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REAL-TIME HYDROLOGIC FORECASTING USING ESTIMATION THEORY AND COMPUTER GRAPHICS

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ABSTRACT

The National Weather Service (NWS) Hydrologic Research Laboratory (HRL) conducts research aimed at improving hydrologic forecasting techniques in support of forecasting activities of hydrologists in field offices. Hydrologic simulation programs provide computer-generated hydrographs for the forecasters. Current forecast techniques can be improved through fuller utilization of available data. Kalman filtering is a technique which uses conceptual models and more complete use of information from available data to produce improved forecasts. Computer-generated graphics can improve current forecasting techniques by enhancing interactions with the hydrologic simulation programs. An Interactive Forecast Program (IFP) using these techniques was developed. Some of the benefits of Kalman filtering and interactive graphics are demonstrated by comparing current forecasting techniques with those possible in the future through the use of the IFP.

INTRODUCTION

The NWS Hydrologic Research Laboratory conducts research in support of field offices which provide daily river and flood forecasts throughout the United States. The mission of the HRL is to advance the state of the art of real-time river forecasting for the NWS River Forecast Centers (RFC's). Since the advent of conceptual hydrologic computer modeling, this advancement has focused within the context of developing the NWS River Forecast System (NWSRFS), a system of hydrologic computer models and data handling and display facilities to aid real-time forecasting.

New technologies (both mathematical and electronic) hold promise for improving the tools available to RFC personnel for producing river forecasts. The HRL is exploring possible uses of these technologies in the NWSRFS. This paper looks at two areas where improvements to current river forecasting methods may be realized: more complete utilization of available data and enhanced interaction with computers.

DATA UTILIZATION

In current forecasting procedures, information from the available data is not used to the fullest extent possible. This is because the technology to use the data more fully has not yet been developed for use by the RFC's. An example of underutilized data is discharge measurements. Current RFC procedures compare simulated and observed data, and try to reconcile the differences between the two time series by modifying the simulated discharge before routing this flow downstream. This change is only cosmetic, however, because the soil moisture contents that produced those discharges are not changed. Any error will propagate in discharge simulations for future times. An improvement to current procedures would be to modify the soil moisture contents so that a discharge time series which more accurately reflected the real world occurrences would be produced. Use of data to modify internal components of the hydrologic models is called updating. For the purposes of this paper, updating refers only to techniques which make internal model adjustments, and not to procedures which blend observed and simulated data.

Estimation theory is being explored as a way to incorporate updating into daily forecasting at RFC's. The use of Kalman filtering, a technique based on estimation theory, to modify the internal components of dynamic models based on observed data shows promise for improving the tools available to hydrologic forecasters. Previous applications of Kalman filtering are numerous (1), (2), (3), and an entire conference has been devoted to the uses of filtering in hydrology (4). The pertinent equations for a Kalman filter adaptation of the model of a dynamic system have been formulated in many previous publications (1), (2), (3), (5), (6), and will not be repeated here. The key issue in this application of filtering is not the details of the mathematical formulation, but the additional guidance information available to the forecaster.

The ability of Kalman filtering to more fully use available data to update the hydrologic models is a benefit of this technique. In addition, information about the certainty of the forecasted values is produced during filtering. This information may be as helpful to the forecaster as the updating capability. Any users of the river forecasts (barge companies, reservoir operators, civil defense agencies, recreational interests, or the general public) must have some feeling for the accuracy of forecasts they use to make decisions. With current forecast methods this feeling has been developed subjectively through a history of receiving a forecast, making a decision, taking appropriate action, and then observing if the forecast was accurate and, therefore, beneficial. The Kalman filtering technique produces an objective measure of the accuracy of all forecasted values, given information on the accuracy of the observations. This measure of uncertainty allows the forecaster, as well as the user, to know how much confidence to put in the forecast.

COMPUTER INTERACTION

The use of complex conceptual hydrologic models in river forecasting has created an environment in which the forecaster must supply to and receive from the computer large amounts of information. The forecaster's link with the computer is important to today's forecasting methods, and new techniques which enhance the forecaster-computer interface are bound to improve the overall forecasting effort. Currently, a river forecaster's time is divided among actual operational forecasting, calibration of the hydrologic simulation models for the various basins within his area of responsibility, and development of procedures to improve forecasts. Each of these activities usually requires interaction with the computer in some form.

