Selective Withdrawal as a Water Quality Management Tool for Southwestern Impoundments

E. GUS FRUH AND HERMAN M. CLAY, JR.[1]

Environmental Health Engineering Program, University of Texas
Austin, Texas 78712

The objective of this study was to develop a preliminary simulation model of impoundment water quality that included an accurate description of stratified flow and selective withdrawal. Two stratified flow solutions were examined to test their applicability to describe reservoir withdrawal hydraulics under field conditions. Although both solutions appeared capable of accurate prediction of the outflow velocity profile, the Bohan-Grace solution, which required less input data, was selected; this solution can be applied to impoundments for which field data are minimal. The simulation model, including the Bohan-Grace solution for reservoir withdrawal hydraulics, was assessed for a 2-year period for which sufficient field data were available. The error in penstock temperature prediction ranged from 0° to 2.78°C (0° to 5°F).

REGIONAL NEED AND PURPOSE OF THE STUDY

The *Texas Water Development Board* [1968] has considered a number of alternatives for transporting water from east Texas and from other states to south Texas as well as to west Texas and the High Plains. A number of waters of different quality will be mixed, stored in existing and 53 proposed reservoirs, and transported by conveyance systems to points approximately 1620 km (1000 miles) away. The effect of impoundment on the water quality of Texas streams is not known. Thus a model that simulates long-term water quality changes is vitally needed.

A priori review of the impoundment water quality problem indicated that several separable but dependent components had to be included in a complete model: (1) a description of the inflows in terms of temperature and chemical concentrations, (2) inflow thermal and chemical routing within the impoundment, (3) meteorological and hydrologic sources and sinks of heat, (4) turbulent diffusion of heat and chemical substances within the impoundment, (5) chemical-biological changes of nonconservative chemicals within the impoundment, (6) a description of reservoir withdrawal hydraulics under stratified and nonstratified flow conditions, and (7) an accounting for continuous changes in the water, heat, and chemical budgets of an impoundment.

The first four components in various forms have been applied with some success to other geographic areas, and in the preliminary phase of modeling it appears only necessary to adapt them for application to the relatively shallow southwestern reservoirs. The chemical-biological changes represent complex interactions that still lack quantitative description; hence preliminary modeling endeavors are applicable only to throughput of water temperature and conservative chemical substances. Accurate impoundment data are vitally needed to fill this void.

The component describing the outflow hydraulics under stratified flow conditions has been developed on a theoretical basis and verified in a laboratory flume by *Koh* [1964]. The Koh stratified flow solution has been found to be adequate as a description of the velocity profile based on reliable field velocity measurements in two deep reservoirs, Lake Roosevelt [*Battelle Memorial Institute,* 1969] and Lake Fontana [*Brooks and Koh,* 1968]. However, field verification of the Koh solution has not been attempted for deep southwestern reservoirs nor for any shallow reservoirs that are more representative of this area of the country. In addition, the Koh solution assumes that there is a linear density variation with depth and that K_z, the turbulent exchange parameter, can be estimated accurately for a priori use in the solution. Both assump-

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[1] Now at O'Malley & Clay, Consulting Engineers, Houston, Texas.

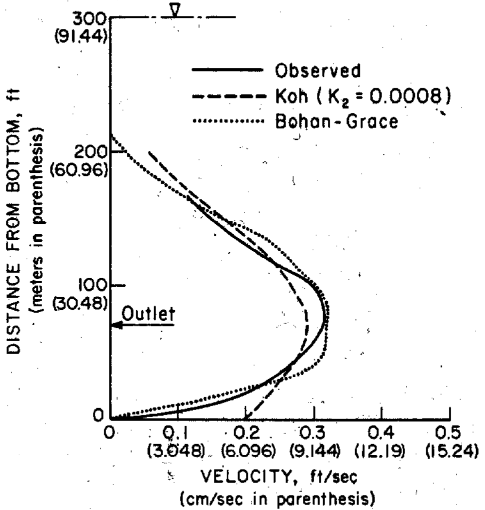

Fig. 1. Velocity comparisons, Lake Roosevelt, August 26, 1967. The flow is 1.96 km^3/sec (69,500 cfs), and the distance from the dam is 1.6 km (5280 feet).

tions for southwestern impoundments have been questioned by *McGill* [1970].

Bohan and Grace [1969] developed a hydraulic flow solution employing dimensional analysis in the evaluation of laboratory scale data. The Bohan-Grace solution avoids the assumptions of the Koh solution but has not been verified by any field studies.

