Hydraulic Transients in Man-Made Lakes

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The movement of water in man-made lakes is directly coupled to the operation of the structures that create these impoundments. In the multipurpose man-made lakes of the Tennessee Valley Authority (TVA) system, hydropower generation, particularly power-peaking operations, is the main cause of the spatial and temporal variation in flow along the principal axis of these reservoirs. Because these waters are the vehicle for the transport of heat from generating plants, for dissolved oxygen, and for waste from industrial and municipal sources, a precise knowledge of water behavior is imperative if one is to meet the increasing demands on water use and maintain and improve water quality. This paper describes the application of a computerized mathematical model to some of these complex flow problems associated with the man-made lakes of the TVA.

GENERATION OF TRANSIENTS IN MAN-MADE LAKES

Transient water movements unique to man-made lakes are caused by the operation of hydroelectric plants, sluices, spillways, locks, and so on. This behavior results mainly from the propagation of shallow-water translatory waves through these bodies of water. There are four basic types of these translatory waves. These are depicted schematically in Figure 1 for an idealized reservoir bounded by control structures at its extremities. Cases *a* and *b* show the translatory waves created, respectively, by a sudden increase and decrease in flow due to the operation of the upstream control structure. Cases *c* and *d* depict similar waves caused, respectively, by a sudden increase and decrease in flow due to the operation of the downstream structure.

The speed with which these wave fronts advance through the reservoir is dependent on the depth of the water body, whereas the magnitude of the motion induced at any point by the passage of the wave depends on the rate of the flow change at the boundary and the magnitude of the change. The effect of a single translatory wave generated at either boundary is quite long lasting. The wave is transmitted and reflected through the reservoir many times before boundary shear and viscous resistance finally overcome the induced motion.

In man-made lakes where operational changes at the boundaries occur frequently (as is the case in power-peaking operations) the actual motion of the water at any location and time is a superposition of many transmitted, reflected, and interfering waves of the four basic types shown in Figure 1. Consequently, the transient water behavior is quite complex. A computerized solution to a mathematical model that uses the hydraulic equations of continuity and momentum governing this motion offers the only feasible and practical solution for analyzing this complex water behavior.

For the past several years, TVA has been using a mathematical model for the analysis of these complex flow problems. This model and some of the excellent results obtained have been described in previous papers [*Buehler et al.*, 1968, 1969; *Garrison et al.*, 1969].

KENTUCKY LAKE TRANSIENTS

Maintaining or improving the quality of the waters in the TVA system is a major concern of the authority and the pollution control boards of the states in which TVA is located. To achieve this goal, both TVA and the Tennessee Stream Pollution Control Board now require that certain waste treatment standards be met before liquid wastes are released into the waters of the system within Tennessee. In addition, it may be required that waste discharges to the system be released in a certain proportion to the instantaneous flow passing the point of release in order to insure that the waste release does not in any way impair the water quality of the receiving reservoir. This re-

