ADVANTAGES OF CONCEPTUAL MODELS FOR NORTHERN RESEARCH BASINS STUDIES

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SUMMARY

The use of hydrological models has greatly increased the understanding of hydrological processes operating in northern research basins. How well the models represent the "true" natural conditions determines the usefulness of the results. Examples comparing the usefulness of conceptual modeling with "black box" fitting are shown.

INTRODUCTION

The National Weather Service River Forecast System (NWSRFS) is a set of conceptual techniques and computer programs used to produce river forecasts in the United States (Curtis and Smith, 1976). Included are programs to manage the large volumes of data (Peck, et al., 1977) associated with a national forecasting system and programs to perform the hydrologic and hydraulic computations necessary to forecast river system response. The NWSRFS models include: land phase, snow accumulation and

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ablation, reservoir operation, extended streamflow prediction, river routing, dynamic wave routing, and dam-failure flood forecasting. The soil moisture accounting model used to simulate the movement of water through the soil profile and the snow accumulation and ablation model used to describe the buildup and subsequent melt of the snowpack are central to the forecasting system. These models are primarily driven by precipitation and temperature data. A series of computer routines is used to calculate mean areal precipitation and mean areal temperature from point observations.

NWSRFS can provide accurate and timely hydrologic information to users with interests in flood forecasts, irrigation, navigation, power, reservoir operation, recreation, or water supply forecasts. In the western United States 80 percent of the water supply comes from the winter snowpack; consequently, accurate and timely water supply forecasts are useful when seasonal water supply allocations are made.

The NWSRFS can be used as a research tool in test basins to better understand the terrestrial physical processes which contribute to stream discharge. This paper discusses calibration approaches used with the conceptual model and a technique to incorporate additional data into the model after the initial calibration.

A primary purpose of this paper is to demonstrate the importance of proper model calibration to the usefulness of the model, especially for research studies. Calibration accomplished only by optimization techniques without adequately accounting for hydrological relationships may result in a hydrologically unreasonable set of parameters for conditions other than those of the calibration period. The use of inaccurate or biased input data (precipitation or temperature) may also result in a set of parameters which fit the calibration data period reasonably well but are hydrologically unrealistic.

CALIBRATION

Catchment Model. The soil moisture accounting program of the catchment model developed in the National Weather Service (NWS) Sacramento, California River Forecast Center by Burnash, et al. (1973) is presently used in the NWSRFS. Figure 1 is a flow diagram illustrating the model and depicting the 16 parameters associated with the soil mosture accounting portion of the catchment model. A brief definition of the parameters (shown in light italics on Figure 1) are given in the Appendix.

A basic characteristic of a conceptual model is that the parameters should have physical meaning when the model is properly calibrated to a basin (Peck, 1976). In deriving parameters for the model good first approximations for some of the parameters may be inferred from streamflow records, precipitation records and basin characteristics. For the NWSRFS catchment model illustrated in Figure 1 the parameters (LZFPM, LZPK, LZFSM, LZSK and PCTIM) can be readily computed from observed hydrograph and precipitation. Parameters LZTWM, UZTWM, UZK and SSOUT can be approximated fairly well for some basins and roughly estimated for others. Relative values can be obtained for UZFWM and PFREE from hydrometeorology data and for SARVA from maps of water area of a basin.

First estimates for ZPERC and REXP (relating to percolation) can be obtained from a general knowledge of the soil, vegetation and other basin characteristics or from values from similar basins that have previously been simulated. Nominal starting values are generally used for the three remaining parameters SIDE, ADIMP and RESERV.

When a trained hydrologist makes maximum use of the hydrometeorological relationships to obtain first estimates of parameter values the work involved in obtaining a satisfactory set of parameters is greatly reduced. In addition, the value of the calibration for use under conditions not experienced in the period of record used for calibration is considered to be much better.