In this study a preliminary water quality impoundment simulation model is assembled from the components outlined above. Particular emphasis is placed on determining by field measurements which stratified flow solution is the best description of the reservoir withdrawal hydraulics occurring in southwestern impoundments.

EVALUATION OF STRATIFIED FLOW SOLUTIONS

The output from the Koh and Bohan-Grace stratified flow solutions is the velocity profile of the outflow as it moves through the impoundment toward the penstock or other release structure. Thus the first stage in the evaluation process was to compare the velocity distributions predicted by each method with observed velocity measurements. Unfortunately, the only reliable field velocity measurements available were from deep reservoirs in other geographic areas. One result from the testing program is illustrated in Figure 1. A more detailed hydraulic analysis is presented by *Clay et al.* [1970].

Because published field velocity measurements are not available for southwestern impoundments and because accurate data are very difficult to obtain [*Wilson and Masch,* 1967], it has been proposed that velocity profile predictions can be verified indirectly by monitoring outflow temperature or chemical concentrations [*Brooks and Koh,* 1968]. Thus the vertical profile of some water quality characteristic that varied with depth could be measured in the impoundment, and comparison of the predicted and observed outflow concentration of that particular characteristic would indicate implicitly the fraction that each vertical layer in the impoundment contributed to the total flow.

The applicability of the two predictive techniques to southwestern impoundments first was tested by a comparison of predicted and observed penstock temperatures for Lake Travis in south central Texas. Figure 2 is a graphic comparison of the results. Although both hydrodynamic solutions produced some scatter, the Bohan-Grace method appears to be superior during the period of low outflow temperature. No clear superiority exists for the period of warmer outflows.

The Bohan-Grace solution was chosen for further development and inclusion in the simulation model since its predictive capability appeared to be at least equal to the Koh solution. In addition, the Bohan-Grace input data re-

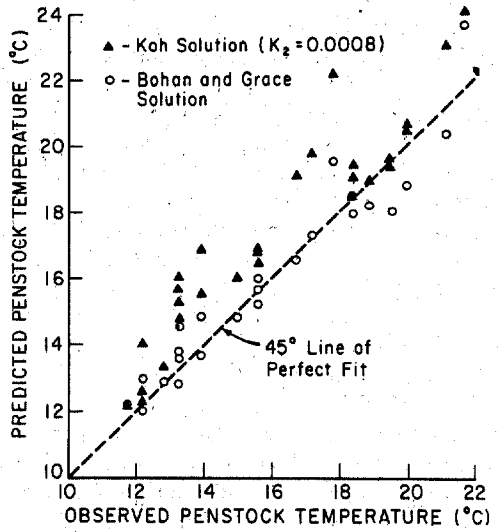

Fig. 2. Observed and predicted penstock temperatures, Lake Travis.

TABLE 1. Comparison of Predicted and Observed Outflow Chemical Concentrations for Lake Travis, August 9, 1968

	Gradient Bottom to top	Observed Outflow Concentrations	Predicted Bohan-Grace Outflow Concentrations
Hardness, mg/l as $CaCO_3$	198 to 154	177	181
Alkalinity, mg/l as $CaCO_3$	159 to 127	146	150
Conductivity, μmhos/cm	472 to 420	463	465
Silica, mg/l as SiO_2	9.2 to 6.3	7.8	8.1
Ammonia, mg/l as N	0.42 to 0.00	0.41	0.37

quirements are less stringent, and therefore this solution can be applied to impoundments for which field data are minimal.

Because interest in selective withdrawal in the southwest is based on the release concentrations of many water quality characteristics other than temperature, the Bohan-Grace solution was used to predict the outflow chemical concentrations of several Texas impoundments. Typical results for deep reservoirs are presented in Table 1, and those for reservoirs as shallow as 16.76 meters (55 feet) are presented in Table 2. The mean difference between the predicted and observed values, expressed as a percentage of the observed gradient, for two separate simultaneous releases from Lake Livingston was approximately 9%.

IMPOUNDMENT WATER QUALITY MODEL

Temperature data from Lake Travis in south central Texas were used to assess the results of the preliminary simulation model. The inflow and thermal structure components were calculated from actual field data. In this manner the results reflected the accuracy of the hydraulic flow solution selected to represent the reservoir withdrawal component.

