Calibration of Conceptual Hydrologic Models for Use in River Forecasting

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List of Acronyms

ALERT	Automated Local Evaluation in Real Time (system and network)
API	Antecedent Precipitation Index
ARS	Agricultural Research Service
ASOS	Automated Surface Observation System
BPA	Bonneville Power Authority
CAP	Calibration Assistance Program
CSSL	Central Sierra Snow Laboratory
ESP	Ensemble Streamflow Prediction
ET	Evapotranspiration
FSL	Forecast Systems Laboratory
FWS	Free Water Surface (evaporation)
GIS	Geographical Information System
HRAP	Hydrologic Rainfall Analysis Project
HRL	Hydrologic Research Laboratory (currently Hydrology Laboratory)
ICP	Interactive Calibration Program
IDMA	Interactive Double Mass Analysis
IFLOWS	Integrated Flood Observing and Warning System
IFP	Interactive Forecast Program
MAP	Mean Areal Precipitation
MAPE	Mean Areal Potential Evaporation
MAT	Mean Areal Temperature
MPE	Multisensor Precipitation Estimator
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NHDS	NOAA Hydrologic Data System
NOHRSC	National Operational Hydrologic Remote Sensing Center
NRCS	Natural Resources Conservation Service (was SCS - Soil Conservation Service)
NWS	National Weather Service
NWSRFS	National Weather Service River Forecast System
OFS	Operational Forecast System
OPT	Automatic Optimization Program
PE	Potential Evaporation
PRISM	Precipitation Regressions on Independent Slopes Model
PXPP	Precipitation Preliminary Processing (program)
QPF	Quantitative Precipitation Forecast
RFC	River Forecast Center
SNODAS	Snow Data Assimilation System
SNOTEL	Snow Telemetry (network)
STATSGO	State Soil Geographic Data Base

List of Acronyms (continued)

TAPLOT	Temperature Plotting (program)
TVA	Tennessee Valley Authority
UCSL	Upper Columbia Snow Laboratory
USGS	United States Geological Survey
WFO	Weather Forecast Office

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.

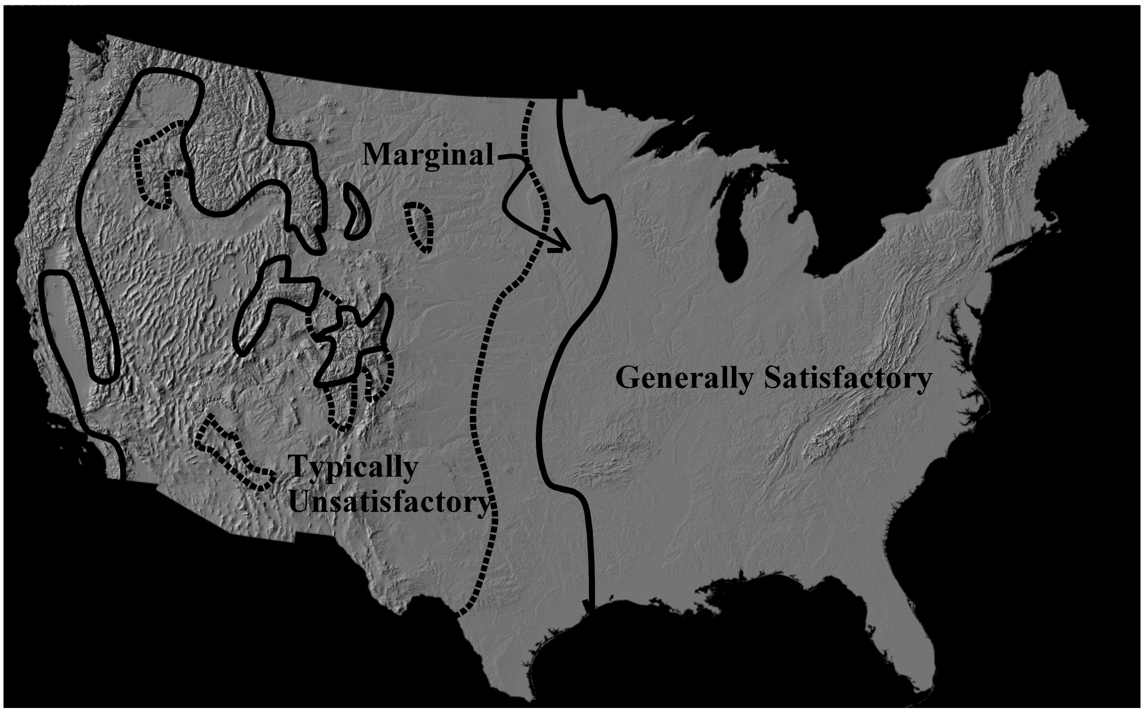


Figure 1-1. Applicability of lumped, conceptual rainfall-runoff models

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.

Chapter 2 – Calibration Overview

Introduction

The calibration of a conceptual model to a large region, such as the entire area of responsibility of a RFC, is a major undertaking. This effort must be carefully planned and monitored in order complete the process within a reasonable time frame and end up with consistent, quality results. In order to keep the overall task manageable, it is recommended that the region be broken down into individual river basins or portions of basins involving in the order of 75-200 precipitation stations, 25-100 temperature stations, and 20-50 river locations. The steps and procedures in this manual can then be applied to each river basin until the complete area is calibrated.

General Calibration Requirements

There are a number of factors that are important in order to be able to complete a large scale calibration effort in a reasonably efficient manner and end up with quality results. Some of the most important requirements are knowledge, experience, teamwork, and leadership for the people involved, computerized tools to aid in doing the work, and following proven procedures and strategies.

- Knowledge and Experience – Calibration of a conceptual model is not a skill that one becomes proficient at by merely taking a course or studying a report. True expertise in the calibration process can take years. Even after being involved with model calibration for many years, one still learns something new from almost every river basin that they work on. Thus, it is important when starting a calibration effort or when a person first begins to work on model calibration, that sufficient time be allocated to learn about the process and gain experience. Those that have gained a reasonable level of experience should be assigned to mentor those that are beginning their first calibration. Usually by the time that someone finishes their first calibration they know enough to realize that they should go back and redo what they have just done. If a person receives the proper training, the right guidance, and a reasonable period to gain some experience (in the order of 6 months), they should be able to become a productive member of a calibration team. It should also be noted that the knowledge and experience gained during calibration should pay large dividends in how well the person is able to use the models and procedures to produce operational forecasts.

- Teamwork – There are many aspects to the total model calibration and implementation process. The overall process involves having people with skills in areas such as data analysis, calibration of snow and soil moisture models, development of parameters for routing models, reservoir operations, operational procedures, and the application of geographical information systems (GIS). It is nearly impossible for one person to have the necessary expertise in all these areas, thus calibration becomes a team effort. In building a calibration team it is important to assess the skills and aptitudes of each member. Not everyone has the background and propensity to become proficient at calibrating headwater models, plus those that are good at calibrating snow and soil moisture models may not have the ability to do the best job at analyzing data or calibrating routing models. Thus, it is important to the successful completion of a major calibration effort to have people with a variety of skills involved and to make maximum use of the abilities of each team member to accomplish the final goal.

• Leadership – Even though a major calibration project requires a team effort, it is also very important that the team has the proper leadership and that the results of the project are carefully monitored and evaluated. Leadership is generally best provided by someone with experience in and a good knowledge of all aspects of the calibration process. This person must also have the necessary leadership skills to work with the other team members and be able to clearly communicate goals, progress, and resource needs to those in charge of the office and others interested in the results. The leader, possibly with the help of others in the office, should carefully review the results of each step of the process to make sure that the results meet performance standards adopted by the office concerning such factors as model selection and basin splitting and that parameter and data values are consistent with nearby watersheds and river basins.

• Computerized Tools – In order for the overall calibration process to be done in an efficient manner, computer tools must be available and used properly to perform many of the necessary tasks. These tools range from number crunching programs to process data and perform data analysis or model computations to GIS applications to display information and generate new data fields to interactive, graphic interface programs that allow the user to better understand the inner workings of models and to interact with the models and data . Without a complete set of tools, portions of the calibration process will become very labor intensive and severely affect the time required to complete the process. In addition such tools assist the user in gaining the knowledge and experience to better calibrate and operationally apply the models and procedures. Tools that exist in NWSRFS or are needed in order to efficiently do calibration in all types of situations include:

- Programs to access historical data bases, inventory the data, and convert the needed data to the proper form for subsequent processing,
- Data processing programs to analyze gage data and compute areal time series of precipitation, temperature, and evaporation,
- Programs that perform the computations for all of the operations necessary to simulate streamflow and other hydrologic variables,
- Calibration Assistance Program (CAP) to perform computations necessary to prepare the input to the data analysis and model calibration programs and to use GIS features to display and generate various data fields, and
- Interactive, graphical interface programs that allow the user to easily view results, make changes, and rerun computations for portions of the process such as model calibration and data consistency analysis.

Many of these tools exist. Others are in the process of being developed. Throughout this manual further details will be given regarding the tools needed.

• Follow Proven Procedures and Strategies – Innovation is periodically required during the calibration process, but there is much that has already been tried and learned. Many procedures and strategies have been developed, tested, and proven that can make the process efficient and more likely to end up with consistent, quality results. It is much better to follow these procedures and benefit from this experience than to try to invent new methods for doing things. If some of the procedures and strategies clearly don't work properly in a given situation, then alternative techniques can be tried. This manual tries to cover the recommended calibration procedures and strategies that have been proven effective.

Basic Steps in the Calibration Process

When calibrating hydrologic models to a river basin there are six steps that are recommended to be followed.

• Gather Information and Data -- The first step is to gather all the information and data necessary for the calibration of the river basin. This includes all available historical data, plus a determination of what real time data are available. It includes gathering maps and data sets that describe physiographic features such as topography, vegetation, and soils, as well as past analyses of the variability of quantities such as precipitation, temperature, evaporation, and snow cover. It also includes information about control structures and their effect on streamflow, plus data on diversions into or out of the basin or between watersheds within the basin and any irrigation effects. Information is also needed on current and possible future forecast requirements. After all this information and data are gathered, the pertinent values need to be accessed and put into the form needed for further processing.

• Assess Spatial Variability of Hydrologic Factors – Before proceeding further with the calibration process it is necessary to take the gathered information and data and get an idea of how various hydrologic factors vary over the river basin. This includes such variables as precipitation, temperature, evaporation, and snow cover, as well as features such as topography, vegetation, soils, and geology. Hydrographs from headwater drainages and local areas can be used to get an idea of how different portions of the river basin respond to the integrated effects of these factors. A knowledge of the spatial variability of hydrologic factors is important in determining how the basin should be divided for modeling purposes and which procedures should be used to analyze the data.