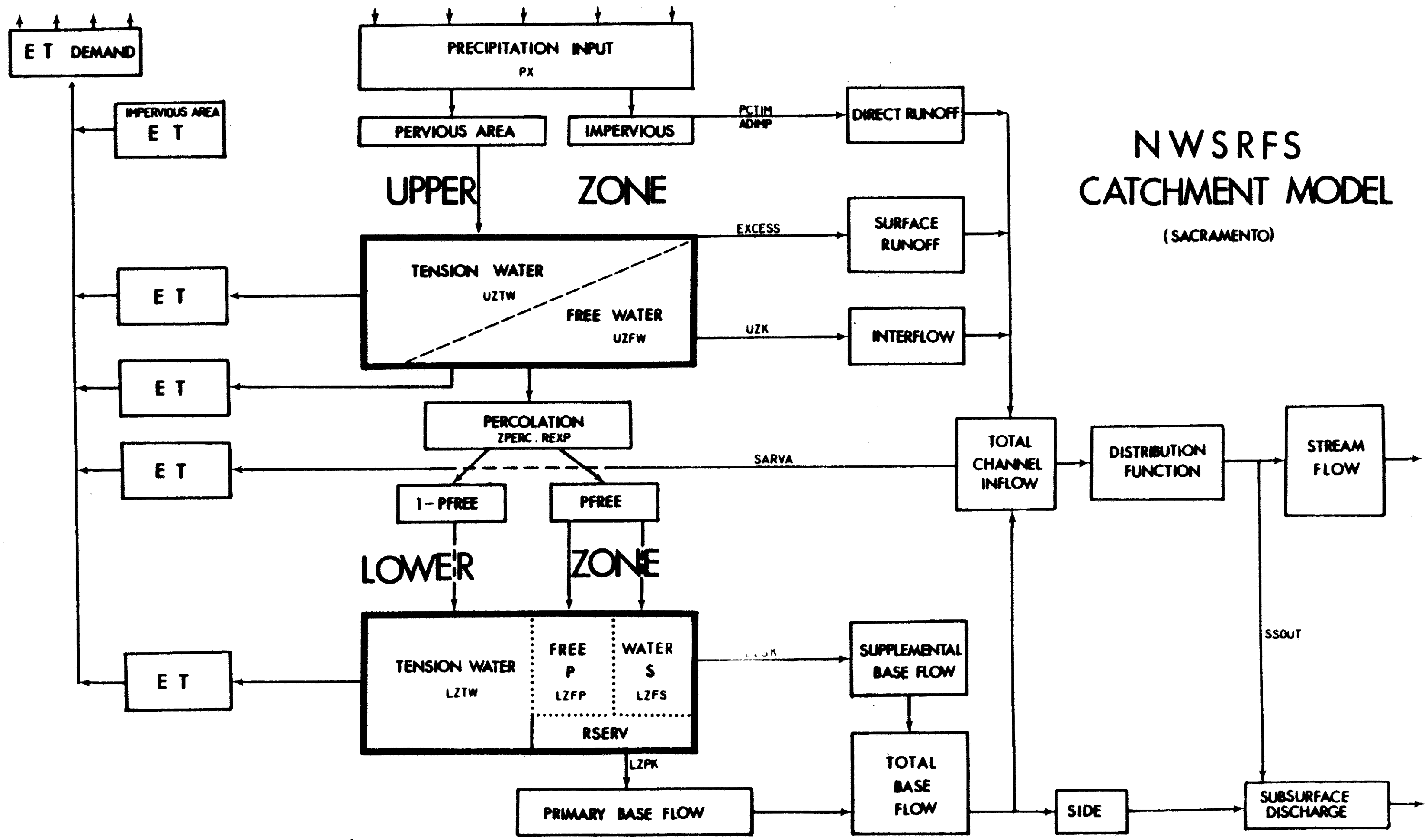

Figure 1. -- NWSRFS catchment model
(Sacramento)

Experience in fitting the NWSRFS catchment model for operational forecasting indicates that the procedure should be one involving both manual and automatic fitting. Steps in calibrating a basin are: derive first parameter estimates from hydrological considerations; second, manually test and adjust the parameters using one or more criteria of fit between simulated and observed streamflow; and third, use an automatic optimizer program to fit a few selected parameters with constraints on the range of values based on information gained from the first two steps.