Input to the operational river forecasts is received in the RFC's in a number of ways. Data are obtained through telephone calls from observers, teletyped information from other offices, communication links with interrogated and automatic gages, and radar and satellite sources. Much of the data currently is transferred to cards in the RFC for input to the computer. The processing of the data into a format acceptable for use by the forecast programs and the actual submittal of forecast jobs are controlled by cards input through a card reader. Computations generally require several minutes of clock time. Results of the forecast program are displayed on line printers and consist of tables and graphs. Calibration efforts require many of the same steps, i.e., preparation of data, and submittal of programs to the computer through the use of card decks. Output from the calibration programs consists of plotted hydrographs printed on the line printer.

The current technique of submitting programs to the computer on cards and receiving output on line printers has a number of disadvantages. Card input is a relatively slow procedure and data keypunch errors are often not easily recognized. Line printers allow limited variety in terms of the type of graphical output desired in hydrologic simulation. Printers also can use a tremendous amount of paper. Operational forecasting and basin calibration are both procedures which require iterative approaches. The traditional method of reading cards and waiting for printer output is not conducive to iterative techniques in which the user wants to make a change in the program input, obtain the results, react to the changes, and rerun the program with newly revised input in minimal time. The time element is much more critical in operational forecasting than in basin calibration; however, the operator-machine interaction is a key element in both procedures. The importance of man-machine dialogue to effective data processing is becoming very apparent (7). Improvements in this interface should allow forecasters to more fully utilize the computer facility as an aid to forecasting.

Computer graphics is a subject which has received a great deal of attention within recent years. Increased interaction with computers has brought the need to provide improved means of data input and output. French, et al. (8) showed some of the advantages of using interactive computer graphics in water resources. The paper stated that two obstacles limit the realization of the full potential of sophisticated hydrologic models: data preparation and input, and interpretation of results. Interactive computer graphics is a means by which users can effectively communicate with the computer and may be a way of improving the utilization of computers by hydrologic forecasters.

Interactive computer graphics allows data to be input to the computer and the results to be displayed through a number of devices. The most important aspect of interactive graphics is the flexibility the user obtains in working with various types of input and output devices in a conversational mode with the computer. In the case of operational hydrologic forecasting, the interaction would allow the forecaster to input the most recently received data during a real-time event, have the program perform the hydrologic computations, display the results graphically, analyze the output, and recycle through the entire procedure. This process would eliminate the need to keypunch cards, submit card decks through the card reader, and wait for the program to send output to the line printer. The use of interactive computer graphics also could significantly change the way hydrologists calibrate the hydrologic models for various watersheds. An interactive calibration session would consist of a hydrologist, sitting at a graphics terminal, inputting data and model parameters to the computer, having the computer perform hydrologic simulations, analyzing graphical output, and recycling through the process to study the effect of parameter changes. The key advantages of interactive graphics in calibration would be the capability of displaying complex components of the conceptual models as an educational tool for the user, and the option to allow the user to perform parameter sensitivity analyses interactively.

EXAMPLE APPLICATION

A computer program has been written to demonstrate the potential for using interactive graphics and estimation theory in real-time forecasting. The program is designed to run interactively, allow the forecaster to input or modify data, perform a hydrologic simulation, and produce graphical displays on a CRT. The simulation is updated with a Kalman filter for the period of available data and a forecast beyond the end of observations can be made if requested. At initiation of the program, a display consisting of the border and list of commands as shown on the right half of fig. 1 is produced. Any valid commands may be entered. These include commands to: input or change observations, plot symbols and draw lines connecting those symbols, print observed and simulated values, simulate using a Kalman filter, and set various switches choosing the type of display desired and the time period and scale to be displayed. Many of the commands have subcommands to choose various options. There are three displays available. The display shown in fig. 1 and 2 can give the value of a state variable and its standard deviation. Fig. 3 shows the observed, predicted, and filtered values for three state variables. The single axis in fig. 4 allows room for plotting several time series on one graph. Commands can be entered or re-entered in any sequence, it is left to the forecaster to determine a logical pattern to produce the desired results.

