Master

USE OF MATHEMATICAL MODELS FOR HYDROLOGIC FORECASTING IN THE NATIONAL WEATHER SERVICE

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ABSTRACT

The National Weather Service is implementing a new system of mathematical models to aid river forecasters throughout the United States. Forecasts of stages and discharges a few days ahead are produced routinely on a daily basis and at six-hour intervals during floods. Also, extended streamflow prediction of high, low, and expected discharges for periods up to several months into the future are made at routine intervals.

This system of models, known as the "National Weather Service River Forecast System" (NWSRFS), was initiated in 1971[9] and is now being improved and expanded. It includes conceptual hydrologic models of snow, soil moisture, and streamflow routing; it includes models of unsteady open channel flow; it has provisions for reservoir operations models; and it will include stochastic hydrometeorologic models to account for uncertainty in streamflow forecasts. NWSRFS also includes programs and procedures for model calibration and verification with the historical data. Studies of the validity and accuracy of the models are reviewed, and some modeling issues in need of further study are summarized.

Information generated by these models could contribute to EPA's overall environmental mission. Hydrologic information is readily available in NWS forecast data files for use with convection and dispersion models to forecast the fate of pollutants suddenly released to the hydrologic environment or to forecast the day to day variations in pollutant transport properties of selected streams. Currently under development is a water temperature forecast model utilizing hydrological and meteorological data readily available in real time in NWS data files.

Problems faced by NWS managers in understanding and utilizing NWSRFS are discussed. NWSRFS is being installed on an IBM 360/195* in Suitland, Md., and is being operated from remote terminals by field offices. NWSRFS is developed and supported by the Hydrologic Research Laboratory, Hydrologic Services Division, and the field offices.

HISTORY OF MODEL USE IN NWS

For many years, river forecasts in the U.S. have been made using an Antecedent Precipitation Index (API) type of rainfall-runoff relation to convert rainfall into rainfall excess or runoff.[7] Unit hydrographs or time delay histograms have been widely used to translate runoff through catchments to forecast points. These techniques historically have worked well and are still in use.

In 1966 a project was initiated in NWS to evaluate newly developed hydrologic models. Models were compared for a group of seven carefully selected basins throughout the country. No single numerical scoring factor seemed adequately to represent model accuracy because important differences between models seemed to be evident only in one or two aspects of the simulation or only in certain hydrologic situations. Several statistical measures based on observed and simulated discharge were used to evaluate model performance. Two models showed an accuracy advantage over API. One was essentially the same as the Stanford Watershed Model IV,[3] the other was the initial version of the Sacramento River Forecast Center Hydrologic Model.[2]

The most notable accuracy advantage of these conceptual models over the API model is during and after a long dry spell. The more complete moisture accounting techniques give the conceptual models enough "memory" to handle situations where large amounts of rain give little or no streamflow response.

In 1971 a modified version of the Stanford IV model was incorporated with other data processing programs into the NWSRFS.[11] A snow accumulation and ablation model was added to NWSRFS in 1973. This snow model accounts in detail for the energy balance of the snow cover by using air temperature to estimate energy exchanges.

The Hydrologic Research Laboratory in 1974 compared an improved Sacramento Model with the NWSRFS Stanford Watershed Model IV. Data from four catchments were used to test model performance. This was part of a WMO project on intercomparison of conceptual models. In general we concluded: (1) there is no significant difference in model performance in very humid areas; (2) there seems to be little difference in ability to simulate large flood events; (3) the Sacramento Model does simulate monthly volumes and small runoff events significantly better in semi-arid and moderately humid areas; and (4) improvements through research seemed easier to make to the Sacramento Model because of its modular structure. Following these model tests, components of the soil moisture accounting of the Sacramento Model replaced the original Stanford IV components in NWSRFS.

Summary of NWSRFS

NWSRFS includes techniques and programs for developing operational river forecasts from initial processing of historical data during procedure development to the preparation of forecasts in real time. The programs are generalized for use on any river system including headwater catchments and downstream river networks.

*Trade names are mentioned solely for purposes of identification. No endorsement by the NWS, NOAA, or Department of Commerce, either implicitly or explicitly, is implied.

Programs and example data sets for the initial version are available to the public through the National Technical Information Service (NTIS). Information to purchase these from NTIS can be obtained from the Hydrologic Research Laboratory (W23), National Weather Service, Silver Spring, Maryland 20910.