TABLE 2. Comparison of Predicted and Observed Outflow Chemical Concentrations for Lake Livingston

	Impoundment Gradient from Bottom to Top	Observed Outflow Concentration	Predicted Bohan-Grace Outflow Concentration
	*Spillway Outlet with Flow of 50.5 m^3/sec (1785 cfs)**		
Temperature, °C	18.5 to 24.0	23.0	23.7
$NO_3 + NO_2$, mg N/l	0.72 to 0.52	0.53	0.52
Fe, mg/l	0.17 to 0.08	0.09	0.09
	Spillway Outlet with Flow of 46.4 m^3/sec (1640 cfs)†		
Temperature, °C	22.8 to 31.5	28.7	29.1
NH_3, mg N/l	0.31 to 0.00	0.05	0.03
Total P, mg/l	1.19 to 0.13	0.21	0.16
Fe, mg/l	0.48 to 0.03	0.04	0.03
Si, mg/l	11.75 to 1.75	2.00	2.00
	Tower Outlet with Flow of 6.7 m^3/sec (238 cfs)§		
Temperature, °C	22.8 to 31.5	29.0	30.5
NH_3, mg N/l	0.31 to 0.00	0.00	0.01
Total P, mg/l	1.19 to 0.13	0.19	0.14
Fe, mg/l	0.48 to 0.03	0.04	0.03
Si, mg/l	11.75 to 1.75	1.70	1.80

*The water depth at this outlet is 16.76 meters (55 feet), and the distance from the outlet to the bottom is 12.50 meters (41 feet). These data were recorded on April 25, 1970.

†The water depth at this outlet is 19.81 meters (65 feet), and the distance from the outlet to the bottom is 12.50 meters (41 feet). These data were recorded on July 2, 1970.

§The distance from the outlet to the bottom is 17.37 meters (57 feet).

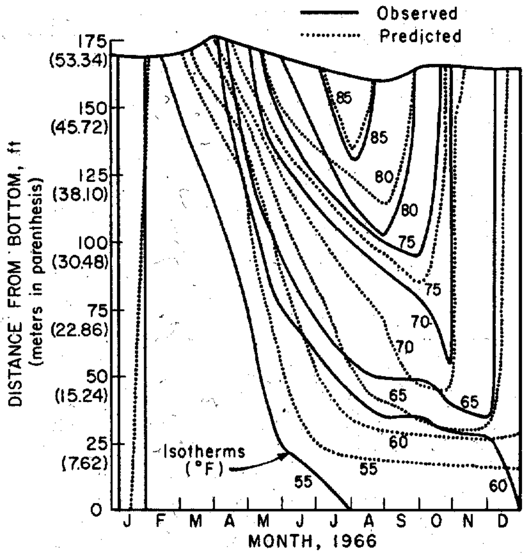

Fig. 3. Temperature structure, Lake Travis, 1966.

Inflow components. Discharges into Lake Travis from upstream Lake Marble Falls and from the unregulated Pedernales River were monitored. Local runoff was computed from a water balance computation.

Although the data [*Applied Research Laboratory*, 1966, 1967; Lower Colorado River Authority, unpublished data, 1970] were the most comprehensive temperature measurements available for a Texas reservoir, a complete record of the thermal properties of the impoundment and its inflows and outflows was not available. The inflow temperature records were particularly lacking, and only approximate monthly estimates of the two principal flow inputs were possible. As an additional approximation for the case reported herein, the mean temperature of the combined inflows was calculated, and the total incoming volume was considered mathematically as a single input.

The inflow was assumed to flow isothermally along the reservoir bottom until it reached a level of density (based only on temperature) equal to that of the inflow. The incoming water subsequently was spread homogeneously across the impoundment at the equal density level, and thus the level of all layers originally above the inflow level was raised. New temperatures then were calculated for all new depths.

Thermal structure components. Division of thermal prediction into two components, the external thermal budget and the internal heat exchange, allows maximum use of the thermal budget, which frequently can be measured or computed accurately. *Water Resources Engineers, Inc.* [1966, 1967] found that it is preferable to exclude advection from the net heat exchange rate because of the frequently large annual hydrologic variations and because all major sources and sinks except advection necessarily are transferred across the water surface. The heat carried by the inflow and outflow then must be accounted for by a separate computational procedure. However, because the magnitudes of some important sources and sinks of the thermal budget depend on the impoundment surface temperature and because the inflow and outflow components are affected by the vertical temperature component, the thermal budget cannot be computed accurately from meteorological and hydrologic data independently of the internal thermal energy transfer.