Snow Accumulation and Ablation Model. The snow accumulation and ablation model described by Anderson (1973) is currently used in the NWSRFS. It has been operationally tested in most of the major snow areas of the United States and in various other countries.

The basin snow model was presented at the Edefors, Sweden meeting in 1975, and its operational use and improved calibration techniques at the Fairbanks, Alaska meeting (Peck and Anderson, 1977). In general, the model uses temperature as the sole index to energy exchange across the snow-air interface. The snow model parameters have been found to be related to climatic and physiograhic characteristics and reasonable initial parameter values can be obtained from a knowledge of typical conditions over the watershed.

In snow areas it is necessary to calibrate the snow and catchment models together. Techniques are available for evaluating the goodness of fit for most of the snow model parameters with observed snow course data prior to coupling the two models together for final calibration with observed streamflow.

CONCEPTUAL APPROACH TO CALIBRATION

Since the model is considered to be conceptual or physically based, it is necessary to accomplish all portions of the calibration procedure as close to "true" basin conditions as possible. The NWSRFS is a bulk input model where areal mean values for precipitation and temperature are used rather than distributed or point values. In many basins, there are large areas of forested versus non-forested areas. For areas having a large range in elevation, an upper portion of the basin may during the winter months have a snow cover while the lower portion of the basin is essentially snow free or has much less snow cover.

In such cases the basin is divided into two or more subareas and sets of parameters are determined for each subarea. This is a step towards distributed modeling. Operationally the model is used with 6-hour input data. For research studies on a small watershed, the period could be reduced to a 1-hour period or less depending on availability of data.

Input Data for Calibration. Mean areal precipitation (MAP) and mean areal temperature (MAT) values are developed using all of the available data for each 6-hour period. Especially careful attention is given in mountainous areas to using all available information (including detailed seasonal isohyetal maps) to insure that computed MAP values for each subarea are realistic. It is very important to have the MAP values as representative of the "true" precipitation as possible if the modeling process is to remain conceptual.

Sample Calibrations

Three basins in the western United States have been used for this study: (1) Sevier River at Hatch in south-central Utah, (2) Dolores River at Dolores in south-western Colorado, and (3) the Eagle River at Gypsum in central Colorado. Each basin was divided into an upper and lower subarea. The mean elevation of the upper subareas were: Sevier River (2941 m), Dolores River (3335 m) and the Eagle River (2600 m). A large percentage of the streamflow in each basin occurs during the spring and early summer from snowmelt.

The quality of precipitation and temperature data vary from one basin to another. Consequently, the ability of the conceptual model to simulate stream discharge also varies from basin to basin. Results from the three research watersheds indicate the ability of the NWSRFS to simulate stream discharge using only precipitation and temperature data.

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, or (2) an early or late simulation of significant melt of the snowpack which results in discharge timing errors, or (3) both volume and timing errors.

Use of Additional Data

Precipitation data are not the only source of information as to the amount of precipitation that falls on a basin. Observed point measurements of precipitation may or may not be representative of the "true" average precipitation that fell over the basin. For mountainous areas the average for the basin is computed based on the normal relation (monthly, seasonal or annual) between each station and the basin average determined from isohyetal maps or other data. However, the actual relation may deviate significantly for a storm, a season or even for several seasons (Peck, 1964). Under these conditions the volume of the simulated streamflow for a season can vary considerably from the observed.

UPDATE PROCEDURE

Carroll (1978) describes an update procedure to incorporate snow course data into the NWSRFS.

The NWSRFS snow accumulation and ablation model computes continuously a simulated water equivalent of the snow cover. This is a value representing the average water equivalent for a subarea at any particular time. The update procedure weights the simulated water equivalent values and observed snow course data for specific dates and computes a new estimated water equivalent value. When the simulated water equivalents are replaced with these estimated values the resulting simulated runoff will on the average be better correlated with the observed runoff. The update procedure is primarily intended to reduce the monthly volume errors in simulated streamflow.