• Select Flow-points and Period of Record for Calibration – The determination of where streamflow is to be simulated during the calibration process is dependent on a number of factors. These include availability of historical streamflow and reservoir data, location of current and future forecast points including those needed to meet all user requirements, location of diversions, irrigation, and control structures, and the variability of hydrologic factors over the basin. The period of record to be used for calibration is dependent on the period of record of the historical data, especially streamflow, and information on changes that have occurred within the basin over time such as the building of control structures or diversions, increase or decrease in irrigated acreage, and vegetation and land use changes.

• Analyze Historical Data and Put in Form Needed by Models – This step involves the generation of areal average values of precipitation, temperature, and evaporation for the local drainage above each simulation point. In mountainous areas it also involves first determining which drainages must be subdivided into elevation zones and what elevation bands are appropriate. Other areas may also be subdivided if the hydrograph shape varies significantly depending on where the runoff occurs and if there is sufficient gage data to adequately define the input for each subarea. This step also includes the checking of discharge data and the adjustment of these data, if needed, to account for diversions and other factors. Regional water balance computations are an important part of this step especially in mountainous areas to insure that the precipitation, evaporation, and runoff estimates are physically reasonable and consistent.

• Calibrate Hydrologic Models (Snow, Soil Moisture, River, and Reservoir) – Finally after completing all the previous steps it is time to calibrate the hydrologic models to the individual headwater drainages and local areas. The recommended procedure involves the calibration of the headwater with the best data and least complications first and then proceeding to other drainages. Parameters from previously calibrated points are used as initial values for the subsequent areas and only those parameters that clearly need to be changed are altered. Areas that can't be calibrated due to the effect of control structures or because the local contribution is small compared to the total flow are assigned parameter values from the most similar calibrated watershed.

• Implement Calibration Results for Operational Use – The final step in the process takes the results of the data analysis and the model calibration and implements them into the operational systems. This includes the NWSRFS Operational Forecast System (OFS) used for maintaining state variables and producing short term river forecasts and the ESP system used to make extended predictions. The most important factor in the operational implementation of the results is to not produce any bias between the operational application and the historical simulations produced during calibration while still trying to reduce random variations to a minimum through the use of new data sources, dynamic data analysis methods, and real time model adjustment techniques. Bias can occur due to differences in data networks, data types and processing methods, and operational modifications made to state variables.

The subsequent chapters of this manual will describe in detail the recommended procedures to follow for each of these steps in the calibration process.

Extension of Historical Records and Recalibration

Besides the initial calibration of the models to each river basin in an RFC area, it will generally be necessary at times to extend the historical record and to recalibrate at least portions of the area. Reasons for extending the historical record include:

- To have more years of data to use for ensemble streamflow predictions, especially extended predictions. Extending the length of record should improve the confidence of the probabilistic statements that are generated by providing a greater assortment of climatological conditions that might occur in the future. Extensions might be done on a regular 5 or 10 year interval when extended streamflow predictions are being generated for the basin.

- The occurrence of events that were not included in the previous model calibration, such as a new record flood, prolonged dry spell, record snow cover, or surface runoff occurring for the first time. The additional data record can then be used to check the extrapolation capabilities of the models and to make any necessary parameter adjustments (doesn't typically require redoing the calibration).

- Changes occurring within portions of the river basin, such as new control structures, changes in how reservoirs or diversions are operated, changes in agricultural practices, large forest fires, or land use changes. When such changes occur, some of the models being used and/or model parameters for the part of the basin affected typically will need to be modified which may require a recalibration of those watersheds.

Reasons for recalibrating include:

- The people doing the calibrations have gained considerable experience and realize that they can now do a much better job at improving all of the calibration objectives.

- Operational use has uncovered problems and situations that were overlooked or modeled improperly during the original calibration.

- Significant changes have occurred in one or more watersheds within the basin as a result of new agricultural practices, large forest fires, or modifications to land use.

- There is a need to establish some new forecast points at locations with historical streamflow data that were not included in the original calibration. This typically doesn't require a recalibration of all models. Generally it involves subdividing the area between original calibration locations so that simulations are produced at the new forecast points. This requires producing new data input and parameters for channel models, but usually only slight modifications to soil moisture and snow model parameters.

- New methods of determining input data, such as precipitation computed from a combination of gage, radar, and other data, become available which cannot be made totally consistent with the data used for the original calibration.

- It is decided to change the way that the historical data were analyzed and processed, such as switching to mountainous area procedures when non-mountainous techniques were originally used.

- New models become available which will replace existing models or simulate situations that were not modeled in the original calibration.

- Climatic changes have occurred which could alter climatological average estimates of ET-Demand or other model parameters.

It is very important when extending the existing historical data record to make sure that the new data are consistent and unbiased compared to the data used to determine the current model parameters. This requires that station and areal means used in the computation of the areal estimates of precipitation, temperature, and evaporation for the new period <u>must</u> be the same as those used to generate the data on which the current calibration is based. For example, if the current calibration is based on data from the period 1949 to 1990 and the record is now being extended for the period 1991 to 2000, the station and areal means established for the 1949 to 1990 period must be used in the processing programs when generating data input for the 1991 to 2000 period. Likewise, if the data are further extended in the future, e.g. for the period 2001 to 2010, the station and areal means for the 1949 to 1990 period must continue to be used so that the additional data remain consistent and unbiased with the period on which the calibration is based. If new stations are included when generating the extensions, the means for these stations should be determined by using ratios (precipitation) or differences (temperature) with long established stations that have well defined mean values for the period used for the calibrations.

Recalibrations can be based on the initially processed period of record plus any consistent and unbiased extensions to it or the entire data period can be regenerated prior to a recalibration. If the entire historical record is regenerated involving new types of data or different processing methods, then the models used for the <u>entire</u> area must be recalibrated unless somehow one can guarantee that the new data values are consistent and unbiased compared to the data previously used for calibration. As examples we can related these statements to the reasons for recalibration listed previously in this section.

- If new data types, such as radar estimates of precipitation, or new processing methods, such as switching from non mountainous to mountainous area procedures, are being used to generate the input data, then the data for the entire data period (may not be the same as the original data period due to the length of record for the new data types) needs to be regenerated and the entire area recalibrated.

- When new models are being implemented, calibrations are being redone based on increased experience, or operational problems indicate a need to reexamine the calibrations, it may or may not be necessary to regenerate the input data. As long as the new models can use the existing data (though additional data types may be needed depending on model requirements) or the simulation problems are not related to the data record, there is no need to regenerate the input for the models. If the new models are being implemented or the existing models recalibrated over just a portion of the river basin, then the possibility of regenerating the input data only needs to be considered for this part of the area.

• Land use changes, new agricultural practices, large forest fires, and climatic changes typically do not require regenerating the historical data record. Generally this situation involves extending the data to cover the period after the action took place and then using this period to modify the model parameters.

• The need to establish new forecast points involves subdividing existing drainages and thus the creation of new areal data estimates. This typically requires that a complete new data record be generated for each new subarea. This only needs to be done for the affected drainage areas. Whenever generating new data input for only a portion of the area it must be remembered that many of the same stations will be used for these areas as are used for surrounding drainages and thus, the station means used to compute the new data input records should be those used when the data were processed for the latest full calibration of the river basin.

When extending the period of historical record or recalibrating all or part of a river basin, the same general principles and recommendations apply as when doing an initial calibration except that certain of the basic steps may not be necessary or require less attention. The gathering of information and data definitely will be a part of an extension of the data record or a regeneration of the model input involving new data types and likely needed when changing processing methods, but, for the most part, will not needed when the existing historical record is sufficient for any modifications to the model parameters. Analyzing the spatial variability of hydrologic factors typically would not be necessary unless completely new data types are now involved though a review of this step could be beneficial in many cases. The considerations regarding the selection of flow-points and the period to be used for calibration should definitely be examined whenever a recalibration, especially a complete recalibration of the entire river basin, is being done. The recommendations regarding the analysis of historical data and the generation of model input applies whenever a new historical data record is being produced. Special considerations apply to the extension of existing records and these will be discussed further in the chapter covering this step. Likewise, the recommendations regarding the calibration of the hydrologic models apply whenever model parameters are being calibrated or modified and the chapter covering this step will include a discussion of items that need emphasis when doing a recalibration. The chapter on the operational implementation of calibration results will also include a discussion of operational changes that may be needed after completing a historical record extension or a recalibration.

Chapter 3

Step 1 - Gather Information and Data

Introduction

The first step in the process of calibrating a conceptual hydrologic model to an entire river basin is to gather all the information and data that will be needed. This includes basic information on the climatology of the area, physical features, control structures and other modifications to natural flow, and operational forecast data and requirements. It also includes all available sources of historical data. This step also involves accessing the relevant historical data and converting it to the form needed for further processing in subsequent steps.

When doing an extension of the data record the exact same historical data requirements pertain to the extension period as are described in this chapter for the initial calibration period. In addition to data for the extension period, data for about 10 years prior to that period should also be gathered so that the consistency of the records over time can be evaluated. When doing an extension of the historical record the basic information that should be gathered is that which indicates changes that occurred during this period such as new reservoirs or other control structures, new forecast requirements, and changes involving agricultural practices, vegetation cover, and land use.

This chapter lists the basic information and historical data that may be needed for the calibration of a river basin, possible sources of the information and data, and data selection criteria. The exact way that the information and data are used in the calibration process are described in subsequent chapters.

Basic Information Requirements

A variety of items should be gathered at the beginning of the calibration process. This includes information about the climate of the basin, physical features such as topography, soils, and vegetation, the location and operating procedures of control structures, and real time data and forecast locations. A number of these should be able to be accessed via the Calibration Assistance Program (CAP). The current features, capabilities, and user instructions for CAP are described in sources outside of this manual. For some basins reports from agencies such as the USGS and Corps of Engineers contain a variety of these types of information that can be helpful in understanding the hydrology of the area.

Climatological Information

- Isohyetal maps showing annual, seasonal, and/or monthly average values of precipitation over the area. This is most important in mountainous areas, but there may be other areas where the variation of average precipitation over the area cannot be ignored when analysing precipitation data and generating areal average time series for model input. Such areas include those with lake or ocean influences (e.g. areas that include zones affected by lake effect snow patterns). The most common source of digital isohyetal maps is the PRISM maps produced by the NRCS and Oregon State University [*Daly et al.,1994*]. There may be other isohyetal maps for parts of the United States that also should be examined.