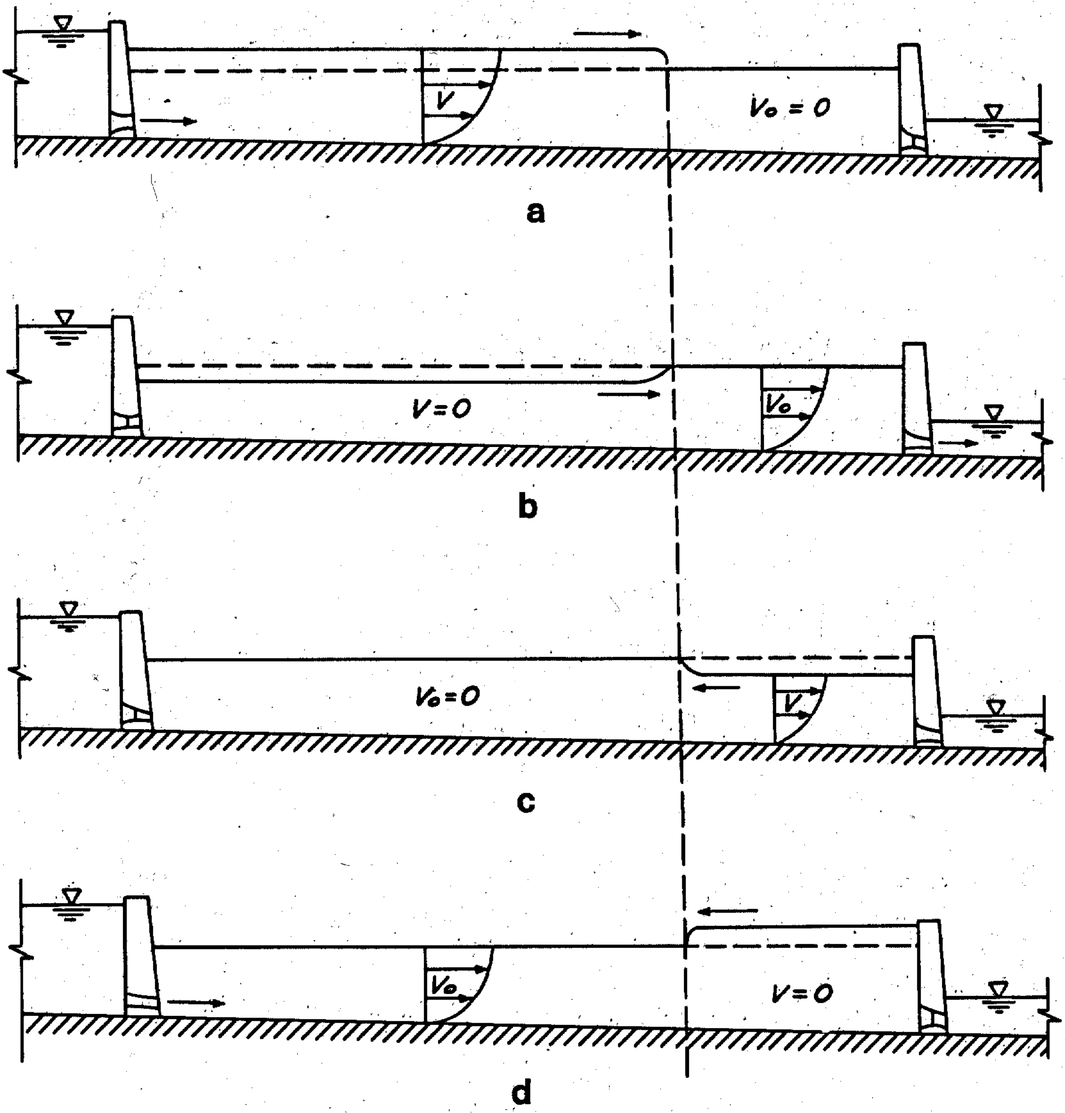