The update procedure is particularly of value when the precipitation data does not represent well the snowfall at higher elevations. Thus for basins where precipitation stations are primarily located only at elevations lower than the snow courses, considerable improvement is expected since the snow course data may have significant informational content not represented by the precipitation data. In some areas of the western United States large deviations from normal precipitation patterns may frequently occur (Peck, 1964). For such basins in any particular year the use of normal precipitation patterns to determine the average precipitation for the basin may be very misleading. In these unusual distribution cases the snow course data may also add considerable information not represented by precipitation data alone.

The update procedure produces streamflow outflow in the same manner as the original NWSRFS would. Since the procedure is primarily for use in snow areas where the principal interest is in volume forecast or water supply outlooks, the criterion to evaluate the results is expressed as

$$c_u = \left| \sum_{i=j}^{k} (sim_i - obs_i) \right| - \left| \sum_{i=j}^{k} (simu_i - obs_i) \right|$$

where

sim = simulated monthly discharge before update (mm)

simu = simulated monthly discharge after update (mm)

obs = observed monthly discharge (mm)

j = first month

k = last month.

In this way, it is possible to evaluate the update results for any duration during the period of record. Typically, criteria are calculated for each water year, C_t, and for a subset based on data from April to September, C_s. Peak snow accumulation generally occurs between mid-March and May 1 in the high elevations of the western U.S.; consequently, the most important water supply forecast are those made when the April 1 snow course data is available. It is possible to update the simulated water equivalent based on the February, March, and April 1 snow course data and use the criterion based on the April to September discharge data to evaluate the improvement generated by the update procedure for the water supply forecast period.

UPDATE APPLICATION

The snow course update technique was applied to the three selected basins and to a second calibration of the Sevier River basin.

Dolores River. The update procedure was tested on the Dolores River at Dolores (1305 km^2) in south-western Colorado from 1956 to 1973. The upper subarea is 522 km^2 with a mean elevation of 3335 m while the lower subarea is 783 km^2 with a mean elevation of 2650 m. Both subareas are updated using data through the April 1 observation from eleven snow courses.

The update procedure reduces the total yearly simulation error for thirteen of the seventeen years. For the calibration period from 1956 to 1973 the mean subset error for the April to September streamflow volume is reduced by 40.0 percent from 21.0 to 12.6 mm.

The snow survey courses for the Dolores Basin are at much higher elevations than the precipitation stations. Thus the snow course data should introduce much additional information on precipitation at higher elevations. The significant reduction of 40 percent as reflected by the criterion is undoubtedly related to the poor representation of the precipitation data.

Eagle River. The update procedure was tested on the larger Eagle River at Gypsum (2445 km^2) in central Colorado for 1949 to 1972. The Eagle basin is divided into an upper (1222 km^2) and a lower subarea. Only the upper subarea is updated using data from six snow courses through the April 1 observation.

For the calibration period of 1949 to 1972 the mean subset error for the April to September streamflow volume is reduced by 18.4 percent 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 south-eastern section of the basin. Consequently, only limited information is added by the use of the snow course data and the improvement in the simulated volume is less than experienced for the Dolores River.

Sevier River. The update procedure was tested using two different model calibrations for the Sevier River basin (881 km^2). The first calibration (to be referred to as the conceptual calibration) uses seasonal isohyetal analyses (October-April and May-September) to assign precipitation to two physically identifiable subareas as was done for the Dolores and Eagle River basins. The upper area represents the primary region of snow accumulation and generates 80 to 90 percent of the runoff; consequently, only the simulated water equivalent of the upper area is updated using the snow course data. For the calibration period of 1952 to 1971 the mean subset error for the conceptual calibraton for the April to September streamflow volume is reduced by 27.3 percent from 9.88 to 7.19 mm.

Some of the snow survey courses in the Sevier River Basin are collocated with or near to precipitation sites. However, several are at higher elevations and do provide better coverage of the basin. The 27 percent reduction in the forecast error on the coverage for the April-September runoff is considered quite significant for the many uses of the seasonal water supply forecasts.