• <u>Evaporation analyses that show the magnitude and variation of evaporation over the river basin</u>. One source is NOAA Technical Reports NWS 33 and 34, "Evaporation Atlas for the Contiguous 48 United States" [*Farnsworth and Peck, 1982*] and "Mean Monthly, Seasonal, and Annual Pan Evaporation for the United States" [*Farnsworth and Thompson, 1982*]. These reports contain maps of May-October pan evaporation, May-October Free Water Surface (FWS) evaporation, annual FWS evaporation, and pan coefficients over the lower 48 states. The reports also contain tables of monthly, seasonal, and annual pan evaporation for various sites in each state derived from pan data and computed from meteorological factors. There is also some information on the variation of pan evaporation with elevation. There may be other reports, typically by government agencies or universities, on evaporation analyses for a given river basin or state which would be helpful to have available.

• <u>Other climatological analyses involving variables such as temperature, runoff, snow cover, frozen ground and/or glaciers</u>. The PRISM project has developed maps of average temperature values. In some river basins maps showing how runoff varies over the area have been produced. These maps are generally done as part of a water balance study. Maps of average snow depth or water equivalent may be available for some basins, as well as reports on the variation in frost depth. In Alaska and in the Pacific northwest it is important to know whether the basin is affected by glaciers and if so, the location and coverage of the glaciated area. Reports on how the glaciers are changing over time can also be very helpful.

<u>Physical Information</u>

• <u>A basic map of the river basin</u>. The map should show location of rivers and streams, major lakes and reservoirs, and contain topographic information. The maps may also contain general information about vegetation cover and show locations of glaciers. The maps can not only be used to get a general understanding of the physical layout of the river basin, but are useful to visualize drainage areas and gage locations.

• <u>Information on vegetation cover and land use</u>. It is important to know how much of the basin is covered by vegetation, and the type of vegetation, as well as how the vegetation or crop patterns may have changed over time (e.g. changes to the amount of forest cover due to reforestation, suburbanization, or large forest fires). It is also helpful know which portions of the basin contain agricultural areas and which are urbanized. In addition, NDVI Greenness fraction data can assist in determining the seasonal variation in vegetation activity.

• <u>Soils information</u>. Can be used to subjectively assess how various soil moisture parameters may vary relatively over the basin. Soils data can also be used to compute initial estimates of parameters for the Sacramento Model. In some northern areas permafrost may exist over portions of the basin and can have an effect on streamflow.

• Geological information. Can be helpful in determining how parameters may vary over the basin, especially groundwater parameters. Such information can also help to determine if parts of the basin significantly contribute to deep groundwater recharge or if karst regions may exist.

Information on Controls and Transfers

• Reservoirs and large lakes. It is important to know where these features are located, how they control the flow, and the magnitude of their effect. Ideally these features should be modeled. In order to do this information such as area-elevation and elevation-discharge curves are needed. For reservoirs, details on how the dams are operated is important.

• Other types of structures. These include small dams (including farm detention reservoirs) and power plants. These structures primarily affect low flows, small storms, and flows after dry periods. It is important to know the general type of such structures and where they exist in the river basin.

• Diversions of water across watershed boundaries for purposes such as water supply, irrigation, and power generation. Diversions can also occur at high water levels when rivers or impoundments may overflow across drainage divides. It is critical to know where such diversions occur so that data can be obtained to model the diversion or adjust the streamflow records to reflect natural flow conditions if the magnitude is significant.

• Irrigation that occurs within a given watershed. Besides removing water from the river, the irrigated land is kept wetter than would naturally occur thus affecting the amount of runoff from subsequent storms, and some of the removed water may reenter the stream later as return flow. It is important to know the amount of irrigated acreage, the rules governing the removal of water, and seasonal changes in irrigation demands.

• Drainage systems. In some agricultural regions drain tiles have been installed under the ground to control the drainage of excess water from the soil. In other areas wetlands have been drained or farming practices may affect runoff generation. It is important to know about these items and when they occurred and how they may have changed over time.

• Large springs. May represent a large portion of the flow at low levels, or they may contain areas where a significant portion of the percolated water can go to deep aquifers. Both of these occurrences can have a important effect on the modeling of baseflow and need to be known and, if possible, quantified.

Operational Information

- Operationally available data. Knowledge of available real time data, especially river and reservoir observations, is needed to help determine how the river basin should be divided for modeling purposes.

- Location of current forecast points and future user requirements. Needed to help determine how the basin is divided for historical data processing and model calibration.

Historical Data Requirements

A variety of historical data needs to be gathered for direct use in calibration. Hopefully the data are already in digital form, however, in some cases critical data may only exist in tabular form and would have to be converted in order to be used. Besides finding the data and determining which records are needed for calibration, the actual data values need to be put into the format required for use by the calibration programs (currently in NWSRFS this is the DATACARD format).

The period of record needed for historical time series depends on how the calibration results are to be used for operational applications. If there is any possible application of the results for extended ensemble predictions, then the longest possible period of precipitation and temperature data should be used in order to generate the most statistically reliable results. Since only a limited number of stations are available in digital form in the National Climatic Data Center (NCDC) climatological records prior to 1948, the longest reasonable data period to process is that from water year 1949 to the time of the most recent available data. If significant changes occurred in the station network over the years, the data for this entire period might not produce time series that consistently represent a reasonable estimate of what occurred over the river basin. For example, in some western areas there were few if any high elevation stations until the advent of the SNOTEL network maintained by the Natural Resources Conservation Service (NRCS). In this case time series produced from only low elevation sites prior to the installation of the SNOTEL stations likely would not produce reasonable estimates of conditions, especially the timing and amount of precipitation, at the higher elevations. Only the period of record after the beginning of the SNOTEL network would likely produce reasonable estimates of model input values and thus would be the period selected for accessing historical data. Chapter 5 contains more information concerning this situation and how to determine if periods of record with very different networks can be mixed.

If the calibration results are only going to be used for short term river forecasting, then possibly a shorter period of record will be sufficient. In this case only the period of record needed to calibrate the models is required. Chapter 5 contains recommendations for selecting a calibration period for a given location, however, since the data are being processed for an entire river basin, the data period must cover the calibration periods of all flow points within the basin. This will allow for the calibration of each point and the routing of flows downstream.

If there are any questions concerning whether a given station should be included at this stage, it is best to include it. When the data are later analyzed, as described in Chapter 6, stations with problems or those that don't add information content can easily be removed, but it is inefficient to go back and retrieve additional data.

The exact programs or procedures to view and access the data are generally not included in this manual. Much of the historical data can be obtained via the NOAA Hydrologic Data System (NHDS). Some of the data are obtained from the agency responsible for collecting the information and then stored and possibly reformatted for use in the NHDS. Various NHDS programs are then available to view and access the data. Other data are obtained directly from agency web sites and then converted into the format needed for NWSRFS by NHDS provided utilities. In other cases individual RFCs have developed programs and procedures to obtain various data from other agencies. Since many of the procedures for obtaining data are changing periodically and may vary from one office to another, this information will not be covered. This manual concentrates on the data needed, selection criteria, and how to use the data.

Precipitation Data

Daily and hourly precipitation data are required in order to generate Mean Areal Precipitation (MAP) time series from historical data.

- Daily Precipitation from the National Climatic Data Center (NCDC). The recommended guidelines for selecting daily precipitation stations for further analysis are:

    - stations within the river basin boundaries and stations slightly outside the boundaries that could be assigned Thiessen weights when computing MAP or would be likely estimators for stations within the boundary that have significant periods of missing data,

    - in mountainous areas, stations that are outside the basin boundaries but represent elevation zones and orographic precipitation patterns within the basin, and

    - stations with at least about 5 years of generally complete data (about 5 years of data are needed to determine a reasonable estimate of the mean precipitation at a given site). Even such short periods of precipitation records are generally included because of its significant spatial variability.

  The NCDC climatological network is comprised primarily of volunteers who receive minimal payments for making observations, thus there are many cases when new observers must be found and stations are moved from one location to another. NCDC station data records are defined by a station number. In some cases when a station is relocated the number remains the same, while in other cases a new number is assigned and thus a new data record is established. Sometimes a station can be moved 10 miles and the number remains the same, whereas other times one station is discontinued and a new station immediately established only a few miles away. In at least one case a new station was established when there was no site or equipment change, only the name was changed. One option when a station is discontinued and a new station established a short distance away, is to merge the data from the two stations into a single data record. This can be done even when the new location has less than 5 years of data and is especially important to do if the new station is part of the operational network.

• Daily precipitation data from other available networks or sources. One such source is the SNOTEL network that is maintained by the NRCS. This data source is very important in most of the west and Alaska. Daily precipitation data may also be available from other networks such as IFLOWS, statewide or local ALERT installations, regional climate centers, historical data bases maintained by some RFCs, and from Canadian or Mexican sources. The recommendations for which stations to include are the same as for the NCDC network. The situation of station relocations normally doesn't exist for automated networks.

• Hourly precipitation from NCDC. The recommended guidelines for selecting hourly precipitation stations for further analysis are:

- stations within the river basin boundaries, plus stations surrounding the basin that will be used to time distribute records of previously selected daily stations,

- in mountainous areas, stations that are outside the basin boundaries but represent elevation zones and orographic precipitation patterns within the basin, and

- stations with at least about 5-10 years of generally complete data.

By having hourly stations surrounding the daily stations, there is a tendency to dampen the precipitation intensity as a storm moves across the basin, however, this is probably better than having an hourly station in only one direction used to time distribute a daily amount and thus offsetting when the event occurred. Where daily and hourly records both exist at the same location, it is generally best to include both, since there is a tendency for more missing data and less accurate estimates of missing amounts at hourly stations using the NWSRFS programs (the estimation of missing hourly data is only based on other hourly stations, whereas missing daily data are filled in using all stations). Hourly stations that may be assigned weights when computing MAP need only about 5 years of data, whereas one may decide to use only those with a slightly longer data period to time distribute daily records. For those stations used only for time distribution of daily data, their period of record should overlap that of the stations they will be used to distribute. Comments regarding NCDC network relocations and merging of records given for daily stations also apply to hourly stations.

• Hourly precipitation data from other available automated networks or sources. The recommendations for which stations to include are the same as for the NCDC network. The situation of station relocations normally doesn't exist for automated networks.

Temperature Data

Air temperature data are needed for snow model computations, frozen ground effects in conjunction with the Sacramento Model, and ET computations in the consumptive use operation (alternative to using a PE time series). The air temperature data are used to compute Mean Areal Temperature (MAT) time series. Currently the calibration program used to compute MAT only uses daily maximum and minimum air temperatures, as opposed to the operational MAT program which uses both instantaneous and max/min temperature data.

- Daily maximum and minimum temperatures from the NCDC climatological network. The recommended guidelines for selecting max/min temperature stations for further analysis are:

  - stations within the river basin boundaries and stations slightly outside the boundaries that could be assigned weight when computing MAT or would be likely estimators for stations within the boundary that have significant periods of missing data,

  - in mountainous areas, stations that are outside the basin boundaries but represent elevation zones within the basin that have limited temperature observations, and

  - if possible, stations with generally complete data for the entire or at least a majority of the period of record, though stations with shorter records should be included when there are elevation zones and portions of the basin that are not represented by stations with more complete data. Stations with shorter records are most commonly used in mountainous areas that don't have sufficient high elevation stations with extended records.

