Hydrological forecasting – Prévisions hydrologiques (Proceedings of the Oxford Symposium, April 1980; Actes du Colloque d'Oxford, avril 1980): IAHS–AISH Publ. no. 129.

Hydrological update techniques used by the US National Weather Service

E. L. PECK, E. R. JOHNSON, K. M. KROUSE, T. R. CARROLL
and J. C. SCHAAKE, Jr National Weather Service, Silver Spring, USA

Abstract. This paper presents a state-of-the-art review of procedures used by the National Weather Service for updating hydrological forecasts. Updating techniques include simple blending procedures, an objective technique for updating both the state variables and the output of the model by adjusting precipitation inputs, and a method using snow course data to adjust simulated snowpack variables. Recent research is aimed at direct updates of hydrological state variables based on observed discharge and using techniques from estimation theory.

Techniques hydrologiques de remise à jour utilisées par le Service Météorologique National des Etats-Unis

Résumé. Ce rapport présente une revue des méthodes utilisées à ce jour au Service Météorologique National pour remettre à jour les prévisions hydrologiques. Sont compris dans ces techniques de remise à jour: des procédés simples de régressions multiples (une technique objective pour réviser à la fois les variables d'état et les sorties de modèle en ajustant les entrées correspondant aux précipitations) et également une méthode qui utilise les données des relevés de l'épaisseur de la couche de neige pour corriger les variables simulées du manteau nival. Les recherches récentes s'orientent vers la révision directe des variables d'état à partir des débits observés et en utilisant les techniques tirées de la théorie de l'estimation.

INTRODUCTION

The problem of adjusting computed hydrographs to simulate observed river conditions more accurately has existed ever since river forecasting activities began. Many of the early river forecasters were skilled at the 'art' of visualizing why a river did not respond in the same manner that their simple empirical technique predicted. The ability to improve the empirical river forecast was not necessarily passed on to new forecasters.

Early river forecasters specialized in a small number of streams. Today most river forecasters in national forecasting services are directly responsible for making a variety of forecasts for a large number of forecast points which may have a wide range of basin and hydrological characteristics. Consequently, most forecasters do not have the experience or time to adjust subjectively the forecasts.

However, with the recent adoption of continuous conceptual models as a forecasting tool, the problem of adjusting forecasts has become considerably more complicated. An understanding of the conceptual model is required to identify the source of error and to make successfully subjective adjustments to improve the river forecast. Additionally, it is difficult to transfer such subjective skills to new forecasters.

NATIONAL WEATHER SERVICE PROCEDURES

In 1966 the National Weather Service (NWS) initiated a project to evaluate newly developed techniques for predicting basin response. These tests and others performed by the World Meteorological Organization (WMO, 1975) led to the adoption of a modified version of the Sacramento River Forecast Center Hydrological Model (Burnash *et al.*, 1973). Conceptual models generally have the capability of forecasting flood events as well as basin response during and subsequent to long dry spells.

In 1971 the initial version of the National Weather Service River Forecast System (NWSRFS) was published (NOAA, 1972). The system is currently being expanded to include additional routines automatically to collect, archive, retrieve, and process data needed by the 13 NWS hydrological field forecast offices to implement the river forecast system.

The hydrological models in the NWSRFS are evaluated continuously and include models to simulate soil moisture accounting, snow accumulation and ablation (Anderson, 1973), reservoir operations, river routing (Fread, 1978), and dam failure (Fread, 1977). The system is designed to use one or more models for any given hydrological component.

The variety of hydrological models in NWSRFS are combined to create a number of software systems. A calibration system is available to access historical data and estimate parameters of the various models. Another system is available for long-range probabilistic forecasting as well as for operational river forecasting.

Neither the models nor data used in river forecasting are perfect. Consequently, updating techniques are necessary to minimize the errors associated with the simulated hydrological conditions and the observed response. Descriptions of update techniques in use and under development by NWS are given in the following sections.

BLENDING

A technique used by the NWS river forecasters is 'blending'. The procedure is objective and merges the observed hydrograph with the simulated. For example, if a measured discharge is 60 m^3/s greater than the simulated discharge at a given time, then the predicted discharge is simply the simulated discharge for the six future time steps plus 50, 40, 30, 20, 10, and 0 m^3/s, respectively.