The following techniques and models are included in NWSRFS:

- Mathematical model of the accumulation and ablation of Snow [Anderson, 1973]

- A catchment model including both (a) a soil moisture model to account for flow through and above the soil mantle and for evapotranspiration and (b) time delay models to move runoff from the soil moisture model through the catchment to the catchment outlet

- Channel routing models to account for movement of water in a channel system

- Techniques for modeling the areal distribution precipitation

- Techniques for estimating mean areal temperature

- Methods to estimate model parameters using historical hydrometeorological data

CRITERIA FOR MODEL SELECTION

Some of the criteria we used for model selection are:

- Input Data Sampling Interval - Operational rainfall data are available from a 6-hour reporting network and a 24-hour reporting network. With this 6-hour reporting interval there is a lower limit to the size of catchment that can adequately be modeled.

- Computational Efficiency - Models are operated for most of the country. Each day, computations are made for the next few days using 6 hour time steps. During flood periods, computations are repeated every 6 hours.

- Data Availability - Historical hydrometeorological data are available in digital form for model calibration (i.e., model parameter estimation). Four types of data are available: (a) hourly precipitation data from the National Climate Center (NCC), Asheville, North Carolina (card deck 488); (b) daily observation data (NCC card deck 486); (c) synoptic meteorological data for estimating potential evaporation (NCC card decks 144, 345, and 480); (d) USGS daily streamflow data. All of these data for the period of digital record are available to NWSRFS users from a tape library of about 500 tapes at the NOAA computer center in Suitland, Maryland. Each of the tapes except streamflow is in a special format (O/H format) developed for the NWS Office of Hydrology (copies of tapes in this format are available to the public from NCC). Another main source of data are USGS topographic maps. (We generally use 1:250,000 scale maps.)

- Physical Validity - Within constraints imposed by computational efficiency and data availability, models should have physical basis for their structure and should simulate observed behavior reasonably well. Although models are usually compared by looking at differences between models, it is of interest to notice many models have some elements of common structure. This occurs because (a) water is held in storage as it flows through the hydrologic cycle and (b) rates of flow depend upon amounts of water in storage and possible other factors such as temperature, humidity, etc. Flow into and out of storage is governed by (a) a continuity relation and (b) a dynamic relation. Models differ in terms of spatial and temporal resolution of these relations and in terms of the factors accounted for in the dynamic relations.

- Building Block Structure - Models of individual processes (precipitation, evaporation, snow cover, soil moisture, channel routing, etc.) have been organized as building blocks. This offers flexibility to represent particular situations with varying degrees of physical detail, and it makes it possible for research on one phase of the hydrologic cycle to be evaluated in an environment that considers other phases.

Benefits Gained from these Criteria

Some of the benefits that accrue from these criteria, particularly the requirement for a strong physical base, are:

- Enhanced likelihood of adequately predicting future events especially during unexperienced hydrologic situations

- Potential to derive initial parameter values from streamflow records and from observable basin characteristics

- Parameters related to basin characteristics may possibly be adjusted without waiting for a new data base if basin characteristics change.

- Conceptual hydrologic models offer potential for application other than for forecasting river stage and discharge such as movement of pollutants through the environment, water temperature prediction, and prediction of soil moisture levels for agricultural purposes.

MODEL APPLICATIONS

Operational River Forecast Preparation

Daily river forecasts are prepared in 12 River Forecast Centers (RFC's) throughout the U.S. These RFC's transmit forecast information to Weather Service forecast offices (WSFO's) for dissemination to the public. The WSFO's gather precipitation and other data and transmit these to the RFC's.

There currently are about 6700 precipitation gages in our operational network. River stage data are gathered at least daily at 3100 locations. These data are used to prepare forecasts of river stage (and possibly discharge) at 2500 locations. Conceptual hydrologic models are now used at less than 10 percent of these forecast points.

Although the actual forecasts are made by professionals, not by computers, the computer is an essential tool in generating forecast information. A new operational forecast computer program currently is being developed under contract. This will be a disk-oriented system incorporating all of the NWSRFS hydrologic models and will be used from remote terminals by our RFC's. It will reside at the NOAA computer center in Suitland, Md. NOAA has 3 IBM 360/195 computers and these are used by NWS's National Meteorological Center (NMC) to operate its atmospheric simulation and forecast models and by the National Environmental Satellite Service (NESS) to operate two Geostationary Orbit Environmental Satellites (GOES). Additional current hydrologic and meteorological data from NWS and NESS operations are available or potentially available in various data files to our RFC's through this new operational forecast program.