To illustrate the use of this program, the passing of a flood wave through a reservoir will be modeled. For the purposes of this example, the reservoir was modeled as a linear reservoir and incorporated in the Kalman filtering algorithm. The inflow to the

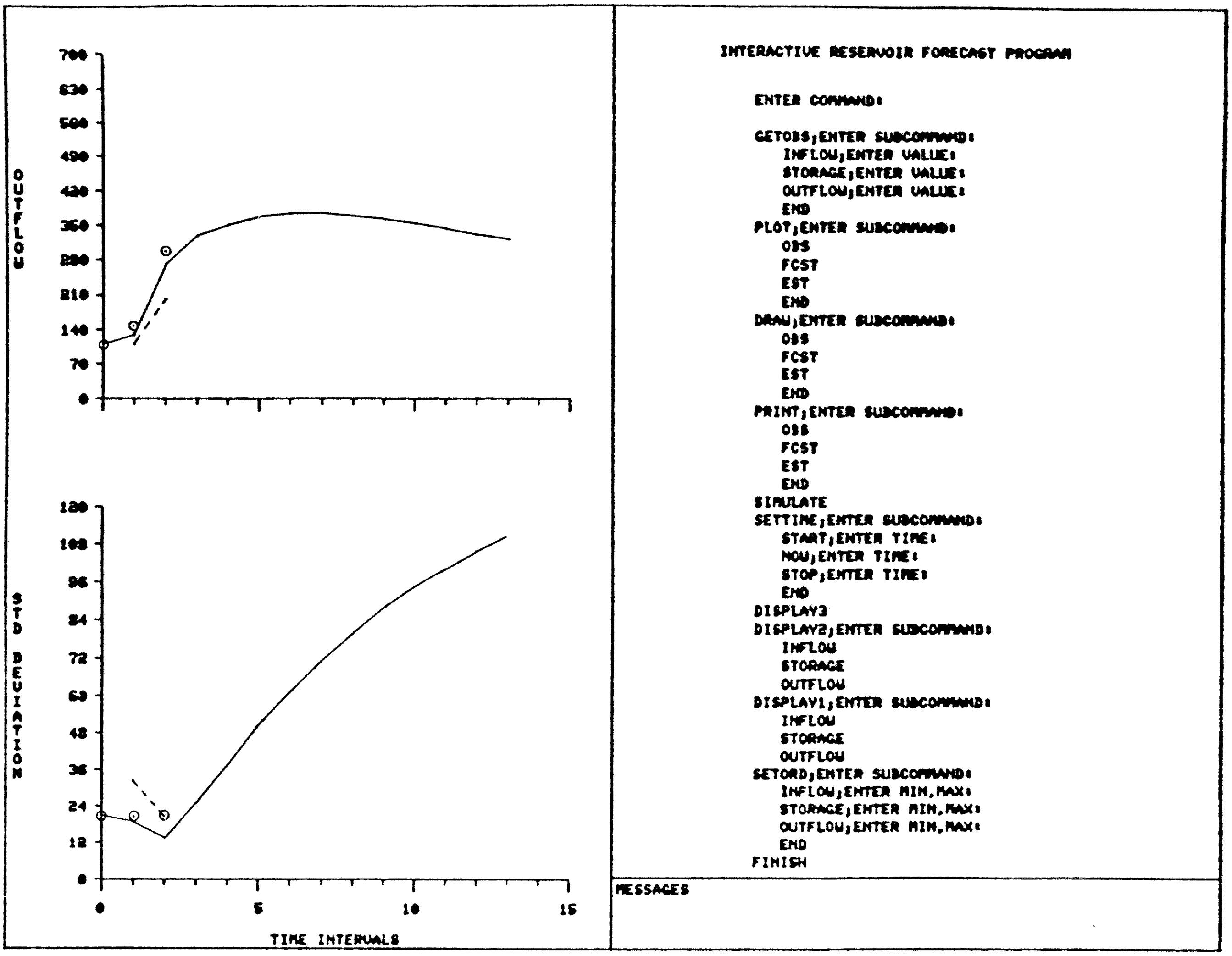

Fig. 1 Typical screen display including menu of all possible commands and sample of reservoir outflow and standard deviation: Two observations and eleven forecast periods. (The circles represent observations, the dashed lines connect one-step-ahead predictions for the period of observed data, and the solid line connects the optimal estimates using the Kalman filter and the model predicted values beyond the end of observations.)

reservoir was modeled as an autoregressive lag 1 process. Measurements of inflow and outflow were obtained from Chow for a "typical" rise (9). Errors in the measurements were estimated for this example. The units of the state variables are cubic feet and the time intervals are days. The scenario for this test case is to follow the forecasting strategy of a hydrologist throughout this rise. At the beginning of the flood wave, information about the total magnitude of the crest is not available, so the best forecast that can be made is depicted in the upper graph of fig. 1. The circles locate the observations, the dashed line connects the one-step-ahead predictions for the period of observed data, and the solid line connects the optimal estimates using the Kalman filter for the period of observed data and the model-predicted values beyond the end of observations.

