meteorological data specific to Randolph Jennings Lake.

4.0 Conclusions

Modification of the existing water quality simulation model for real-time use is a feasible project. The modification would require two major modeling tasks. First is the inclusion of the equilibrium chemistry for the carbonate system to allow the prediction of pH at the release tower. The equations and solution techniques for this have been described in the literature. The second task is the development of operating rules within the short-term framework. This requires some discussion with COE personnel to characterize the more promising selections of the open port combinations. Solution techniques for the operating rules may be developed which are compatible with PC capabilities, and the flow and water quality data required on a real-time basis are available. The resulting models would constitute a useful operational tool which should aid in the effective management of the water quality portion of Jennings Randolph Lake.

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