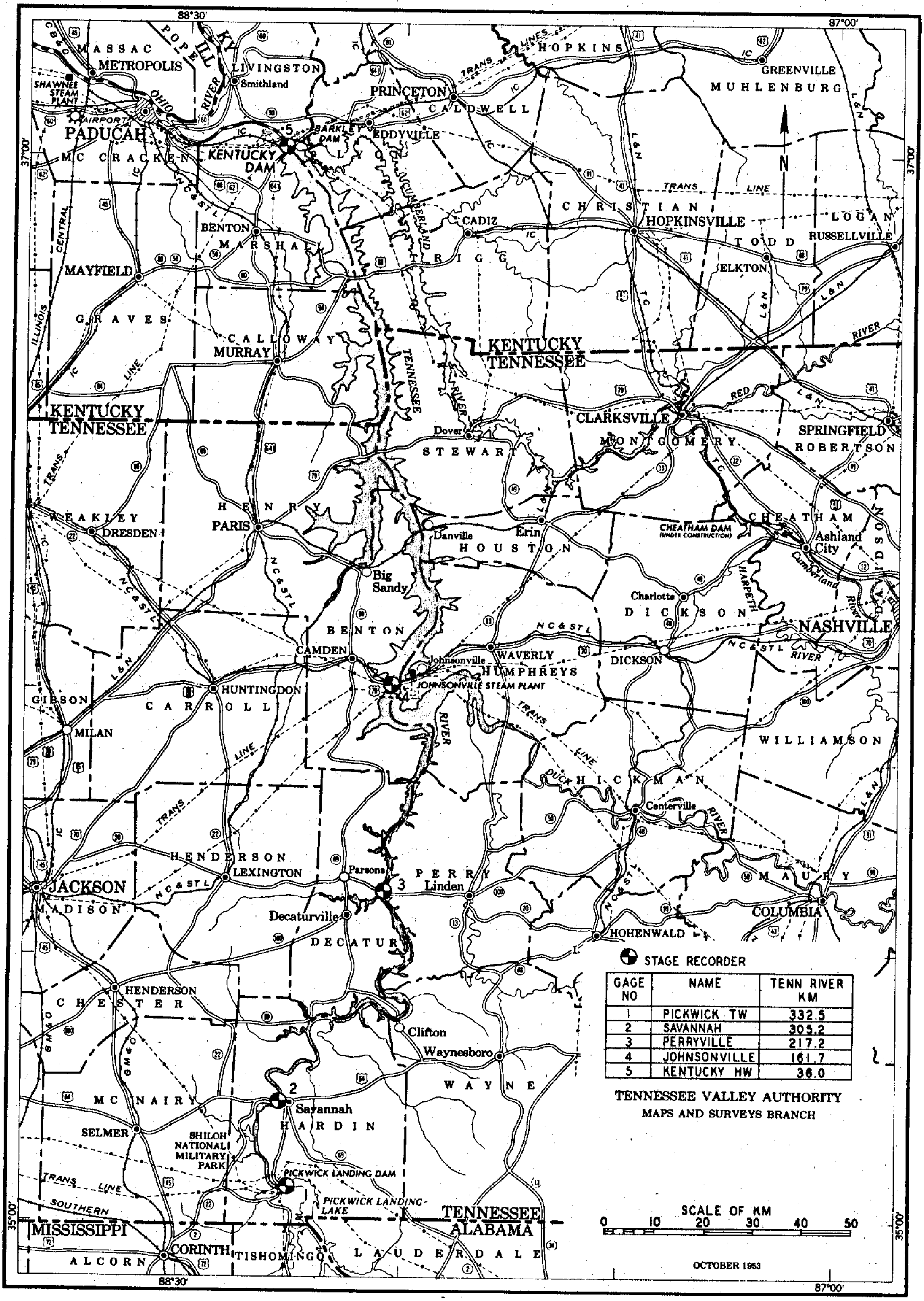