As the time of the crest draws nearer, the upper part of fig. 2 shows how the forecast has changed. The peak of the rise can now be seen more accurately, and the total magnitude of this flood is becoming apparent.

The lower graphs on fig. 1 and 2 display additional information available to the forecaster. These consist of the standard deviation of the state variable over time. Fig. 1 shows how uncertain the peak forecast is early in the event. Fig. 2 demonstrates the reduction in uncertainty in the peak forecast as more data are processed.

At the conclusion of the event, the full picture comes into view in fig. 3. The state variables of inflow, storage, and outflow are shown for the entire period of the flood.

A synopsis of the changing forecasts can be seen in fig. 4. The dashed line connects the optimal filtered estimates (for the first two periods) and the model-predicted values for periods 3 through 13 (as shown in fig. 1). Optimal estimates for five periods of observed data followed by eight predictions (as shown in fig. 2) are represented by the long-and-short dashed line. Because the dashed and the long-and-short dashed lines coincide with the solid line for the first two and five time periods, respectively, they do not appear for those time intervals. The

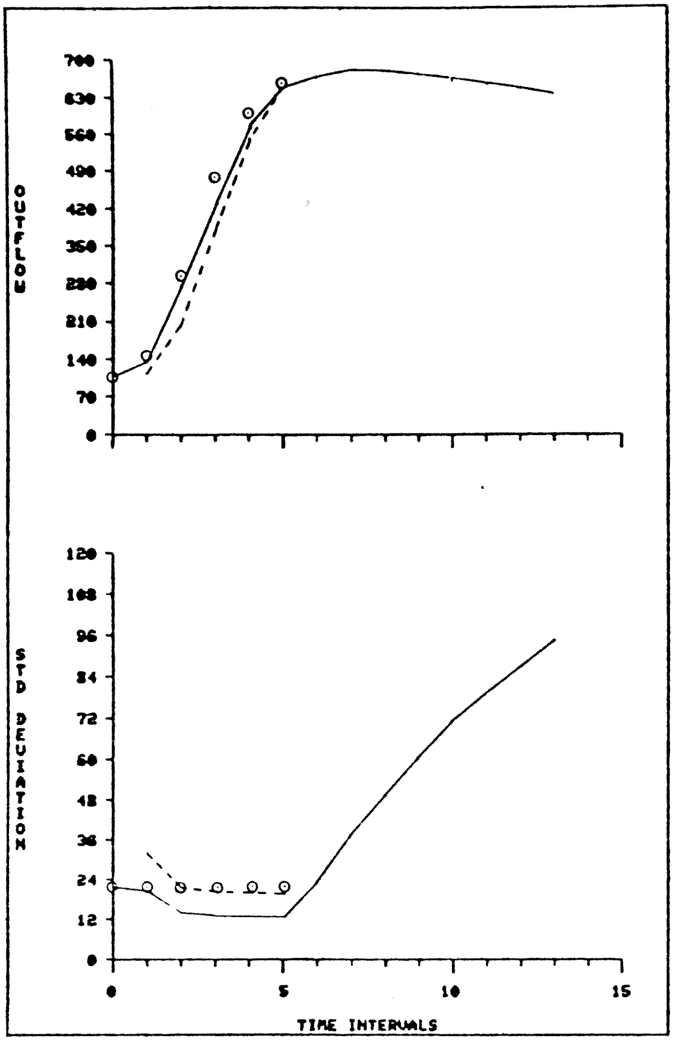

Fig. 2 Reservoir outflow and standard deviation: Five observations and eight forecast periods. (Notation for points and lines same as for fig. 1.)

