Chapter 1 – Introduction and Background

Introduction

Continuous, conceptual hydrologic models were first developed in the early 1960's with the advent of digital computer technology. Such models have been used for many applications over the succeeding years. One of the main applications is for river forecasting. In order to get the maximum benefits from the use of conceptual models, especially when used for river forecasting applications, the models must be properly calibrated at each point on the river system where a forecast is to be generated. This manual describes the steps and procedures needed to calibrate conceptual models for use in river forecasting and issues involved in the implementation of the calibration results into operational use. Many aspects of this manual are applicable to any conceptual model or any river forecasting system, however, the manual is specifically focused on the models in the National Weather Service River Forecast System (NWSRFS) and the use of these models for river forecasting in the United States.

NWSRFS was initially developed in the 1970's. In the mid 1980's the system was completely redesigned. NWSRFS contains programs for the processing of historical data and the calibration of models using these data, as well as programs for operational forecasting. In recent years graphical, interactive interfaces have been developed for many of the programs. The portion of NWSRFS where the hydrologic models reside is referred to as the forecast component. This component is very modular. Models and other techniques needed to produce simulations and forecasts are coded as separate modules called operations. The operations can be strung together in whatever sequence is appropriate for a given application. This sequential group of operations is referred to as an operations table. Information is currently passed from one operation to another in the form of time series. In a future redesign, operations will be able to process and communicate with each other via gridded fields.

There are several types of river forecasts. There are specific forecasts of river stage or discharge for time periods of hours or days into the future. There are extended forecasts, generally of a probabilistic nature, for weeks or months into the future. There are also area wide forecasts, generally involving very fast responding, i.e. flash flood, events, that warn of the possibility of flooding over a specific city, county, or other entity. In the National Weather Service (NWS), short term (hours or days into the future) forecasts of river conditions at many specific locations are produced at 13 River Forecast Centers (RFCs), each with areas of responsibility encompassing major drainage basins. The RFCs are also increasingly more involved with producing extended probabilistic predictions of river conditions using ensemble techniques. Ensemble techniques are also being applied to short term forecasts in order to generate probability statements for this type of prediction. The public issuance of river forecasts within the NWS is performed by the local Weather Forecast Office (WFO). The WFOs also issue site specific and area wide flash flood watches and warnings using information supplied by the RFCs. NWSRFS is the river forecast system for use by the RFCs, thus it needs to be able to generate short term river and flood forecasts, ensemble streamflow predictions (ESP), and initial state and guidance information needed by the WFOs to produce flash flood forecasts. In

NWSRFS different programs are provided for calibration and historical simulation, short term deterministic forecasts and model adjustments, and ESP, however, all the programs use the exact same models and techniques.

Even though NWSRFS contains a number of rainfall-runoff models, this manual will concentrate on the calibration of the Sacramento Soil Moisture Model (SAC-SMA) [*Burnash et al.*, 1973]. This is the rainfall-runoff model used by almost all of the RFCs. The Sacramento Model and the NWSRFS snow accumulation and ablation model, referred to as SNOW-17 [*Anderson*, 1973], are the primary models referred to in this manual though various channel response and routing models, as well as other NWSRFS operations, are needed to generate streamflow forecasts and thus will be mentioned.

The proper calibration and correct operational implementation and use of a model is critical in obtaining the maximum benefits of river forecasting. The primary benefits of a good calibration and proper operational application of a model are:

- *Short term river forecasts should more closely track observations, thus improving forecast accuracy and lead time and requiring fewer adjustments by the forecaster.*

- *Models can be used to generate reliable extended probabilistic predictions.*

When models are not well calibrated and/or not defined or used properly in an operational mode, the simulated results will quickly deviate from observed values under most circumstances. This reduces the accuracy and lead time of short term forecasts and requires that the forecasts be updated much more frequently. In addition, an improperly calibrated model cannot be used to generate predictions further out into the future, i.e. weeks and months, if it can't reproduce what has happened in the past. For many hydrologic models, values of model parameters or coefficients can be assigned *a priori* based on soils information or other physiographic factors or based on values for a similar nearby watershed. These parameter sets can produce adequate results for some applications, but for river forecasting they will not provide the level of accuracy and reliability that a well calibrated and properly applied model can produce. These *a priori* methods of determining parameter values are helpful in getting initial parameter estimates, but significant improvement is usually possible by continuing the calibration process.