Air temperature doesn't have nearly the amount of spatial variability as precipitation, thus one can be more selective when choosing which temperature stations to use. It is not necessary to include stations with short records that represent portions of the basin or elevation zones that have sufficient stations with longer records.

When analyzing temperature data and computing mean areal time series, all stations must have mean monthly max and min values. Unlike for precipitation, there is currently no preliminary processing program that will estimate mean values for the entire period of record in a consistent manner from stations with varying lengths of data observations. Mean monthly values are computed from the existing data for each station. Thus in order to get a good estimate of the long term mean, the station should have data for as much of the period of record as possible (ideally for 70% or more of the historical data period being used). When stations with short data periods are included, the mean monthly values will need to be estimated manually using the procedure outlined in Section 6-4.

• Daily maximum and minimum temperature data from SNOTEL stations and any other available sources including regional climate centers and historical data bases maintained by some RFCs. The selection guidelines are the same as for NCDC stations.

Evaporation Data

Evaporation data are used by several of the NWSRFS rainfall-runoff models (SAC-SMA, API-CONT as an option, API-HAR, API-HAR2, and XIN-SMA), reservoir models to compute surface evaporation losses (RES-J and RES-SNGL as options), and some other operations (CHANLOSS as an option to compute stream evaporation loss and CONS_USE as an option to compute evaporation from irrigated areas). Several of these operations will accept evaporation input in two forms, daily time series or average mean monthly values. Also, the quantities needed vary from Potential Evaporation (PE), to mean values adjusted for vegetation activity, to lake evaporation adjusted for heat storage. In order to obtain the proper input for a given operation, the starting point is either daily or average monthly estimates of PE.

• Daily estimates of PE are obtained in one of two ways:

- Computed from meteorological factors at selected synoptic sites using NHDS programs. These programs currently estimate solar radiation from manual sky cover observations using the method of Thompson [1976]. Since the advent of the ASOS, these sky cover observations are no longer available. Other methods exist for determining solar radiation including direct observations, computing from percent sunshine data, and satellite derived values. None of these options are currently included in the NHDS programs. Based on a study by Lindsey and Farnsworth [1992], it was shown that using sky cover to estimate solar radiation causes the resulting PE estimates to be biased. The bias varies spatially over the lower 48 states. The NHDS procedure includes an adjustment for each available station to remove this bias so that the average annual PE that is produced matches the average annual lake evaporation given by NOAA Technical Report NWS 33.

- Generated using the Mean Areal Potential Evaporation (MAPE) program. This program can use daily PE time series computed from meteorological variables and daily pan evaporation time series to generate daily MAPE values. Daily pan data are obtained from NCDC. Missing pan data are estimated in the MAPE program. Pan coefficients, used to adjust pan observations to become lake evaporation estimates, must be included in the consistency corrections applied to the stations.

• Average monthly estimates of PE can be obtained in the following ways:

- Use the average monthly values computed from meteorological factors generated by the NHDS programs or tabulated in NOAA Technical Report NWS 34.

- Apply the proper pan coefficient to the average monthly pan evaporation values obtained for NCDC stations with pan observations or tabulated in Technical Report 34.

- Use annual and seasonal average lake evaporation values shown in NOAA Tech Report NWS 33 and prorate these to monthly values using distributions based on stations given in NOAA Tech Report NWS 34 or obtained from NCDC stations with pan measurements. These lake evaporation values have been digitized and seasonally distributed using formulas based on Report 34 data so that monthly estimates of PE can be obtained using CAP.

Streamflow Data

Streamflow data are needed at all river locations where comparisons are going to be made between simulated and observed flows during the calibration of the river basin. Streamflow data may also be needed at locations just downstream from reservoirs so that reservoir inflow can be computed and thus compared to simulated inflow even if the operation of the reservoir itself is not going to be modeled (pool elevation or storage data are also required to compute inflow). Streamflow at locations below a reservoir or at the lower end of an area that is not yet or cannot be reasonably modeled, are also used to generate flows to route downstream. In addition, streamflow data can be used in calibration to remove the contribution from a portion of a watershed significantly affected by a control structure, diversions, irrigation, or another influence which is going to be accounted for operationally, but not during calibration (i.e. information is available in real time to estimate the contribution, but not historically – during calibration only the uncontrolled portion of the watershed is to be modeled).

Since at this point in the process a determination has not yet been made as to which river locations are to be included in the calibration process (to be determined during step 3 and described in chapter 5), it is best to just determine exactly what streamflow data are in a readily available form and wait to access the data and put it in the proper form until the river basin breakdown is completed.

Streamflow data can be in the form of mean daily flows or instantaneous discharges. Mean daily flow values are used to determine the volume of flow and its general timing. Instantaneous discharges are needed for faster responding streams and for locations with diurnal variations in flow in order to refine the timing of the simulated streamflows. Mean daily flows are needed on a continuous basis over many years to verify model performance, whereas it is generally sufficient to have instantaneous discharges available only during major events.

- Mean daily flow time series are primarily available at locations maintained by the U.S. Geological Survey (USGS) and available via the USGS web site. These data have been checked and quality controlled. There may also be some other sources of daily flow data in some parts of the country and in Canada and Mexico.

- Instantaneous discharge data is generally more difficult to obtain. Such data may be available, at least for a portion of the historical record, from the local USGS district office. Typically the district offices have such data in digital form for more recent years. These may be raw values that have not had the same quality control checks and adjustments as the mean daily flow data. Data for earlier years are for the most part only available in a hard copy form, such as printouts of periodic stage readings or strip charts. In this case the values must be extracted and converted to discharge using the appropriate rating curves.

Instantaneous discharge data can also be obtained from the RFC's archived operational files. Programs are available within the NHDS to assist in extracting data from the operational files and generating time series. Instantaneous discharges obtained from operational files are based on real time stage reports and were converted to discharges using the rating curve defined at that time in the RFC files. There are no quality control checks or adjustments applied, plus the time when rating curve changes are applied may not be the same as used by the USGS when processing the mean daily flow data.

Instantaneous discharges may also be able to be obtained from other agencies or from Canadian and Mexican sources for rivers that cross these international boundaries.

In addition to continuous flow data, peak flow values can also be useful in model calibration. The USGS maintains an archive of peak flow data on their web.. Unfortunately the USGS only archives the peak flow, peak stage, and day of occurrence of the peak. The time of the peak during the day, which is available in the USGS Water Resources Data reports, is not maintained in the archive files. The peak flow data can be downloaded and put in a form that can be used by the NWSRFS PEAKFLOW operation by following the directions given in the NWSRFS User's Manual.

Reservoir and Lake Data

Reservoir data are needed during calibration to either compute reservoir inflow time series or to verify simulated reservoir operations. This also applies to lakes which have a significant influence on the timing and magnitude of stream flows. The main data that are frequently available historically for reservoirs and large lakes are pool or lake elevation and/or storage (storage can be computed from elevation or vice versa using an elevation-storage relationship). To compute inflows either pool elevation or storage values are needed, as well as outflow data. Some reservoirs may have design features and/or operating rules that would require obtaining additional historical time series in order to compute inflows or verify operations.

- The USGS maintains records of daily pool elevation or storage for a number of reservoirs around the country. These records are published in the USGS Water Resources Data reports for each state. At this point in time these reservoir and lake data are generally not available via the USGS web site and there is only limited reservoir data available via the NHDS.

- Reservoir data may also be available from the agency or private company that operates the dam. This includes the Corp of Engineers, Bureau of Reclamation, government authorities such as BPA and TVA, local river basin commissions, and power companies.

<u>Snow Data</u>

Snow data can be used during calibration to verify computations of the snow model. This includes checking and adjusting, if necessary, the form of precipitation and comparisons of observed and computed water equivalent, areal snow cover, and snow depth. Thus, the snow data that are most useful during calibration are water equivalent, snowfall, depth of snow on ground, and areal extent of snow cover.

- Daily values of new snowfall and depth of snow on the ground are available at many climatological stations from NCDC. Water equivalent data are also available at a few of these stations.

- Daily water equivalent at SNOTEL sites as measured by sensors located under the snow cover.

- Periodic snow course data (water equivalent and depth) are collected at many sites throughout the U.S.. In most of the western states and Alaska the data are collected by the NRCS. In California, west of the Sierra Nevada mountains, snow course data are collected by the State of California. In the upper mid-west and northeast parts of the country, these data are collected by various government agencies and private power companies. Access or information on these data can be obtained from NOHRSC.

- The NOHRSC archives two types of snow data that they are responsible for collecting and processing. The first is snow water equivalent determined from aerial gamma measurements from airplanes. These data represent the average water equivalent over a flight line. Measurements are typically made when requested during periods of significant snow accumulation. The second is areal extent of snow cover determinations derived from satellite data. These data are generated periodically on a routine basis over most of the western states. Data are available for specific drainages and for specified elevation bands within many of the watersheds. Data are also available in a form for visual display and processing using GIS applications. Areal snow cover data are also available for some periods for other parts of the U.S. from the NOHRSC.

<u>Other Data Types</u>

There are other data types that are needed or can be helpful when calibrating a river basin. Which of these data types are available or are needed depends on the hydrology and climatology of the basin and the types of transfers across watershed divides.

- When water is transferred across watershed divides it is necessary to have data to quantify the magnitude and timing of the diversions. In some cases it is possible to get only a general idea of the magnitude of the diversion. If the magnitude is small relative to the total amount of flow and actual data values are not readily available, the diversion may only implicitly be included in the modeling process. If the amount of the diversion is significant, it should be directly accounted for in one way or another. There are two general ways of handling significant diversions. One way is to adjust the mean daily flow hydrograph to reflect natural flow conditions by adding or subtracting daily diversion flows (may be routed first if travel times are significant). The other way is to explicitly model the diversion and verify by comparing simulated and observed diversion amounts.

Daily data on some diversions are available from the USGS via their web site. Monthly values of some diversions are also published in the Water Resources Data reports of the USGS. Monthly values in many cases can reasonably be distributed into daily amounts for use in adjusting mean daily flow data. It may also be possible to obtain diversion data from the agency, group, or private concern that operates the diversion.

• In some watersheds large springs exist which may contribute a significant portion of the overall flow. The flow from such springs should be explicitly accounted for if possible rather than lumping their effect into the rainfall-runoff computations. The USGS Water Resources Data reports contain periodic flow measurements just below such springs in some cases. These measurements can be used to adjust the daily flow records to remove the contribution from the spring.