For computational purposes it is necessary to calculate the heat exchange to the impoundment during a short time increment on the basis of knowledge of the existing internal temperature and the external sources and sinks. Then the new temperature structure within the impoundment can be computed from the mathematical description of the internal heat exchange mechanisms. The computational cycle is repeated for successive time increments.

To simulate the thermal structure components as accurately as possible, the total net heat ex-

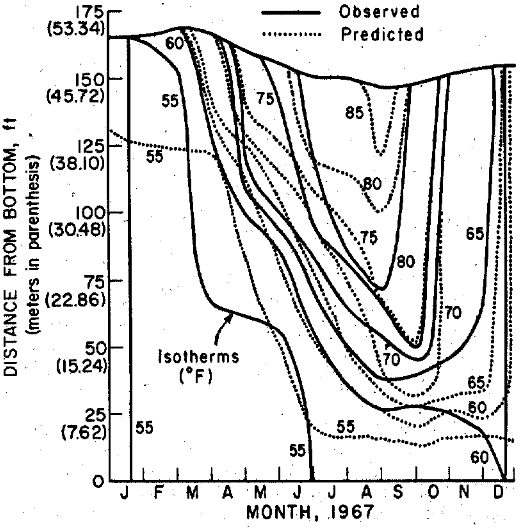

Fig. 4. Temperature structure, Lake Travis, 1967.

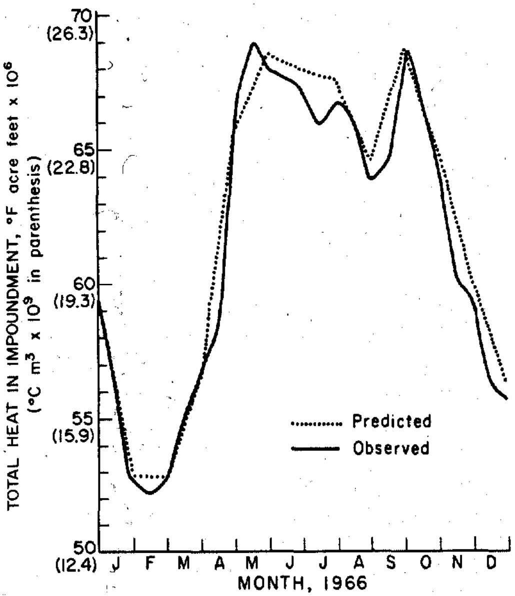

Fig. 5. Total heat content, Lake Travis, 1966.

change rate was computed by integrating graphically the changes in the observed Lake Travis temperature profiles. The advective and evaporative heat contributions were computed on the basis of the volume and temperature of the water added or removed. The heat changes from advection and evaporation then were subtracted from the total heat exchange, and the contributions of the meteorological sources and sinks were left.

Review of the existing temperature prediction techniques [*Water Resources Engineers, Inc.*, 1966] indicated that numerical differentiation of Fick's first law would provide a mathematically simple description of the downward flux of heat within the impoundment. Assumption of horizontal homogeneity within the impoundment reduced the heat exchange to the vertical direction. It also was necessary to include vertical convective mixing, particularly during the fall when stratification still existed but when the flow of energy was away from the impoundment. Details are described by *Clay et al.* [1970].

Reservoir outflow component. Changes in the water and heat content of the impoundment caused by releases were accounted for in a manner similar to that used for the inflow. An outflow velocity profile was calculated by the Bohan-Grace method, and then the resulting volume withdrawn from each layer was computed. The outflow from each layer was assumed to leave a void that was subsequently filled by water from higher layers. The resulting contents of each layer were subsequently mixed, and new temperatures and a new impoundment depth were computed.

Evaluation. Three comparative criteria were used in evaluating the performance of the simulation model. Comparisons were made of the observed and predicted temperature profiles, the impoundment heat content, and the penstock temperatures for the 1966–1967 period.

Figures 3 and 4 illustrate the 1966 and 1967 variation in predicted and observed temperature profiles for Lake Travis. The errors that exist are believed to be caused by the limiting assumptions inherent in the simulation model: one dimensionality and the Fickian description of the internal heat exchange process.