For use in river forecasting conceptual models must be properly calibrated and applied over large areas. While there are many references in the literature to calibration techniques, in almost all cases the emphasis is on the calibration of models to a single headwater drainage area. When applying models to all the river basins in an RFC area of responsibility, the procedures used must not only produce a quality simulation at each point that is modeled, but must be efficient and generate consistent data input and model parameters over the entire region. Efficient procedures are required so that the initial calibration and subsequent updates and recalibrations can be accomplished within a reasonable time period and without an unrealistic amount of resources. Consistent results are necessary so the spatial variability of the input data and model parameters make physical sense and to make it easier for forecasters to make realistic operational modifications to data and model state variables as they proceed down a river system. In order to produce high quality simulation results that are spatially consistent in an efficient manner requires a regional approach to calibration. That is the type of approach described in this manual. Data are processed for entire river basins involving many forecast points at one time utilizing regional analyses of spatial and temporal variations of the variables. The determination of model parameters is accomplished by first calibrating the headwater area with the best data and least complications and then using these parameters, plus information on the variability of hydrologic conditions over the river basin, as a basis for determining appropriate parameters for the other drainages.

This manual will discuss the steps necessary to properly calibrate and operationally implement and use conceptual models for river forecasting. It will describe the reasoning and procedures behind each step in the process. The manual will focus on the data needed for calibration, methods to analyze the data, techniques for calibrating models in an efficient and consistent manner, and suggestions for the operational implementation of calibration results. References will be made to some of the main NWSRFS historical data processing and model calibration programs, but the manual doesn't contain program input summaries. The manual will not describe the algorithms of individual models and operations, but will concentrate on how to use the models. The manual will also not cover the details of software or web based tools to access historical data and physiographic information. The user should refer to the NWSRFS User's Manual to get information on specific program input and descriptions of models and operations and to individual user guides for other relevant software (the NWSRFS User's Manual can be accessed via www.nws.noaa.gov/oh/hrl/nwsrfs/users_manual/htm/formats.htm - some of the other user guides can be found at www.nws.noaa.gov/oh/hrl/general/indexdoc.htm). This manual is concerned with the concepts behind the calibration process rather than details concerning the software and data sets. The manual attempts to provide the user with the steps and procedures to follow to produce an efficient, consistent, and reliable application of the models to a large area with many forecast points. Opinions expressed in the manual are those of the author.

Conceptual Models and Methods of Application

A conceptual hydrologic model is a model that represents the major physical processes of the portion of the hydrologic cycle it is intended to mimic, however, these processes are described in a simplified form. Most conceptual models, including all those in this manual, are applied continuously and not on an event basis. Conceptual models can be applied on a lumped or distributed basis. A distributed application generally involves breaking a watershed down into many small subareas either based on a grid or physical characteristics. This manual covers the lumped application of such models which includes cases where a watershed is divided into a few subareas based on elevation, travel time, or significant difference in other physiographic factors.

When models are applied on a lumped basis, the input variables are areal averages. If conditions vary considerably over the watershed, the drainage area may be subdivided into a few zones to account for significant variations in precipitation, temperature, snow cover, melt rates, etc. or significant differences in watershed properties. In that case areal average values of the input variables are used for each zone. This is a common approach in mountainous regions. For the lumped application of a conceptual model to produce reasonably reliable results for river forecasting, several factors are important:

- Significant events must have runoff contributions from most of the area. Subdivision of the watershed can improve the results if there are sufficient data to define the spatial variability of the input.

- The amount of runoff must be reasonably large (as a rough guide annual runoff should exceed about 5 inches for marginal results and 10 inches for generally satisfactory results).

- Significant runoff from snow, though adding to the complexity of forecasting, will improve the chances of acceptable results in regions with low runoff amounts since the accumulated snow cover smooths out the spatial and temporal variability of individual precipitation events and makes it more likely that most of the watershed contributes runoff.