• In some river basins water flows across watershed divides during times of high flows. This typically occurs in regions or parts of the basin with little topographic relief. The USGS Water Resources Data reports will normally note where such conditions exist and may at least indicate when such occurrences took place. Further inquiries may be needed in order to quantify the magnitude of such transfers.

• Data on frost depths may be available in some northern areas to help in verifying model simulations of frozen ground effects. These may be in the form of soil temperature measurements at specific sites or direct estimates of frost depth. For example, the Wisconsin State climatologist, gets measurements of frost depth from grave diggers and produces periodic maps of estimated frost depth over the state.

<u>Meta Data</u>

Besides gathering actual data values for use in calibration, it is also very important to obtain information on the methods of making the measurements and how these may have changed over time. This includes the type of equipment used, the observation time, and station relocations. For precipitation especially, it is important to know the type of gage that is used and whether the gage had a wind shield and whether either of these changed over time. Studies have shown significant differences in precipitation catch based on the type of gage and kind of wind shield.

The observation time of daily precipitation and temperature data is important in getting the data values assigned to the proper time. Information on equipment changes and site relocations are very important in trying to assess the consistency of the data and when determining if adjustments should be applied to correct for inconsistencies. General knowledge of measurement methods can be very helpful in assessing the magnitude of possible errors in all the data types and thus the overall reliability of the values. This will be of great benefit in evaluating possible problems in observed data and thus determining when simulated values should possibly not match observations.

- Information on station relocations and observation times of daily reports can be obtained for the NCDC climatological network via the NHDS. Observation times and changes to these times are available only for stations with long records that were used in computing 30 year normals. Similar information for climatological stations are also available from the B44 forms that are filed by the network managers periodically and when changes occur and from information published by NCDC in the Daily Climatological Bulletins. These sources may also contain information as to if and when precipitation gages were equipped with a wind shield. However as a word of caution, the meta data available from NCDC from these sources is not always accurate or complete. This is partly due to the minimal amount of money allocated to the climatological data program. Comparisons between these various sources of meta data for specific stations have shown that the information is not consistent and certainly no one source is complete. One cannot say with certainty that a relocation or equipment change did not occur just because it is not listed in one of these sources. Information on changes at synoptic stations used in the computation of PE from meteorological factors are documented in the NCDC Local Climatological Data Bulletins. Changes in anemometer height should be included in a file used by the NHDS program that computes PE from meteorological factors.

- Meta data for other measurement sites should be obtained from the agency that maintains the data. Information on changes over time to USGS stations is included in the Water Resources Data reports. Location information and observation times for SNOTEL sites is available from the NRCS.

Chapter 4

Step 2 - Assess Spatial Variability

Introduction

After gathering all the information and data that may be needed for the calibration of a river basin, the next step is to carefully analyze the spatial variability of physiographic factors and hydrologic conditions over the basin. This analysis will be very beneficial in all of the succeeding steps. The spatial variability of conditions over the basin is very important in determining which streamflow points should be included in the calibration. Climatic variability will determine the methods used to analyze and process the historical data. It will also be used to determine if the watersheds need to be subdivided into elevation bands or split based on significant variability of soils and/or vegetation. This analysis of spatial variability will also be of great benefit in predicting how model parameter values might vary over the river basin. It will also form the basis for selecting initial parameter values and for assigning values to model parameters for portions of the basin that cannot be calibrated.

There are two general ways to assess the spatial variability over the basin. The first is to look at the variability of various physiographic factors such as topography, precipitation, temperature, evaporation, snow cover, soils, vegetation, and geology. The second is to look at variations in hydrograph response which is an integration of all the hydrologic factors.

Analysis of Physiographic Factors

Introduction

There are a number of physiographic factors, physical and climatic, that should be examined to understand how conditions vary over the river basin. Much of the physiographic data and certain analyses of these data are available in a digital, gridded form that can be processed using GIS applications. Some of these data may still only be in hard copy form. Most of these data should be able to be viewed and analyzed via CAP. Since the data available in the form needed for GIS applications are ever expanding and the features in CAP are periodically changing, this manual will not describe the details of how to obtain, view, and analyze these data.

Physical Factors

The physical factors that are important to examine include topography, soils information, vegetation cover and types, and geologic information. Displays of this information are based on information gathered and analyzed at some point in time. Generally the topography and geology of an area remain constant over the time frames involved in calibration. Soil characteristics also should remain basically constant over the period of record. Vegetation types and patterns can change in areas subject to land use changes, changes in agricultural practices, and forest variations due to harvesting or large fires.

- Topography – The main question when viewing topographic information is how much does elevation vary over the river basin and within possible subbasins. Significant changes in elevation (more than about 1000 feet) generally indicate that there could be differences in precipitation, temperature, and evaporation that will need to be taken into account when analyzing and processing the data. The greater the range in elevation, the more chance that these variations will be important. One can also look at area-elevation curves for the basin and possible subbasins to determine if the vast majority of the area is at similar elevations and only a small fraction of the area is significantly different or whether there are major portions of the area at different elevations. If there is a significant difference in elevation affecting major portions of the area, it is very likely that mountainous area procedures need to be used when processing the data. As the elevation range increases there is also the likelihood that the individual drainages may need to be divided into multiple elevation zones for data processing and modeling purposes. Significant elevation differences also indicate that, if possible, it is important to include data that represent what is occurring at a variety of elevations.

  Topographic maps also generally show rivers and thus one can get a general idea of the shape of the individual watersheds with the basin. If there are watersheds that are long and narrow, this would indicate that these drainages may have a different shaped hydrograph depending on where the runoff occurs and may need to be subdivided if the necessary data are available. Also included on most topographic maps are lakes and reservoirs. It is important to note whether there are large lakes and/or reservoirs which may have a significant effect on hydrograph response and thus will need to be modeled separately. In extremely flat terrain, especially ones with many small lakes and ponds, it may be difficult to determine drainage boundaries and contributing areas. This will result in the drainage area, which is normally known, to be treated somewhat like a parameter in the calibration process. Topographic maps also typically show the location of large population centers and the general extent of forest cover. All of this information should be useful in the subsequent steps in the calibration process.

- Soils – The main thing to examine at this point regarding the soils data is whether there are significant differences in soil properties from one part of the river basin to another. In mountainous areas it could be helpful to see how the soil properties vary with elevation and whether a large change occurs within a particular elevation range. Differences in soil properties from one watershed to another within the river basin may indicate how certain model parameters should vary. Significant differences within watersheds may suggest that these watersheds possibly could be subdivided to improve simulation results. Since this author is not that knowledgeable regarding the details of the information contained in soils reports and gridded data sets of soil properties, only some general insights on what to look for will be offered. First, any information that indicates how the permeability of the soils may vary over the basin is important. This could be measured properties or general classification of the type of soils (e.g. clays versus silts versus sandy soils). This information will be helpful later in judging how the parameters involved in the percolation equation might vary from one watershed to another. Second, information on how the depth of the soil layers varies over the basin could be helpful in determining variations in tension water capacities from one watershed to another.

• Vegetation – Several things are important to get an understanding regarding the variation in vegetation cover and types over the river basin. First is the general distribution of forest, open areas, and agricultural lands. Second is the variation in the types of forest cover, primarily between conifers and deciduous trees, and the type of crops in agricultural lands. In mountainous areas changes in vegetation cover and types with elevation, especially from semi-arid types of cover to forest types that require a significant amount of water every year, can be helpful in determining if and at what elevation watersheds in these regions should be subdivided. The vegetation information should be helpful in determining variations in certain snow model parameters from one watershed to another and how vegetation types and seasonal activity patterns effect changes in evaporation demand rates over the basin. Variations in vegetation over the basin can also serve as an indicator of how the LZTWM parameter in the Sacramento model may vary as this parameter is partly dependent on the depth of the root zone.

With vegetation it is also important to try to determine if significant changes have occurred in the amount and type of cover over time. These changes could be due to factors such as changing agricultural practices, large scale harvesting of trees, forest fires, or rural areas being suburbanized. In these cases it will be important to use a period of record that reflects current conditions to calibrate the models.

• Geology – Again this author is not that knowledgeable concerning the details of the information contained in geologic reports. Some people within the NWS have indicated that there are relationships between certain model parameters, especially lower zone free water storages in the Sacramento Model, and variations in the geology of the area. Since soil types are probably related in many cases to the underlying geology, soils data and geologic information may show similar general patterns. If geologic information is available, one mainly wants to be aware of significant changes in properties across the river basin. The more knowledge of geology that one has, the better this information can be put to use during the calibration process.

<u>Climatic Factors</u>

Climatic factors to examine at this point in time are precipitation, temperature, evaporation, snow cover, and frozen ground. One is primarily interested in analyses that show the average value of these quantities on a annual, seasonal, or in the case of snow cover and frozen ground, the average value at various times during the year. The values of these factors during extreme years are also of interest. These climatic factors will have a significant influence on how the river basin is subdivided and how the data are analyzed and processed.

- Precipitation – Isohyetal analyses are needed to assess the variability of precipitation over the river basin. Ideally both annual, plus monthly or seasonal, analyses are available to examine. The primary source of these analyses are the maps produced for the NRCS using the PRISM technique developed at Oregon State University. In some areas there may also be other isohyetal maps available, some which may even involve the use of other data, such as runoff, to assist in the analysis. What is important at this stage is the variation of annual precipitation over the area. This will determine if mountainous area procedures should be used when analyzing the data. If the variation in annual precipitation is small, in the order of ±5% or less, or if the annual average changes very slowly across the basin, then non-mountainous area data processing procedures should be adequate. If there are significant variations in mean annual precipitation over the basin, then mountainous area procedures should be used when generating areal precipitation time series. Variations may be significant even if the terrain is relatively flat due to variations in precipitation amounts based on, for example, distance from a large water body. If mountainous area procedures are indicated, they should typically be used over the entire river basin even though the variation in precipitation may be slight in some subbasins. This is because the ratio of monthly averages between stations is used to estimate missing data in the mountainous area procedure. In order to ensure one station is not estimated from another with a significantly different average value, generally monthly average values need to be defined for all stations. Operationally, over an RFC area a transition can be made from defining monthly averages for each station to not providing these values, as long as monthly averages are defined for all stations that could possibly ever be used to estimate a mountainous station.

- Temperature – The variation in average temperature over the basin determines whether mountainous area procedures should be used when generating Mean Areal Temperature (MAT) time series. Variations in average temperatures can generally be determined using either annual or monthly analyses. These analyses normally use temperature and elevation data. Such analyses are available from NRCS as part of the PRISM project. Significant variations in temperature over portions of the basin indicate that the mountainous area procedure using a synthetic station for each subarea should be used for these regions. The use of the mountainous area procedure for temperature can vary from one watershed or subbasin to the next, depending on the variation of temperature over the area. In general a significant range in elevation indicates that there will be a significant range in temperature. In some cases the variation in temperature could be significant even with flat terrain (e.g. based on the distance from the ocean).