The general configuration of our new operational program appears in Figure 1. Forecasters enter data as they become available from cards into time series files through a time series input routine. When a forecast is to be made, a preprocessing routine checks available data, estimates missing values, converts stages to discharges and computes mean areal precipitation, temperature, and potential evaporation. Then, the forecast routine reads the new mean areal time series data, the carry-over files from the previous forecast, and the model parameter data file. The forecast routine produces river forecasts and updates the carry-over files.

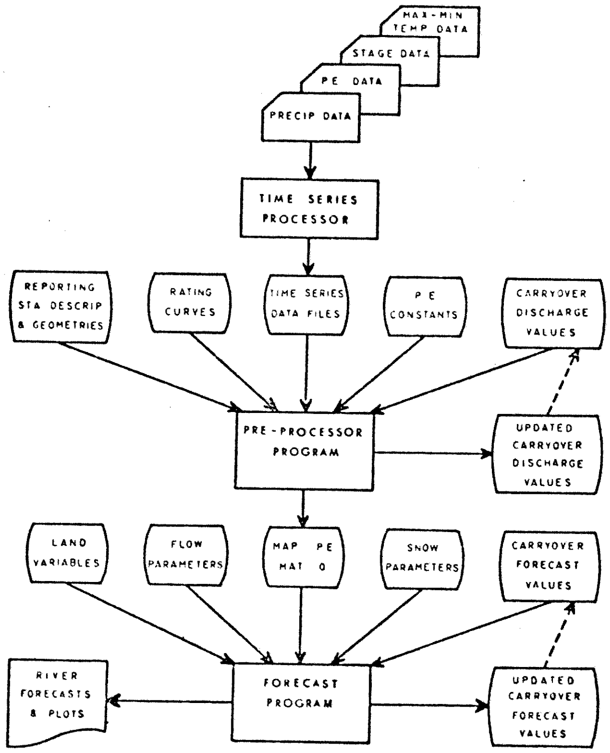

Figure 1. General Configuration of the NWS Operational Forecast Program

When new forecast points are added, model parameter values must be entered in the parameter data files and initial state variables must be entered in the carry-over files. The main problem, however, is to estimate the model parameters by analysis of historical data.

Parameter Estimation

To reduce the manpower costs of extending NWSRFS to the entire U.S. it would be nice to completely automate the parameter estimation process. However, it seems essential in mathematical optimization of parameters to start with good initial values and to constrain the domain of variation to avoid unrealistic estimates. This means some method other than automatic optimization is needed to analyze available information to find good initial values.

Our present approach is first to analyze historical precipitation and streamflow data to make initial estimates.[10] These are then used to simulate the system and results are analyzed to find possible adjustments. Finally, a pattern search[8] automatic optimization is used to "tune" the parameter estimates.

The most difficult part of our estimation procedure is to know how to make manual adjustments. Not only must one understand physically the dynamics of the natural process, but one must also understand mathematically the dynamics of the model of the process. There seems to be extremely strong tendencies for most professionals to rely only on their understanding of the physical process. We tend to assume how parameters should change rather than deduce this from our knowledge of the mathematics.

Historical Data Processing

Before parameter estimates can be made, historical data must be organized. We begin with a library of about 500 data tapes containing 4 different types of hydrometeorological data. We hope to add SCS snow course data in the near future to aid parameter estimation for our snow model. We also hope to add some USGS bi-hourly stage or discharge data. Data tapes are immediately available to our RFC's and we have programs to inventory individual tapes. We also have programs to strip selected time series and enter these into permanently mounted disk data files for future analysis. These disk files are part of our NWSRFS data file system. All of our data analysis and parameter estimation programs read and write time series using these files.

The initial version of NWSRFS was tape-oriented. All time series data, both measured and computed, were processed with magnetic tapes. This was extremely cumbersome because many intermediate tapes were required in preparation for model calibration. The direct access disk files in our current version greatly simplified our data handling problems.

Figure 2 illustrates the data processing options available to our RFC's to estimate parameters in our models. The inventory programs and preliminary processing programs strip data from tape to disk. The program MAP is used to convert raw precipitation data at hourly and daily stations into 6-hour mean areal values. Consistency checks are made via double mass plots of one station vs. any combination of other stations. Adjustments can be made in inconsistent data and missing data are estimated. Programs MAT and MAPE perform similar functions to produce mean areal temperature and potential evaporation data. Our manual calibration program, MCP, is used to simulate historical events using given parameter estimates. Our automatic optimization program uses direct search to find better parameter estimates.