These factors are based on experience with applying conceptual models to a wide variety of watersheds under different climatic conditions throughout the United States. Based on these factors, Figure 1-1 gives an indication of how the applicability of lumped, conceptual models varies across the lower 48 states. This figure indicates that for most of the eastern portion of the country and along the west coast there are frequent, large scale storms that produce enough runoff so that simulation results using a lumped application of a conceptual model are generally satisfactory. Also in the high mountain areas of the west satisfactory results are generally attainable due to the significant snow cover that occurs. In the plains region and the lower elevation portions of the intermountain west storms are generally infrequent and localized, resulting in unsatisfactory results when trying to apply a model on a lumped basis. In-between these areas a transition occurs where generally the results from using a lumped application of a model are only marginally satisfactory. This assessment is based on having areal precipitation estimates based on multiple gages.

In recent years gridded estimates of precipitation have become available allowing for the potential to apply hydrologic models on a distributed or at least pseudo distributed basis. Prior to this, distributed applications of models were only possible in areas with very dense gage networks which are very rare under operational forecasting situations. In the NWS, gridded estimates of precipitation are generated on a hourly basis by combining radar derived precipitation estimates with precipitation gage data and other variables [*Seo et al.*, 2000]. The merged radar-gage estimates of precipitation are generated on a 4 km grid. The quality of these estimates varies from generally good results during summer type storms to less than adequate estimates under winter storm conditions, especially snowfall events, and in mountainous areas. Early studies also showed that a significant bias (under estimation) generally occurred when comparing radar estimates to gage catch over an extended period. New processing methods have been developed and are being implemented to minimize this bias.