- Evaporation – NOAA Technical Report NWS-33 contains maps showing the variation in Lake or Potential Evaporation (PE) over the 48 contiguous states. In regions of the country where PE varies slowly, the non-mountainous area procedure can be used to determine Evapotranspiration (ET) Demand for use with the Sacramento Model. In regions of the country where there is a considerable variation in PE over a river basin, these maps typically don't define the variation in evaporation in sufficient detail for modeling. In these areas, the mountainous area procedure involving the development of a ET Demand versus elevation relationship is recommended (see Section 6-5). This also true for Alaska.

• Snow Cover – Snow cover data are used first to determine if the snow model should be included when simulating the hydrograph. In areas where snow occurs infrequently or only in small amounts, snow depth data from climatic stations can be used to determine when the most significant snow events occurred. By examining the hydrograph response to snowmelt after such events, one can judge whether snow computations need to be included when simulating the hydrograph. If the response is small compared to even moderate rain events, then the snow model is probably not needed.

Snow Cover data are also used, along with precipitation and temperature data, to help determine if headwater and local drainages will need to be divided into multiple zones. When significantly different amounts of snow typically accumulate in different parts of a drainage, then the area probably needs to be divided into zones in order to get reasonable simulation results. Averages from snow course sites during the time of maximum accumulation can be used to make this judgment. Also, variations in snow depth from climatic sites during large accumulation periods could be used. Satellite snow cover data may also be helpful. In locations where multiple zones are needed, these comparisons will typically not only show different amounts of snow in different parts of the area, but also depletion of the snow cover will occur at different times.

• Frozen Ground -- In regions where data on frozen ground are available, these data can be used to determine if frozen ground needs to be considered when simulating the hydrograph. These data could consist of soil temperatures at individual sites or frost depth analyses. What is most important from a streamflow modeling point of view is whether significant frozen ground can occur and whether there is significant variation in the amount of frozen ground from one year to another. In region, where soils are frozen every year, e.g. permafrost areas, the soil moisture model parameters can probably absorb the effect the frozen soil has on runoff. In such regions frozen ground doesn't need to be included in model computations. Also in regions with significant amounts of snow every year, very little frost will develop in the soil, thus there is no need to model the effect of frozen ground. The primary areas where frozen ground needs to be explicitly accounted for is where cold temperatures occur frequently in the winter and the amount of snow cover varies considerably during these cold periods. It is also more likely that frozen ground is important in non-forested areas since a dense forest acts like a snow cover to insulate the ground. In addition, frozen ground will have a greater effect in regions where the soils are reasonably permeable than in areas with low soil permeability. This is because the existence of frost will have a greater effect on the percolation rates.

Integrated Analysis of Hydrologic Conditions

Introduction

The hydrograph at a point on a river integrates all of the factors affecting runoff generation above that point. By comparing hydrographs at different points within a river basin it is possible to determine if the factors controlling runoff are similar from one area to the next or whether differences exist. These differences may be partly the result of differences in climatic input, i.e. precipitation amounts, temperature, etc. and will hopefully be accounted for by the input time series used for modeling. Other differences may be the result of differences in soil properties, vegetation cover, etc., and thus indicate variations in model parameters from one part of the basin to another. Still other differences can be caused by the effects of lakes, reservoirs, channels, diversions, etc., and thus indicate the need for additional models or runoff adjustments. Generally two types of hydrograph comparisons are useful to examine. The first involves comparing watersheds with few man-made controls in order to get an indication of how parameter values might vary across the river basin. This includes headwater areas and those local areas where a good definition of the hydrograph can be generated by merely subtracting upstream flows from downstream flows. The second involves comparing hydrographs at locations with man-made controls and downstream river locations to determine the effects of such items as reservoirs, irrigation, and channel routing.

Headwater Comparisons

These comparisons involve headwater areas with few complications (i.e. no significant reservoirs, diversions, or regulation of flow). In some cases local areas without complications can be included if a good definition of the local hydrograph can be obtained by merely subtracting upstream from downstream daily flows or by using a simple routing of the upstream flows before computing the local contribution. Also headwater inflows to reservoirs can be included if a good definition of the inflow hydrograph can be computed from pool elevation or storage and outflows from the reservoir. The purpose of the comparisons at these sites is to determine if model parameters should be similar over the river basin or whether they are likely to vary. Variations in the hydrograph response from different parts of the basin can be used to predict which parameters are likely to change and the pattern of these changes. This information may be able to be associated with physical attributes such as soils and vegetation to help in determining which headwater area’s parameters are best to use as the starting point when calibrating other headwaters, including those with complications, and local areas.

The comparisons are done by plotting the results using the WY-PLOT operation graphical display in ICP. Typically in order to not have too many lines on the screen so that one can properly visualize the differences between individual locations, no more than about 7 hydrographs should be included on a single WY-PLOT. In river basins with more than 7 gages to plot, several plots can be created by grouping the streamgage locations in various ways (e.g. by general location within the river basin or by separating those with no complications from those with minor disturbances). Before plotting the hydrographs, some scaling needs to be done so that a proper assessment can be made of the displays. First, the hydrographs should all be scaled to a common drainage area. The drainage area of one of the locations is typically selected as the base and then the other hydrographs adjusted to that drainage area by using a WEIGH-TS operation for each. The WEIGH-TS operation multiples all the daily flows by the ratio of the base area to the area of the drainage being adjusted. Second, in river basins where there is a significant difference in runoff from one part of the basin to another, it may be helpful, in addition, to scale the flows to a common mean annual runoff amount. This again can be done by using WEIGH-TS operations and the ratio of a selected base annual runoff to the annual runoff at each location. A common period of record should be used to compute these ratios. Once the hydrographs are scaled, then the responses can be evaluated.

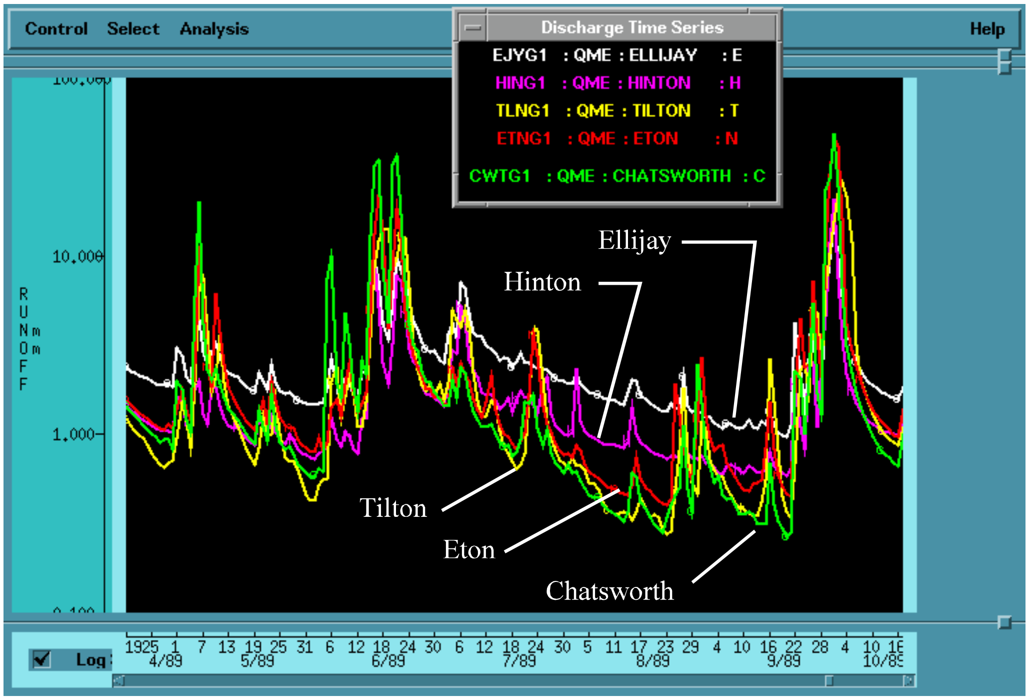


Figure 4-1 - Hydrograph comparisons for Oostanaula River basin.

Figure 4-1 shows a semi-log comparison of 5 locations within the Oostanaula River basin above Rome, Georgia. Eton and Chatsworth are small headwater areas above the Tilton streamgage. The Tilton plot is for the entire drainage above that location. First, it can be seen that the response for the Eton and Chatsworth drainages are very similar to the response for the entire area above Tilton. Since Eton and Chatsworth are not points that require a forecast, they were not modeled separately based on this comparison. If the response for Eton or Chatsworth were different from the entire area above Tilton, then improved simulation results would be likely by modeling the small headwaters separately from the rest of the area above Tilton. Second, it can be seen that there are significant differences between the responses from the Tilton, Ellijay, and Hinton drainages. The amount of baseflow is greatest above Ellijay and least above Tilton. The amount of storm runoff is greatest for Tilton and least for Ellijay. This pattern clearly indicates that the percolation rates for these areas are quite different, since percolation separates fast response storm runoff from slow response baseflow. Most of this difference should be able to be modeled by altering the lower zone free water capacities (LZFSM and LZFPM) from one area to the next though there is also some evidence that the slope of the supplemental baseflow (model parameter LZSK) probably also varies between the drainages (greatest for Tilton, least for Ellijay). Since there are apparent differences in the immediate storm runoff, the UZFWM parameter may also vary between the drainages in addition to the percolation rates. All of this information will be very helpful in deciding how to divide the river basin to get the best simulation results, in making parameter adjustments, and in assigning parameters to other portions of the river basin.