The external sources and sinks, the internal heat exchange, and the volumes of water advected are significantly interrelated. For example, failure to predict accurately the temperature profile will cause an incorrect amount of heat to be advected away by outflows and by evaporation. In that case the predicted impoundment heat content with time would diverge increasingly from the observed values. Similarly, any other type of malfunction in the predictive process, either thermal or volumetric, will cause a noticeable divergence. Therefore, the total impoundment heat content is the best single indicator of the accuracy of the simulation. The

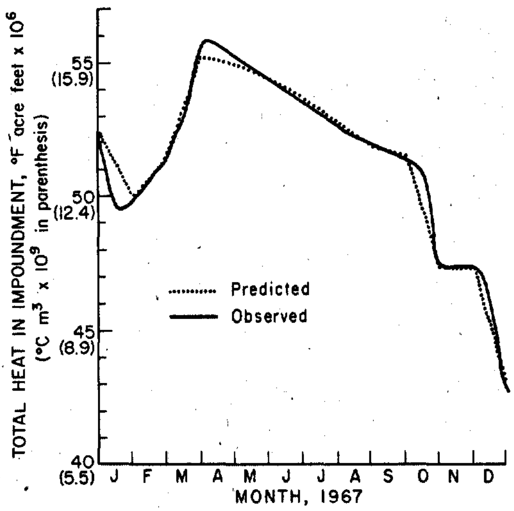

Fig. 6. Total heat content, Lake Travis, 1967.

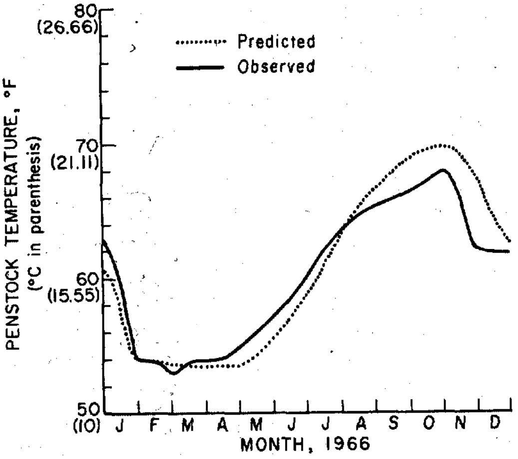

Fig. 7. Penstock temperatures, Lake Travis, 1966.

differences in the predicted and observed values in Figures 5 and 6 were largely caused by the use of average monthly values as input to the model, whereas the observed values reflect measurements at considerably smaller intervals. Thus the predictions were not expected to exactly follow the observed short-term variations and, on a monthly basis, were considered to be satisfactory.

Figures 7 and 8 illustrate the predicted and observed penstock temperatures for 1966 and 1967, respectively. The outflow predictions were within 2.78°C (5°F) of the observed values. This correspondence is particularly significant since parts of the input information were relatively crude estimates. Such data are frequently the best information available; therefore the use of rough approximations was considered a stringent test of the capability of the model's selective withdrawal component to function under realistic conditions.

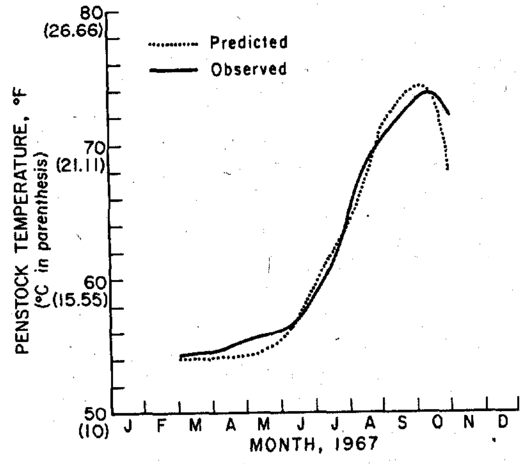

Fig. 8. Penstock temperatures, Lake Travis, 1967.

CONCLUSIONS

Extensive testing indicated that the Bohan-Grace solution was at least as accurate as the Koh solution in describing reservoir withdrawal hydraulics in a stratified impoundment. Since its input data requirements were less stringent, the Bohan-Grace solution was included in the preliminary impoundment water quality simulation model. The simulation model was a realistic representation of the behavior of seasonally stratified impoundments. The error in predicted penstock temperatures for Lake Travis over a 2-year simulation ranged from 0° to 2.78°C (0° to 5°F); this error range indicated satisfactory compatibility of the Bohan-Grace solution with other components of the simulation model.

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