Forecast Updating

Updating is needed in river forecasting because computed river stages up to the present time do not agree exactly with observed stages. Differences are due to errors in estimation of mean areal precipitation (our average precipitation gage density is only one gage per 450 square miles) and to modeling errors. In general improved forecasts can be made if

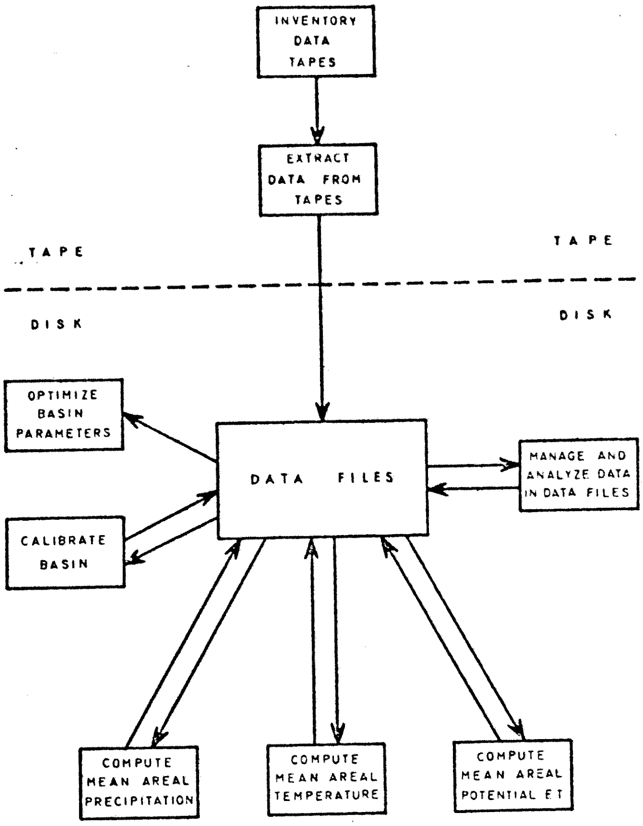

Figure 2. Data Processing for Parameter Estimation in NWSRFS

differences between observed and computed stages are used to adjust forecast stages.

This can be done in several ways. One is to "blend" computed and observed stages directly by adding a proportion of the latest difference to the forecast. This proportion would decrease to zero into the future and the computed forecast would eventually prevail. A physically more attractive approach would be to adjust precipitation input data or unit hydrograph ordinates until observed and computed values agree within acceptable limits. Such adjustment procedures are now being studied by our Hydrologic Research Laboratory.

Mathematically, this updating problem arises whenever observations can be made of computed state variables. For example, we can observe snow water equivalent, extent of snow cover, soil moisture content, and ground water levels. Each is related in some way to model state variables. Unfortunately there is no general and practical way to use these additional data as input to conventional deterministic models. Perhaps a theoretical or conceptual framework can be derived from the Kalman filter in estimation theory. But this remains a difficult area of hydrologic research not only in river forecasting but wherever measurements of some output state variables are to be used to improve the estimates of other state variables.

POTENTIAL INTEREST TO EPA

Water is an important vehicle for transporting pollutants from point and non-point sources in the environment. Information on the current and forecast states of motion of water throughout the United States are continuously available in NWS data files.

Streamflow Routing

Potentially the streamflow routing models in NWSRFS could be of particular interest to EPA. We use several types of routing models ranging from unit hydrographs and time delay histograms to dynamic routing models based on the St. Venant partial differential equations for unsteady flow in open channels.

Unit hydrographs and time delay histograms are used currently to route runoff in headwater basins and local inflows to a downstream forecast point. Most widely used to route flow in streams and rivers is a "variable lag and K" method of accounting for the attenuation and delay of flood waves moving downstream. We currently are investigating possible use of Kinematic Wave and Diffustion Wave models in addition to these other models.

We have spent the last few years developing a dynamic routing model that would be computationally efficient and sufficiently accurate for operational forecasting.[4,5] We have a project underway to apply this model to the Mississippi and Ohio Rivers, including their junction.

Pollutant Transport Models

The potential exists for NWS or EPA to operate convection, dispersion, or other water quality models in conjunction with NWS models for such purposes as to forecast the fate of pollutants suddenly released into the environment, to aid in estimating the quantities of pollutants present (as opposed to concentrations), to forecast the day to day pollutant transport properties of selected streams, or to forecast quality changes in reservoirs.

ACKNOWLEDGMENTS

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