Blending techniques do not correct the underlying cause of the discrepancy, but they are objective and easy to implement. However, they cannot correct for certain common sources of errors such as erroneous precipitation reports or timing errors.

CONCEPTUAL UPDATE APPROACH

The conceptual models of the NWSRFS contain complex soil moisture accounting systems in which the quantity of water in storage in various parts of the soil mantle is represented by state variables. The discharge generated by the model in response to a moisture input is dependent upon the current values of these variables. If the simulated discharge is not in satisfactory agreement with the observed, one or more of the state variables may differ from their true values by an unacceptable amount. Because of the inherently long memory in the conceptual hydrological model, the accuracy of the simulation of the *next* runoff event may suffer. Consequently, a procedure is required to adjust not only the model output, but also to adjust the state variables to represent the true state of the system more accurately. The two criteria that an adjustment procedure must fulfil are: (1) the soil moisture accounting variable must be adjusted with the output, and (2) the adjusted output must be at least as accurate as that which might be arrived at subjectively by a skilled human forecaster.

The NWS Computed Hydrograph Adjustment Technique (CHAT) procedure (Sittner and Krouse, 1979) is applicable to runoff events not involving snow and to hydrographs which represent headwater basin outflow. The procedure treats the source of error rather than the error itself. Simulation errors arise from errors in input data, model parameters, model structure, and observed discharge. For headwater application the predominant source of error is in the estimation of mean areal precipitation. The technique makes adjustments to the precipitation input, within limits of probable error, and modifies the shape of the unit hydrograph until the simulation is in satisfactory agreement with the discharge observation. The degree of fit between the computed hydrograph and the array of observations available at the time of forecast preparation is measured by an objective function. However, only a *portion* of the rising limb of the observed hydrograph is available for comparison. Consequently, the use of a conventional objective function such as an RMS criterion is precluded. Thus, CHAT utilizes a unique objective function that models, to some degree, the thought processes which a human forecaster uses in judging the seriousness of a disagreement between the rising limb of a simulated hydrograph and the discharge observations. Unlike conventional optimizing techniques, CHAT does not seek to minimize the objective function, but rather, attempts to reduce it to an acceptable value.

Although intended primarily for use with the NWSRFS conceptual model, the CHAT adjustment procedure can be used with any hydrological model that uses mean areal precipitation as input to produce a discharge hydrograph at the outlet of the basin.

SNOWMELT FORECAST UPDATE PROCEDURE

The snow accumulation and ablation model of the NWSRFS is a conceptual model which simulates physical characteristics of the snow cover over time such as snow water equivalent, areal extent of snow cover, and snow cover temperature. Whenever an observation of the simulated value is available, it is possible to modify, or update, the simulated value based on the information contained in the observation.

Typically, simulation errors in basins which have a significant snowmelt runoff contribution are due to: (1) over or under simulation of snow water equivalent in the basin which results in discharge volume errors, (2) an early or late simulation of significant melt in the snowpack which results in discharge timing errors, or (3) both volume and timing errors.

Carroll (1979) describes an update procedure to incorporate snow course data into the NWSRFS. The NWS snow accumulation and ablation model continuously computes a mean areal simulated water equivalent of the snow cover. The update procedure weights the simulated water equivalent value and the observed water equivalent to determine an estimated water equivalent. The technique is intended primarily to reduce the monthly volume errors in simulated streamflow.

The update procedure is of particular value for those cases where the precipitation data do not accurately represent the snow accumulation at higher elevations. In basins where precipitation stations are located primarily at elevations lower than the snow courses, considerable improvement can be expected because the snow course data may contain information not represented by the precipitation data. In some basins of the western US, large deviations from normal seasonal precipitation patterns may occur frequently (Peck, 1964). During years of abnormal precipitation distribution the snow course data may contain considerable information not represented by precipitation data alone.

The most reliable seasonal water supply forecasts from mountainous snow areas in the western US are made using 1 April snow course data when the snow accumulation is near a maximum. The snow course update technique has been applied to three basins in the western US and the results are based on the improvement of the volumetric forecast for the April–September period.