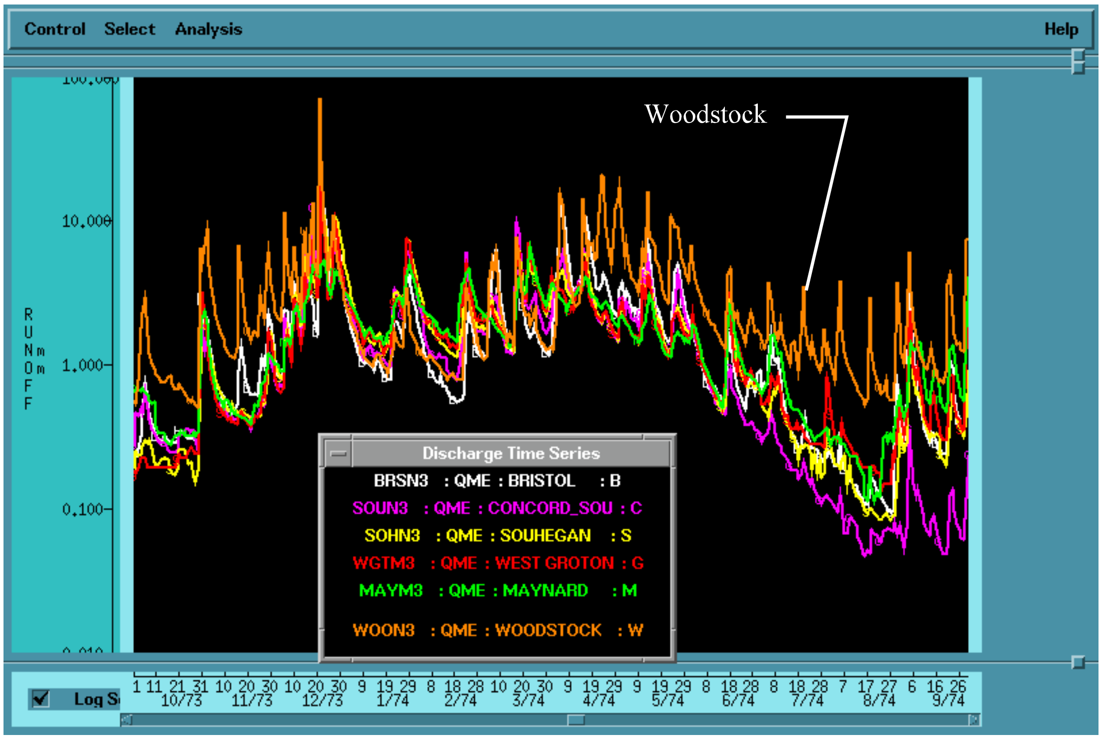


Figure 4-2 - Hydrograph comparison for the Merrimack River basin.

Figure 4-2 shows a comparison of a number of headwater drainages scattered across the Merrimack River basin in New Hampshire and Massachusetts. Even though there is some difference in annual runoff amounts (especially more runoff above Woodstock), the plots are scaled only by drainage area. In this case the shape of the hydrograph response is, in general, very similar from one headwater to the next. This would indicate that there should only be small variations in model parameters from one area to the next. The area above Woodstock (in the White Mountains at the northern end of the river basin) shows some differences in response from the other areas. There is more and later snowmelt runoff in the spring which is expected because of the mountain location. Low flow levels in the summer are higher than for the other areas suggesting that the lower zone primary storage (LZFPM) may be greater for the White Mountain drainages. There is also more quick storm response which is partly due to more rain in the mountains, but may also indicate more frequent surface runoff in this region and thus a lower value of UZFWM.

Figure 4-3 is from a number of headwater areas draining from the east into Puget Sound in Washington. Since there is a very large difference in annual runoff from one drainage to another in this region, the hydrographs are scaled by annual runoff amounts in addition to drainage area. During the fall and winter period the hydrograph response is very similar for all the drainages. During the spring and summer, there are differences in the magnitude and timing of the response. In the spring most of the variation is due to differences in the amount and timing of snowmelt. Some of the areas, such as Arlington, get very little snow accumulation, while others, such as Goldbar, get a lot of snow. During the summer most of the variation is due to differences in glacial contributions, with National, which drains off Mount Ranier, having the greatest glacial effect. Thus, in order to determine whether the variations in hydrograph response between areas can likely be accounted for by varying model parameters or whether there are other causes, one needs to have a reasonable understanding of how factors such as topography, snow cover, and glaciers vary over the region. In this case, it appears that the model parameters should be very similar from one drainage to another and that the differences in the response will be accounted for by the magnitude and timing of snowmelt and the size of the glaciated area.

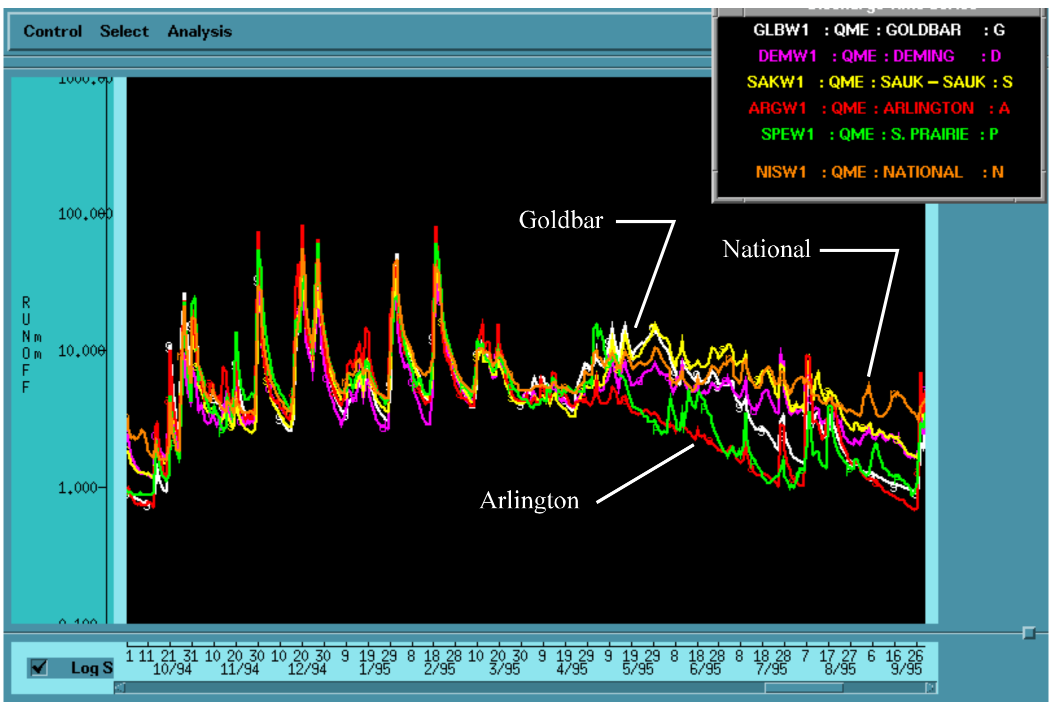


Figure 4-3 - Hydrograph comparison for eastern Puget Sound drainages.

<u>Hydrograph Comparisons at Other Locations</u>

Hydrograph comparisons can be made at other stream gage locations to assist in understanding the effect of features such as reservoirs, lakes, diversions, power plants, etc. and to get a general idea of the lag and attenuation of the flow as it passes downstream through the river channels. In general, these plots will not help with determining possible variations in model parameters, but will assist in determining what modeling procedures and adjustments will be needed to generate reasonable flow simulations and how to divide the river basin for modeling purposes. For these comparison plots, it may or may not be appropriate to scale the hydrographs before plotting the values. If a semi-log plot is going to be used to view the streamflow traces, then the discharge time series should be scaled to a common area since the WY-PLOT operation uses a single area to convert daily flow into depth of runoff. This may be the case when one is comparing the response from headwater areas, affected by such features as lakes or reservoirs, diversions, or power plants. If an arithmetic plot is going to be used, which is normally the case with many of these comparisons, then no scaling is needed. An arithmetic plot is generally used when comparing the flows at a series of downstream river locations to assess the effects of the channel, reservoirs, or other features that affect the magnitude and timing of the flow.

Figure 4-4 shows a semi-log comparison of upstream locations in the Merrimack River basin that exhibit man-made effects. The hydrograph for Bristol is included to show the response for a location with minimal complications. The flows at Ashland, Lakeport, and Tilton are significantly affected by large lakes. Ashland is downstream from Squam Lake. Lakeport is at the outlet from Lake Winnipesaukee and Tilton is further downstream below the outlet from Lake Winnisquam. The effect of the lakes definitely needs to be explicitly modeled in order to produce reasonable simulations at these locations. The low flows at Goffstown during this period are affected by a power plant, which appears to release only a minimal flow on weekends. At this location it will be difficult to adjust the model parameters that control low flow with any degree of confidence. These parameters will most likely be obtained from a similar nearby watershed.

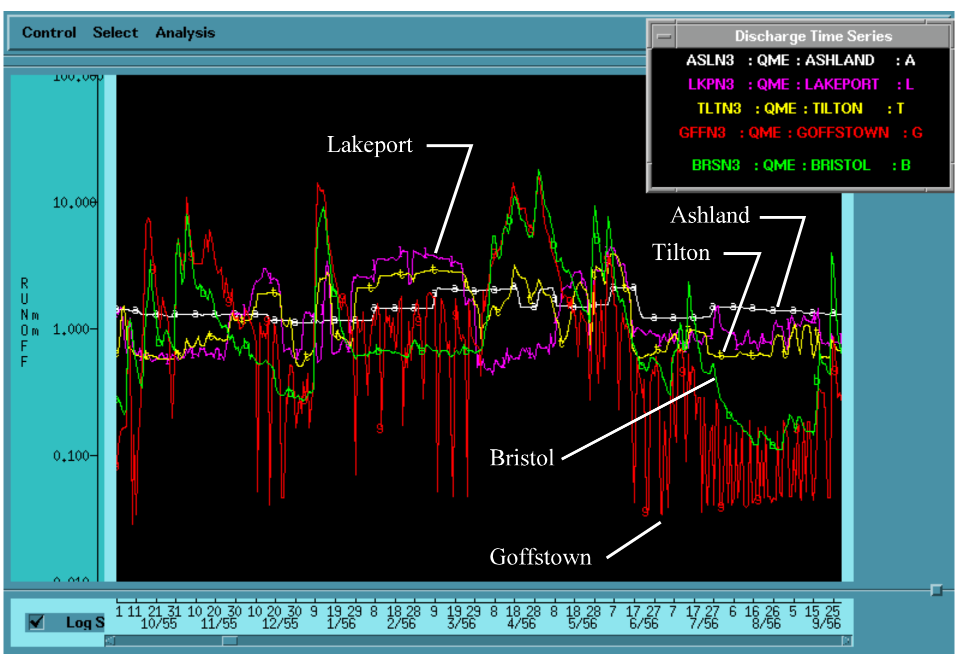


Figure 4-4 - Merrimack River basin locations with man-made effects.

Figure 4-5 shows an arithmetic plot of the hydrographs at several downstream locations on the Merrimack River. This figure indicates that the amount of lag and attenuation is not large as the water moves through the channel system or does it vary significantly with the flow magnitude. It also shows that there are some minor low flow controls, at times, above the further downstream locations. This comparison indicates that channel routing should be fairly straight forward in this basin and that local area hydrographs, determined by subtracting upstream flows from downstream, will exhibit a lot of noise at lower discharges, though a reasonable definition of the local area contribution might be possible at high flows. The computation of the local area flow will also require subtracting gaged tributaries between these river locations and this will affect whether a reasonable local hydrograph can be obtained. Whenever the local area is small compared to the upstream areas, it is difficult to obtain a good definition of the local hydrograph.