Sevier River (forced fitting). The update procedure was also applied to a second calibration for the Sevier Basin. The primary difference was in the input data for precipitation. The basin was subdivided into two subareas with the average mean areal precipitation for the two subareas approximately equal to the mean for the entire basin. However, the precipitation for the lower elevation basin was only slightly lower than that assigned for the upper basin. In the case of the conceptual calibration, mean values for seasonal isohyetal maps were used and the lower subarea precipitation was only 60 percent of the higher subarea values. Since both areas were assigned nearly equal precipitation it was deemed necessary to update both subareas. The average error and correlation coefficient for simulated versus observed daily flow values was only slightly lower than found for the conceptual calibration (0.95 compared with 0.96). The parameter fitting is assumed to have been forced since, in contrast to the conceptual calibration, the parameters had to vary from "true" values to accommodate the bias in the precipitation input. Thus in a sense the fitting can be referred to as a "black box" calibration.

The mean subset error for the April-September streamflow volume was reduced by only 6.2 percent from 9.57 to 8.98 mm for the forced fitting calibration.

DISCUSSION

The improvement in the simulated streamflow gained by updating the three NWSRFS calibrations with snow course data is considered very significant. Although there are not sufficient cases to prove the significance, the results tend to justify the original thought that if the calibration was reasonably conceptual the incorporation of more information could improve the calibration. Conversely only little improvement could be gained for the forced-fit (or black box) calibration.

From the authors' experience the use of a good conceptual model does not insure a good fit unless sound hydrological principles are employed in optimizing the model parameters.

A great deal is dependent upon the "calibrator." The person calibrating should have a good knowledge of the hydrometeorological aspects of the basin, have the ability to understand the real hydrology, and that revealed by the model, as well as the ability to recognize the limitations of manual and automatic optimization procedures for calibrating. Conceptual models when properly calibrated do offer an aid to researchers for various study purposes. The indication from this brief analysis is that black box models, or black box fitting of conceptual models, would not provide nearly the value as from properly calibrated conceptual models. Calibrations of many additional basins are planned for use of the conceptual models in the snow areas of the western United States. Comparisons for additional basins between conceptual calibrations and black box calibrations will be accomplished to further document the findings of this study.

APPENDIX

SOIL MOISTURE PARAMETERS

The parameters for the catchment model dealing with various phases of the soil moisture accounting are:

Direct runoff

- PCTIM   Fraction of impervious basin contiguous with stream channels.
- ADIMP   That fraction of the basin which becomes impervious as all tension water requirements are met.
- SARVA   Fraction of basin covered by streams, lakes and riparian vegetation.

Upper soil moisture zone

- UZTWM   Maximum capacity upper zone tension water in mm.
- USFWM   Maximum capacity of upper zone free water in mm.
- UZK   Lateral drainage rate of upper zone free water expressed as a fraction of contents per day.

Percolation

- ZPERC   A factor used to define the proportional increase in percolation from saturated to dry lower zone soil moisture conditions. This parameter indicates, when used with other parameters, the maximum percolation rate possible when upper zone storages are full and the lower zone soil moisture is 100% deficient.
- REXP   An exponent determining the rate of change of the percolation rate as the lower zone deficiency ratio varies from 1 to 0 (1 = completely dry; 0 = lower zone storage completely full).

APPENDIX (continued)

Lower zone

LZTWM	Maximum capacity of lower zone tension water in mm.
LZFSM	Maximum capacity of lower zone supplemental free water storage in mm.
LZSK	Lateral drainage rate of lower zone supplemental free water expressed as a fraction of contents per day.
LZFPM	Maximum capacity of lower zone primary free water storage in mm.
LZPK	Lateral drainage rate of lower zone primary free water expressed as a fraction of contents per day.
PFREE	The percentage of percolation water which directly enters the lower zone free water without a prior claim by lower zone tension water.
RSERV	Fraction of lower zone free water not available for transpiration purposes (incapable of resupplying lower zone tension water).
SIDE	The ratio of unobserved to observed baseflow.
SSOUT	A fixed rate of discharge lost from the total channel flow.

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