Fig. 1. Four basic waves in man-made lakes.

quirement was the case for a recently completed industrial plant located on Kentucky Lake near New Johnsonville, Tennessee.

Kentucky Lake, which is almost 300 km long, is bounded upstream and downstream by Pickwick and Kentucky dams, as shown in Figure 2. Turbine operations at these two plants are intermittent, and as a result the flow at any given time and location within the reservoir is quite variable. In addition, Kentucky and Barkley lakes are connected by an uncontrolled navigation canal just upstream from Kentucky and Barkley dams, as shown in Figure 3. Variations in water surface at the two ends of this canal determine the flow that takes place to or from Kentucky Lake. This flow is quite variable and is a contributor to the overall transient flow behavior of this reservoir.

Quantitative daily flow forecasting to achieve the multipurpose objectives of the reservoirs of the system has always been practiced by TVA. Among the data available for these forecasts are the anticipated hourly turbine releases required to meet the generating demands for power. A



GAGE NO	NAME	TENN RIVER KM
1	PICKWICK TW	332.5
2	SAVANNAH	305.2
3	PERRYVILLE	217.2
4	JOHNSONVILLE	161.7
5	KENTUCKY HW	36.0

Fig. 2. Map of the Kentucky Lake vicinity.

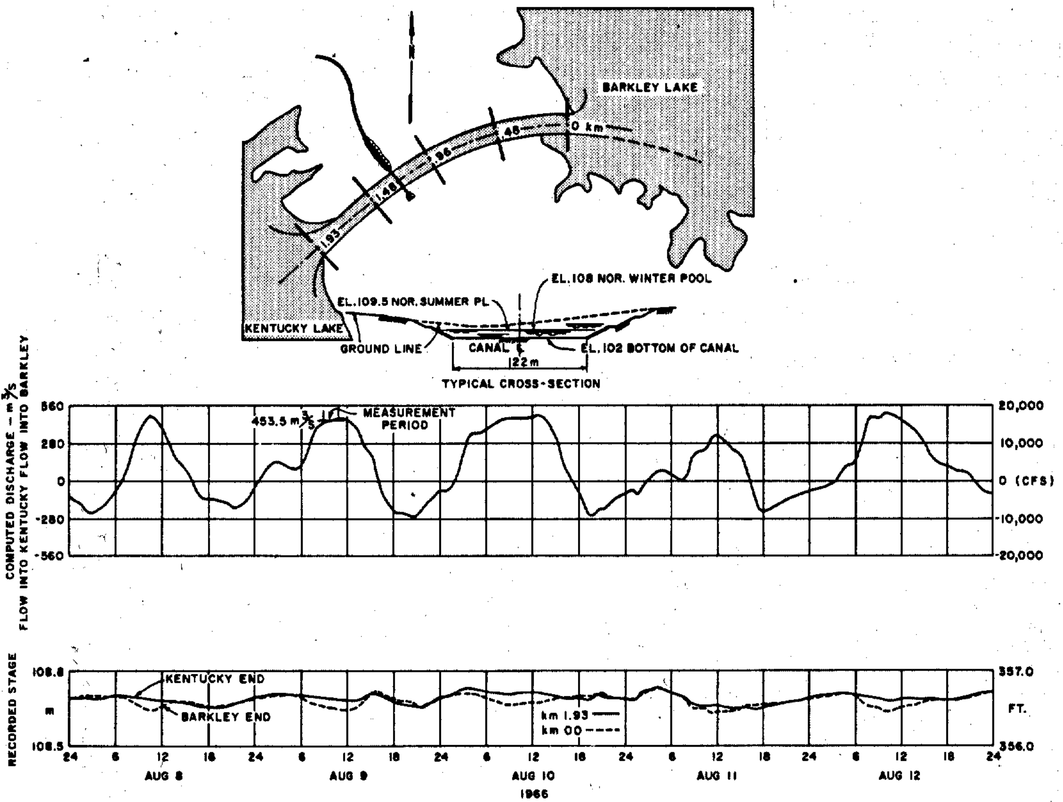


Fig. 3. Flows between Kentucky and Barkley lakes.

mathematical model of Kentucky Lake that uses these anticipated hourly values of releases from the Pickwick and Kentucky turbines and from the anticipated canal and other local inflows offers the most feasible solution for predicting instantaneous flows at Johnsonville and thereby permits waste to be released in proportion to flow. However, to be useful as a predictive tool for daily forecasts, the model had to be streamlined so that it could be used quickly and efficiently on a routine daily basis. To achieve these ends, two models were used. One employs a detailed geometric description of the reservoir at 3.4-km intervals, and the other uses average sections at 14.8-km intervals and is aimed toward minimizing the routine input data requirements and reducing the size of the program. A time step of 3 min was used in both cases.