The update procedure was tested on the Dolores River at Dolores (1305 km^2) in southwestern Colorado. For the calibration period from 1956 to 1973 the mean error for the April–September streamflow volume is reduced by 40.0 per cent from 21.0 to 12.6 mm. The snow courses for the Dolores basin are at much higher elevations than the precipitation stations. Consequently, the snow course data seem to introduce additional information on precipitation at higher elevations.

When the update procedure was tested on the larger Eagle River at Gypsum (2445 km^2) in central Colorado for the calibration period from 1949 to 1972, the mean error for the April–September streamflow volume was reduced by 18.4 per cent from 19.3 to 15.7 mm. The precipitation stations and the snow course sites used for the Eagle River simulation are in close proximity in the southeastern section of the basin.

The update procedure was also tested for the Sevier River basin (881 km^2) in southern Utah. For the calibration period of 1952–1971 the mean error for the April–September streamflow volume is reduced by 27.3 per cent from 9.9 to 7.2 mm.

Some of the snow courses in the Sevier River basin are co-located with or near precipitation stations. However, several are at higher elevations and do provide a more representative coverage of the basin.

STATE ESTIMATION THEORY

Almost all the hydrological models used for operational river forecasting are deterministic models. They process inputs (e.g. precipitation, temperature, rainfall excess) and produce outputs (e.g. discharge, snowmelt). Any measurement of model outputs is redundant information to the model because it does not allow for any uncertainty. To use all the information available, it must be recognized that an operational model may not generate perfect output.

To make the best use of all information, it is necessary to quantify the reliability of each source of information which includes measured outputs, estimated inputs, and the modelled hydrological variables. If all sources of measurement, input estimation, and modelling error can be quantified, then state estimation theory can provide techniques to combine the source of information to produce the best estimates of past, present, and future states of the hydrological system.

State estimation theory considers complete probability distributions of all states, measurements, and inputs; this allows complete freedom in defining the 'best' (i.e. minimum variance) estimates of past, present, and future states. The procedure used to implement a second-order description is generally called the Kalman filter (Gelb, 1974). Application of Kalman filtering to hydrological modelling promises a number of improvements in operational hydrology, but it also requires that a number of research problems be solved.

The update problem in hydrology is to adjust the values of the modelled hydrological states to maintain consistency between state estimates and all measurements available at a given time. The Kalman filter solves the update problem in a direct and general manner. A secondary advantage is the ability to calculate a forecast variance which is a quantification of forecast uncertainty. To apply the Kalman filter it is necessary to quantify the various sources of forecast uncertainty. This effort may help to identify those research areas and improvements in data acquisition which can be most productive in increasing forecast accuracy.

The long term goal of NWS research is to incorporate all operational hydrological models and all available measurements into a Kalman filter framework which will require, in turn, identification of all necessary covariance terms. Meeting this long-term goal will require ongoing research to incorporate new measurement technologies and new hydrological models. Currently, hydrological models are being incorporated into a Kalman filter framework, and more accurate estimates of the model, measurement, and input noise terms are being developed.

Application of estimation theory to hydrology is an attractive research area in which NWS is supporting several projects.

(1) The Sacramento soil moisture accounting model with certain modifications (Peck, 1976) has been incorporated into a Kalman filter framework (Kitanidis and Bras, 1978). The model was written in continuous state–space form, i.e. a system of simultaneous ordinary differential equations. These equations were linearized using various techniques and then integrated to find the state transition matrix for a discrete time Kalman filter. An automatic procedure to estimate the model noise covariance matrix and input noise covariance was developed. A generalized likelihood ratio test was developed to detect input errors.

Preliminary research has produced an important first step in applying state estimation theory to conceptual hydrological models with promising results. However, it has several limitations: (a) it considered only the Sacramento soil moisture accounting model with a crude procedure to time-distribute channel inflow and route to the gauging station; (b) it considered the model and input noise covariance to be constant, and (c) the procedure used to identify input errors did not consider the pure timing error. Continuing research is directed at minimizing these limitations.

(2) A current project estimates the mean square error of mean areal precipitation as a function of a storm classification and the number and location of gauges used (Resource Analysis, 1979). This research will develop a more accurate estimate of the most important input error covariance term. The current analysis ignores non-homogeneities (e.g. orographic effects) and temporal correlation in the rainfall field.