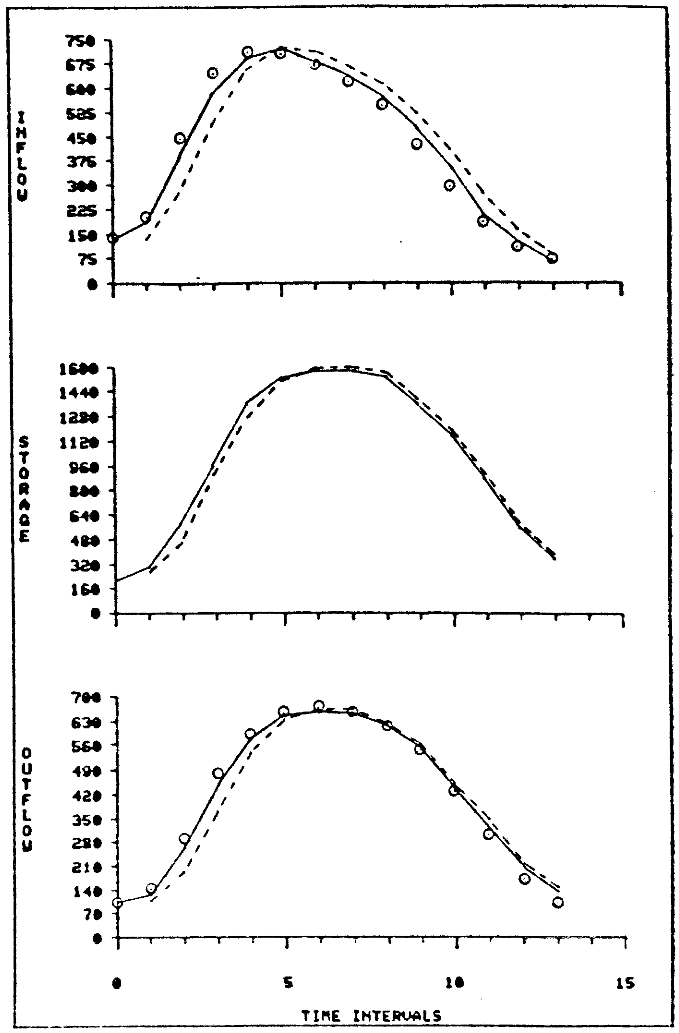

Fig. 3 Reservoir inflow, storage, and outflow: Thirteen observations. (Notation for points and lines same as for fig. 1.)

solid line shows the optimal estimates when observations for all 13 periods are included.

A comparison of the standard deviations of two simulations produced with differing assumptions is shown in fig. 5. The solid line depicts the standard deviation of the optimal filtered estimates of the outflow time series. This estimate was obtained by processing measurements of inflow and outflow, and by specifying error in the measurements so that the filter could balance the uncertainty in the predicted and measured values. The dashed line was computed by processing only inflow observations and assuming that they were perfect. This is typical of the approach currently taken in many forecasting situations. The advantage of filtering the outflow measurements can be seen in this figure. For this example and the assumed measurement errors, the standard deviation of the best estimate was approximately halved by processing the outflow measurements. The Kalman filter substantially reduced the uncertainty of outflow values by incorporating all the available data.

In this example, estimation theory has aided the forecaster by updating the simulation model based on the observations, and by providing an objective measure of the uncertainty of the forecasts. Additional benefits are realized through the use of interactive graphics as the forecaster can view any of the displays shown in fig. 1-5. Data can be entered at the interactive terminal, and any modifications can be quickly made. Various contingencies of possible future inflow time series can be entered and results obtained immediately.

The hydrologist can focus on forecasting without the interruption of punching and submitting cards, and then waiting for a batch job to be run. These new technologies have the potential to provide additional information to the hydrologist and user about the certainty of the forecasts, update the internal components of the hydrologic models, and allow RFC personnel to operate in an interactive environment where they can focus on the forecast, aided by various graphics tools.