By reproducing stages at several locations in the reservoir that accompanied known turbine releases from Pickwick and Kentucky turbines and known local inflows, the detailed model was verified (Figure 4*a*). Because flow in the uncontrolled navigation canal is a contributor to the transient behavior of the reservoir and is also an unknown quantity in the predictive model, the effect of canal flow at the Johnsonville site had to be determined. By using hourly observed values of the releases from Pickwick and Kentucky turbines and daily average values of all other local inflows (consisting of one main tributary and rainfall-evaporation over the entire reservoir), mathematical model routings were performed by using a canal flow determined by three different methods:

1. Instantaneous canal flows were determined from a mathematical model of the canal that uses the stages at each end of the canal to determine the canal flow. Results of such a routing are shown in Figure 3.

2. The daily average of the canal flow computed in method 1 was the second method used.

3. The daily average value as computed from the manual routing procedure used for the daily forecasts was the third method used to determine canal flow.

It was found that the differences in stages computed by method 1, 2, or 3 were negligible, all of them being in complete agreement with the observed stages. Differences in computed flows by the three methods amounted to <100 m^3/sec in the middle portion of the reservoir, where Johnsonville is located. This result was of great practical significance, since generally the local inflows are uncontrolled and therefore are not as predictable as the boundary flows. It is also valuable to know that only daily values for all local inflows are required; input data preparation is thus greatly reduced.