(3) Another research area involves the development of a minimal state representation of an arbitrary unit hydrograph (TASC, 1979). There are two primary reasons for this project: (a) the computational burden in applying the Kalman filter increases rapidly with the number of state variables; consequently, it is desirable to reduce the state dimension, and (b) the NWS has a considerable investment of manpower in existing unit hydrographs estimated for many basins throughout the US so the unit hydrographs shapes should not be restricted.

A number of issues are raised where the Kalman filter is applied to a linearized form of very nonlinear hydrological models in the presence of non-Gaussian noise. The magnitude of these effects is also under investigation by TASC for the Sacramento soil moisture model which is a complex nonlinear model.

CONCLUSION

The NWS has developed specialized techniques for use in updating hydrological forecasts. At the present time the Computed Hydrograph Adjustment Technique (CHAT) is programmed for runoff events, not including snowmelt, and to hydrographs representing headwater basin outflow. A procedure for using observed snow course measurements to update seasonal volumetric forecasts using a conceptual model is also operational. For the future, the application of estimation theory techniques, in particular the Kalman filter, to hydrological models offers a general solution to the update problem in hydrological forecasting. It requires an estimate of the covariance of errors in the model, input estimates, and measurements, as well as a formulation of the hydrological model in stochastic state–space form.

REFERENCES

Anderson, E. A. (1973) National Weather Service River Forecast System, snow accumulation and ablation model. *NOAA Tech. Memo. NWS HYDRO-17, US Dept of Commerce, Silver Spring, Maryland, USA.*

Burnash, R. J. C., Ferral, R. L. and McGuire, R. A. (1973) *A Generalized Streamflow Simulation System: Conceptual Modelling for Digital Computers*: US Dept. of Commerce, NWS, and State of California, Dept. Water Resources, Sacramento, California, USA.

Carroll, T. R. (1979) A procedure to incorporate snow course data into the National Weather Service River Forecast System. *Proceedings, Modeling of Snow Cover Runoff* (AGU, AMS, Corps of Engineers and NWS, Hanover, New Hampshire, September 1978), pp. 351–358.

Fread, D. L. (1977) The development and testing of a dam-break flood forecasting model. *Proceedings, Dam-Break Flood Routing Model Workshop* (Bethesda, Maryland, 18–20 October) pp. 164–197: US Water Research Council.

Fread, D. L. (1978) NWS operational dynamic wave model, verification of mathematical and physical models in hydraulic engineering. *Proceedings, 26th Annual Hydraulics Division Specialty Conference*, (University of Maryland, College Park, Maryland, August) pp. 455–464: American Society of Civil Engineers.

Gelb, A. (editor) (1974) *Applied Optimal Estimation*: The MIT Press, Massachusetts, USA.

Kitanidis, P. K. and Bras, R. L. (1978) Real time forecasting of river flows. *Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Dept of Civil Engineering, MIT, TR235.*

NOAA (1972) National Weather Service River Forecast System, forecast procedures. *NOAA Tech. Memo. NWS HYDRO-14, US Dept of Commerce, Silver Spring, Maryland USA.*

Peck, E. L. (1964) Little used third dimension. *Proceedings, Western Snow Conference* (Spokane, Washington), pp. 33–40.

Peck, E. L. (1976) Catchment modeling and initial parameter estimation for the National Weather Service River Forecast System. *NOAA Tech. Memo. NWS HYDRO-31, US Dept of Commerce, Silver Spring, Maryland, USA.*

Resource Analysis (1979) Accuracy of mean areal precipitation estimation. Interim report under NWS NOAA contract 7-35111, May.

Sittner, W. T. and Krouse, K. M. (1979) Improvement of hydrologic simulation by utilizing observed discharge as an indirect input (Computed Hydrograph Adjustment Technique–CHAT). *NOAA Tech. Memo. NWS HYDRO-38, US Dept of Commerce, Silver Spring, Maryland, USA.*

TASC (1979) Applications of Kalman filtering and maximum likelihood parameter identification to hydrologic forecasting. Interim report under NOAA contract NA79SAC00668, July.

WMO (1975) *Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting.* Operational Hydrology Report no. 7 (WMO no. 429).