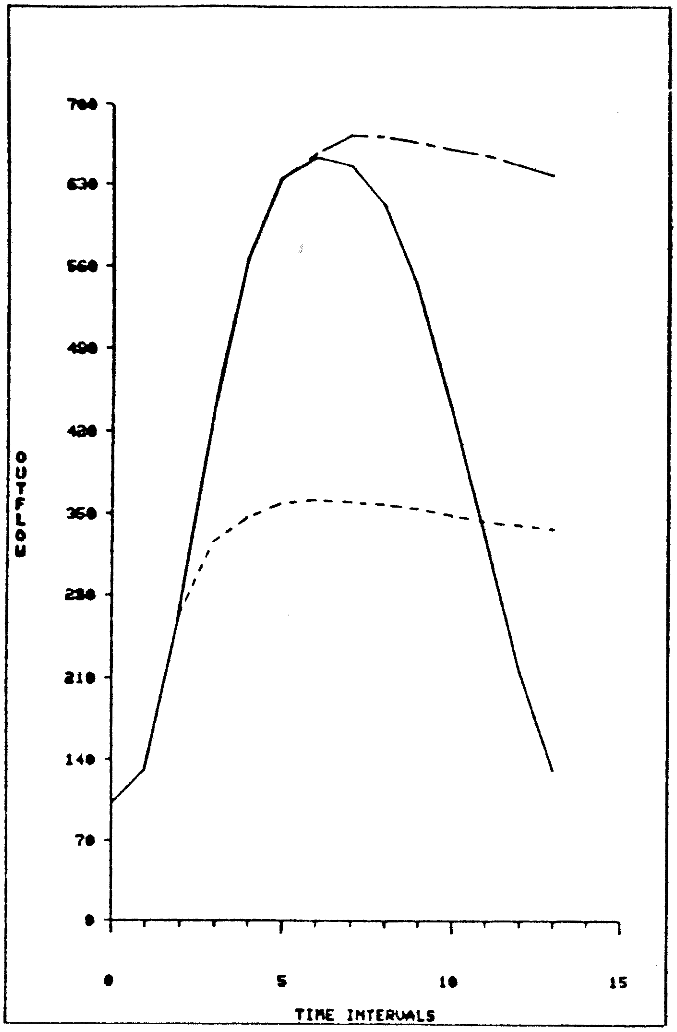

Fig. 4 Best estimates of reservoir outflow: Two, five, and thirteen observations. (The dashed and long-and-short dashed lines represent optimal estimates and predicted values for observation periods of two and five intervals, respectively. The solid line shows optimal estimates with observations at all 13 periods.)

CURRENT AND FUTURE RESEARCH

The example presented in this paper demonstrates the use of estimation theory and interactive computer graphics for a simple hydrologic forecasting application. The simple hydrologic model was chosen because it was linear, a property required by the Kalman filtering algorithm. Current and future research in this area centers on the adaption of more complex, non-linear hydrologic models to the Kalman filter configuration. The Sacramento soil moisture accounting model (10) and various non-linear channel routing models are being transformed to the linearized formulation required for this estimation technique (2). As these models become available, the applicability of updating in the real-time mode described above will expand.

Current research being performed at HRL in the use of interactive computer graphics is still at an early stage. The primary research emphasis is initially being aimed at incorporating computer graphics into calibration procedures. Interactive graphics should enable users to better understand the components of the hydrologic models and, thus, develop improved trial-and-error calibration approaches. The possible future applications of computer graphics to hydrologic forecasting are almost unlimited. Ultimately, river forecasters should be able to interact with the computer through various graphical input and output devices to perform functions such as analyzing data, producing forecasts, examining topographical maps for inundation, and calibrating basins.

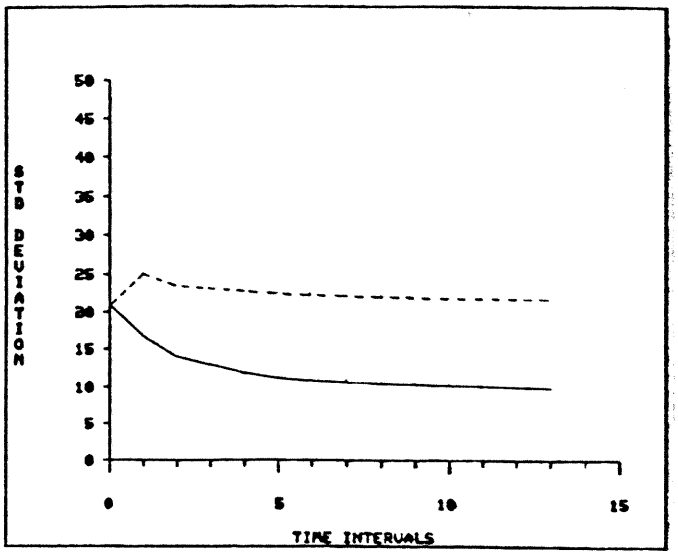

Fig. 5 Standard deviations of reservoir outflow: With and without using outflow observations to update. (The solid and dashed lines represent optimal estimates with and without outflow observations, respectively.)

CONCLUSIONS

Two relatively recent technological advancements, estimation theory and computer graphics, can be used to improve real-time hydrologic forecasting. The incorporation of estimation theory into forecasting procedures results in forecasts which more fully utilize the most recent data and which are accompanied with an objective measure of uncertainty. The example application shows that estimation theory provides two improvements over traditional forecast techniques: a means for updating the model and a method for objectively blending the observed and simulated values. The iterative nature of real-time forecasting and updating is particularly suited to interactive programing. Interactive computer graphics can be utilized as a means by which the forecaster can improve his communication with the computer. In this case, an interactive graphics program was written to illustrate updating, using a simple reservoir model to forecast in a real-time time mode. Procedures such as these should be available to assist river forecasters in the future.

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