Once the reliability of the model with the 3.4-

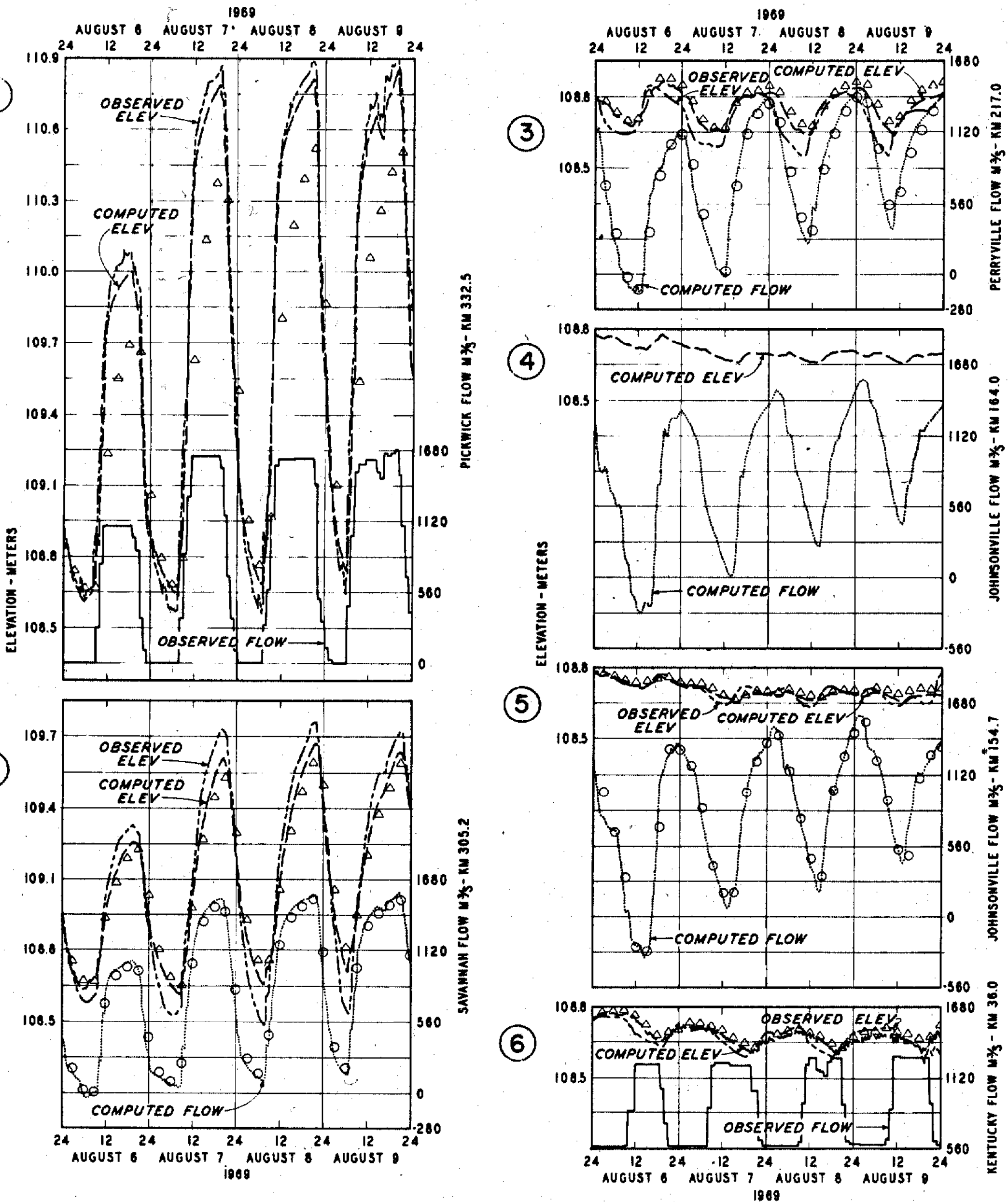


Fig. 4*a*. Comparison of observed and computed flow conditions.

km steps was established, simplification procedures were undertaken. The main disadvantages of the 3.4-km reach model are the large core storage requirement, lengthy input data preparation (initial conditions must be given for 89 cross sections), and long computation time. For these reasons the 14.8-km reach model was developed by using 21 average cross sections. It was found that at the common locations in the two models the computed flow was practically the same and that, except in the extreme upper reach of the reservoir, where there is considerable slope, the stages also agreed. In this part of the reservoir a 14.8-km reach is too long to accurately reproduce the water surface profile. This comparison is presented in Figure 4*a*.