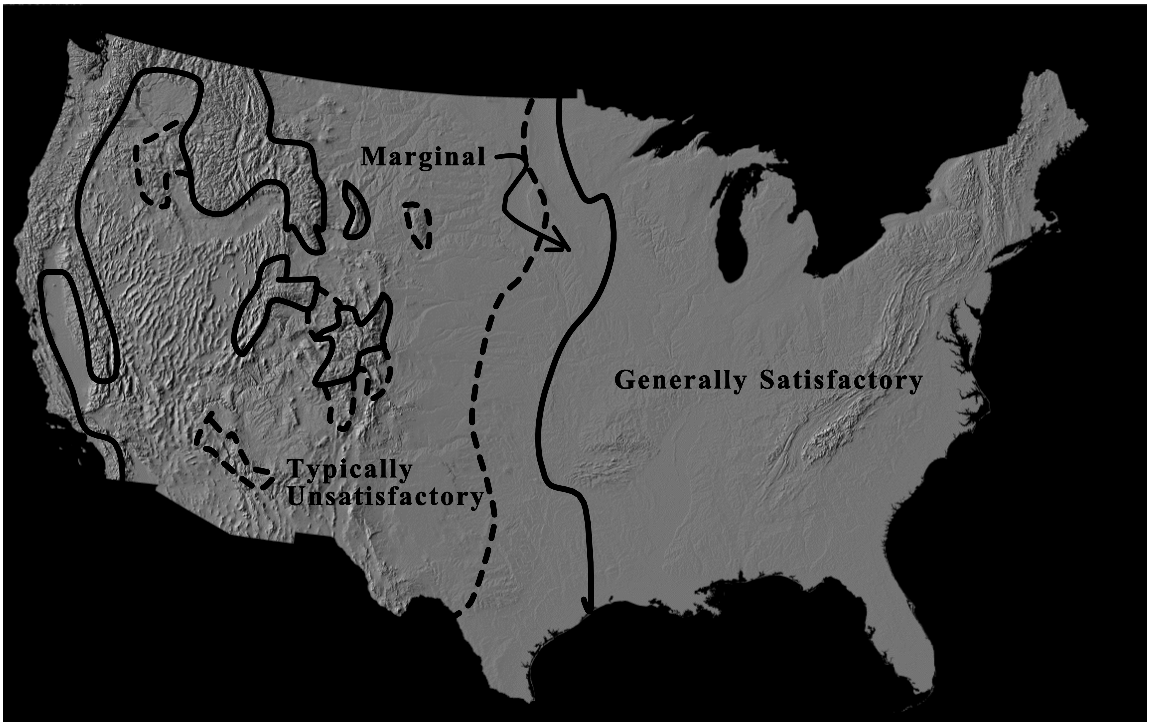

Figure 1-1. Applicability of lumped, conceptual rainfall-runoff models

It is very important to minimize any bias between the input data being used to calibrate a model and the estimates of the input variables being used operationally. Most hydrologic models are very sensitive to data bias. If the data used operationally are biased compared to the calibration input, the benefits of calibration can be negated (discussed in detail in chapter 8). Because of the relatively short period that gridded precipitation estimates have been available and because of periodic changes to the methods used to process the radar data and generate the precipitation estimates, there is generally not a sufficient length of record of these data to fully calibrate a model. Thus, historical gage data must be used to generate input data for calibration. The spatial and temporal density of the climatological networks are such that only lumped applications of the models are possible with the historical data. Also it is normally not possible to obtain reasonably reliable estimates of input variables for time periods less than about 6 hours due to the sparseness of hourly historical data. Thus, besides possible bias in input data values between calibration and gridded operational estimates, there are also issues involving how the models are affected by the different spatial and temporal scales.

The NWS has had a major research effort for a number of years focused on how to best apply models in a distributed mode for operational river forecasting [*Smith et al.*, 1999]. This research has focused on quantifying problems with the radar-gage estimates of precipitation and trying to determine under what types of hydrologic conditions distributed applications of the models will produce significant improvements in forecast accuracy. The research is also trying to determine how the results are affected by the method and degree of subdividing the watershed, how to determine distributed estimates of model parameters, how to operationally adjust state variables across multiple subareas when simulated and observed conditions differ, and looking at alternative modeling approaches. Early results have indicated that in some areas there is little difference in simulation accuracy between those obtained with lumped and distributed applications of a conceptual model while in other areas there can be significant improvements. These results seem to indicate that the more variation in soils and other physiographic factors and the greater the spatial variability in the precipitation patterns, the better the chance of obtaining improved results by applying the models in a distributed mode. Also it is logical to expect more improvement in areas where the streams rapidly respond to precipitation than in regions with a more damped response.

Another factor affecting the application of hydrologic models in a distributed mode for river forecasting is the case of extended streamflow predictions. It is generally only feasible for an RFC to maintain a single operational model across their area of responsibility. The amount of effort to monitor model simulations and make operational adjustments to input variables and model states as needed, as well as all the other operational and development tasks that must be done, make it impossible to maintain separate models for short term and extended forecasts. Presently extended predictions are generated by taking the current states of the short term forecast models and applying many possible future input scenarios, typically involving 20 to 50 years of data, to generate an ensemble of likely streamflow traces. The input scenarios are generated by attempting to modifying historical data sequences for short term and extended meteorological predictions. Historical data are used because of the difficultly of statistically generating input traces that maintain the proper relationship between different data types, e.g. precipitation and temperature, and the correct spatial correlations over a large region. The input traces currently used for extended predictions are the same as are generated and used for model calibration from climatological networks. Thus, the problem to be resolved for those rivers where extended predictions are needed and a distributed application of the models would be beneficial, is how to generate short term forecasts and maintain model states in a distributed mode and yet make extended predictions efficiently using lumped historical data.

Taking all of these factors into account seems to indicate that the greatest potential for distributed applications of models to improve river forecasts is in the typically unsatisfactory and marginally satisfactory regions from Fig. 1. There is also the potential for improvements in the portions of the generally satisfactory regions where the basins respond rapidly, especially in areas with significant spatial variability in rainfall patterns. However, it is also clear, given all of the data and operational problems, that the lumped application of models and their calibration using historical data will continue to be important for many years into the future in order for the NWS to meet its river forecasting responsibilities in a reliable and timely manner. Thus, the material in this manual should continue to be relevant.