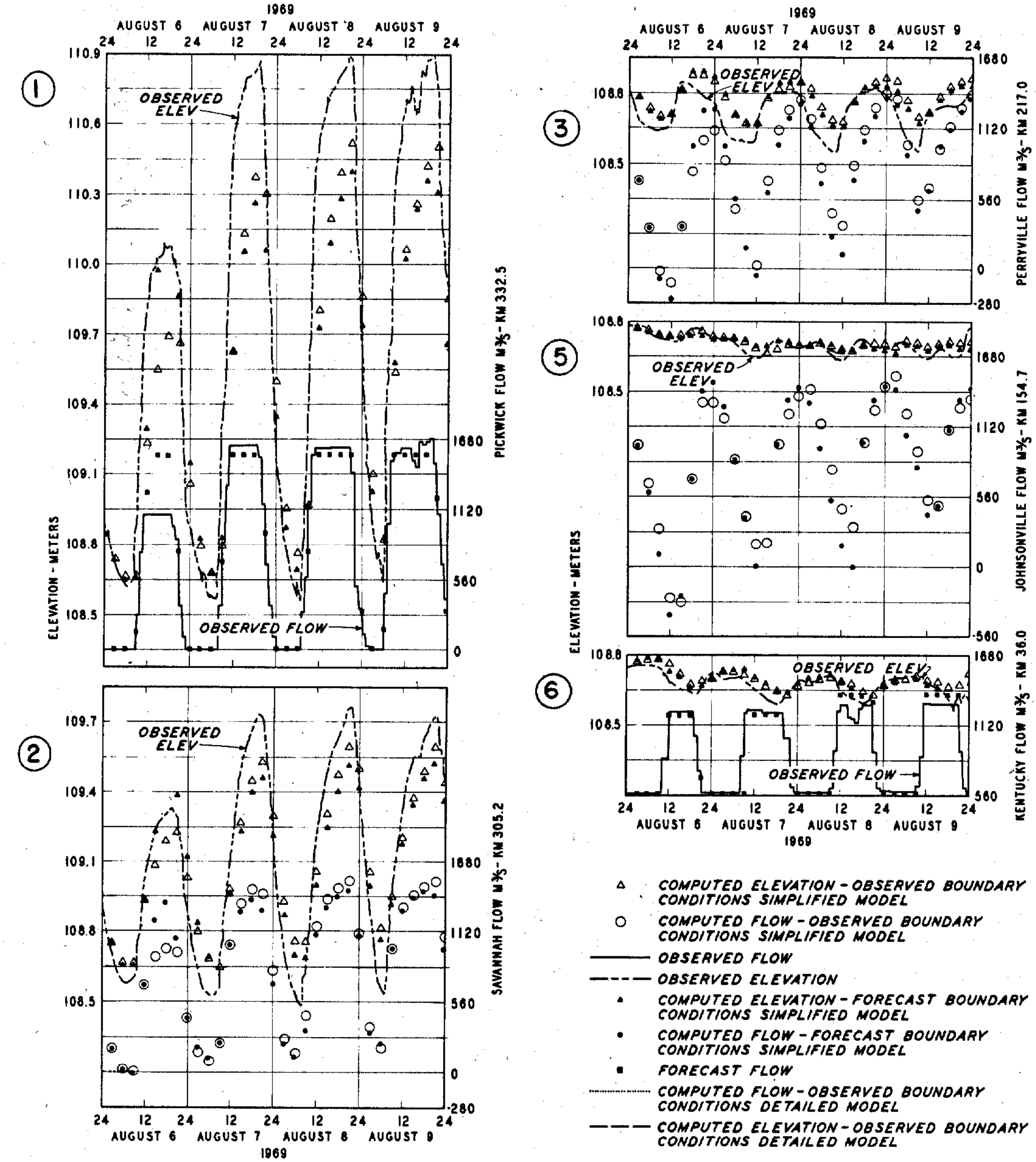


Fig. 4*b*. Comparison of observed and forecast flow conditions.

Because the point of waste release is located in the central portion of the reservoir where the results from the simplified model are satisfactory, it was decided to use this model for these predictions. The anticipated hourly turbine releases are determined by the System Loading Branch of the Office of Power, and the River Control Branch of the Division of Water Control Planning performs the actual routing and furnishes the forecast hourly flows to the industrial plant daily. The program requires initial conditions of stage and discharge at each of the 21 cross sections. These conditions are obtained from the previous day's forecast and are checked against the observed stages at the five gages located in the reservoir (see Figure 2) and the hourly anticipated turbine flows. All this computation requires only 15 punched cards. Less than 1 min of computer time on an IBM 360/50 system yields predicted flows and stages at 1-hour intervals for a 42-hour forecast period at any of the 21 cross sections along the reservoir. For the simplified model, Figure 4*b* shows a comparison between the results that were obtained by using forecast flows and the flows that were later observed.

It must be pointed out that the reliability of these predictions depends on how closely the actual operating schedules for the Pickwick and Kentucky turbines follow the anticipated schedules on which these predictions are based. Fortunately, in the past the predicted and actual operations of these plants have usually been nearly identical.

Although the simplified model approach is aimed specifically at providing instantaneous flows at 1-hour intervals at a particular point within Kentucky Lake, values of stage, discharge, and velocity at each of the 21 points in the reservoir are also determined and available from a single prediction run. The TVA has agreed to furnish these transient flow forecasts on a trial basis for a 1-year period to establish the usefulness and practicality of the method as a means for improving water quality control. Such an approach in all man-made lakes where the boundary operating conditions can be predicted with some degree of reliability offers hope for optimizing the use of these reservoir waters to meet the diverse and frequently conflicting demands placed on them.

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