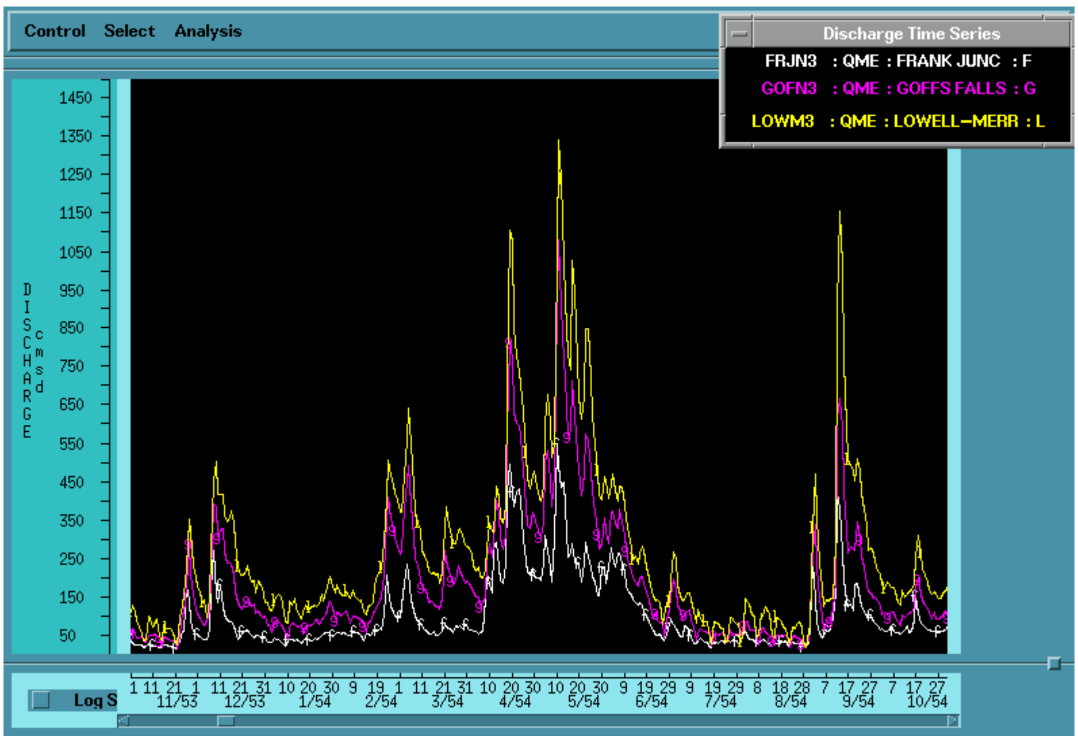


Figure 4-5 - Comparison of Merrimack River basin downstream locations

Chapter 5

Step 3 – Select Flow Points and Period of Record

Introduction

The next step in the calibration of a river basin is to select the locations at which streamflow will be modeled and the period of record to use. The locations to model streamflow are primarily selected based on the location of historical daily flow data, the location of forecast points, the real time operational data network, the spatial variability of hydrologic conditions, and the location of control structures. During calibration streamflow may need to be modeled at more locations than just forecast points in order to properly handle the variation in hydrologic response and the effect of reservoirs, diversions, etc..

There are two periods of record involved in the calibration process. The first is the period to use when processing the historical input data. This period is dependant on the length of the available historical precipitation, temperature, and evaporation records, the consistency of the historical network over time, and the type of forecast products to be generated. The second is the period of record to use when calibrating the models. This period is dependant on the length of the historical streamflow records, the variability and noise in the streamflow data, and changes in vegetation and land use.

It is important to carefully assess all these factors and make a deliberate decision regarding which locations to model and the periods of record to use before processing the data and beginning to calibrate the models. Making these decisions at this point will save a considerable amount of time and effort in the long run.

Selection of Points to be Modeled

The following steps can be followed to determine which river locations should be modeled during the calibration of a river basin.

1. All forecast points with historical streamflow data should be modeled. This includes both existing forecast points and new or potential forecast points. In the case of reservoirs and lakes where inflow or water level is to be forecast, historical pool elevations and possibly outflows will be needed. This is an excellent time to review forecast needs in the river basin and, with input from WFOs and users, decide if all existing forecast points are still needed, whether there are new locations for which forecasts should be provided, and try to anticipate future needs. This includes the consideration of all types of forecasts, including floods, low flow, water supply, recreation, navigation, and reservoir operations. It also includes both short term and extended forecasts. If there are forecast locations that don't have any historical data, then typically a procedure is later developed for operational use that takes the results from a location with historical data and extrapolates those results to the forecast point.

2. River locations that have real time data available and a historical record should in many cases be modeled even if they are not forecast points. Such locations can be valuable in that operationally computations can be verified and adjustments made to improve the lead time and accuracy of forecasts at downstream points. However, if the drainage area reflected at such a location is small and especially when data are sparse, the combination of streamflow measurement and data input errors may make it very difficult to make realistic adjustments. Errors need to be averaged over a sufficiently large area in order to make real time adjustments that will improve the forecast results at a downstream location.

3. Locations at the outlet of reservoirs or lakes that have a significant effect on movement of water through the river system and locations of diversions into or out of the stream network need to be considered for modeling during calibration. Typically there are two options at such locations. First, the control structure can be modeled. In this case historical data such as pool elevation, storage, outflows, or diverted quantities are needed so that a comparison can be made between simulated and observed values. Second, the outflow from a reservoir or lake or the amount of diverted water can be obtained from the agency that operates the structure. Operationally this must include actual, as well as forecast values, so that the operation of the structure will not need to be modeled. During calibration the historical streamflow record will need to be modified to reflect natural flow conditions (described in Section 6-6).

4. Other river locations with historical streamflow data also need to be considered for modeling during calibration based on the variability of hydrologic conditions over the river basin and the available data networks. These gages may be upstream from a headwater forecast or real time data point or they maybe at intermediate locations within the river system. If these gages are at locations where there is likely a significant variation in hydrologic response based on hydrograph comparisons or other information such as soils or vegetation data, then these gages should be considered as possible sites for calibration. Also if the hydrograph response for the area above or between previously determined calibration locations can vary considerably based on the spatial variability of rainfall, then these additional sites may need to be included during calibration. Another factor to consider is whether there is sufficient historical and real time input data, primarily precipitation, to adequately define the areal input if the drainages are subdivided in order to model these additional locations.

After considering all these factors the flow points to be modeled as part of the calibration process can be selected. In many cases, especially in areas with significant variability in hydrologic conditions or rainfall amounts, calibration simulations and comparisons with observed values will be produced at more locations than just forecast points. The inclusion of these extra locations should improve the simulation results at downstream locations and result in more accurate and timely operational forecasts.

Selection of Periods of Record

As mentioned in the introduction for this chapter there are two periods of record that need to be determined. First, is the period to generate input time series such as precipitation, temperature, and evaporation. This is referred to as the historical data period. Second, is the period used to determine the parameters for the hydrologic models. This period is referred to as the calibration period and is typically a subset of the historical data period.

1. Historical Data Period of Record – This period depends on the length of available historical data, the consistency of the network over time, and the type of forecast products to be generated. An appropriate period is based on the influence of each of these factors.

a. Generally in the United States digital records of climatic variables are only available starting in 1948. This is when NCDC started to put the data for all climatic stations in digital form. Records prior to that time have been added to the digital archives when additional funding was available, however, in most parts of the country these earlier records are only for selected locations and do not result in a network that is dense enough for hydrologic modeling.

b. While in most parts of the country the density of the historical network and the representativeness of gage locations are fairly similar over time there are some regions where significant changes occur in network coverage. A prime example is in the western states with the advent of the SNOTEL network maintained by the NRCS. The SNOTEL network consists primarily of high elevation sites where a sizeable snow cover can exist. In some portions of the west there were a reasonable number of high elevation sites prior to the advent of the SNOTEL network, but in other parts of the region there were few, if any, high elevation locations during the earlier years. Most of the runoff in much of the west is generated at the higher elevations. It is generally impossible to produce realistic time series of precipitation at high elevations based only on data from low elevation sites. One can adjust for the annual or seasonal difference based on an isohyetal analysis, but the time distribution and frequency can't be accounted for properly. Much of the precipitation at high elevation locations occurs when no precipitation is falling at lower elevations.

When there are significant changes in the network during the period of available historical data, it may be that only a portion of the data can be used to generate input time series for use in calibration. This is certainly the case in the west for basins where there were little or no high elevation data sites prior to the SNOTEL network. In these basins only the period of record after the advent of the SNOTEL network should be used to generate input time series. In other areas of the west there are a reasonable number of high elevation sites prior to SNOTEL. In some of these areas the entire period of available data can be used to generate time series that have similar properties. In other areas there may be statistical differences in the time series produced with data before and after SNOTEL such that parameter determination and simulation results will differ significantly from one period to the other. In such cases it may be necessary to do some comparisons at selected locations to determine if the different periods of record are compatible. This can be done by generating input time series for the entire period of available data and then calibrating the models using the period with the best data coverage, typically the period with SNOTEL data. After this is done, the parameters determined from this period would be used to simulate the earlier period and a comparison made of the simulation results. If the results are similar for both periods then the entire length of available data can be used to generate input time series, whereas if there are significant differences in results then the two periods will not produce compatible time series and only the later period should be used during calibration.

c. If extended probabilistic forecasts are to be generated anywhere in the river basin or at locations further downstream using flows routed from the current basin, then the longest possible period of record that will produce consistent values should be used to generate input time series. In this case the time series will not only be used for determining model parameters, but will be used as inputs to generate possible streamflow traces with the ESP procedure. The more traces available to statistically analyze after an ESP run, the higher the confidence in the results. Extended probabilistic predictions produced using ESP are primarily of value in river basins where the current state of the system can have a significant effect on what happens in the future.

On the other hand, if extended applications of the ESP procedure will never be used in the river basin or at downstream locations, then only a period sufficient to determine model parameters needs to be used to generate input time series. The considerations in determining this period are discussed in the next section. Due to differences in periods of streamflow data at different locations and the effects of vegetation and land use changes on the period used to calibrate the models, the calibration period for one location within the river basin may not be the same as for others. The period used to generate input time series should overlap the calibration periods to be used for all locations.

2. Calibration Period of Record – This period is based on the length of historical streamflow records, the variability and noise in the streamflow data, and vegetation and land use changes. An appropriate period is selected for each point to be modeled after considering the influence of each of these factors.

a. At a given location within the regions where lumped, conceptual models produce satisfactory results (see Figure 1-1), typically about 10 years of streamflow data are adequate for determining model parameters. This length of record is needed so that one can have reasonable confidence that the noise in the data signals is random. The shorter the period of record the greater the chance that the data noise will not be random, thus resulting in biased parameter values. Parameter sets based on only a few years of data will typically vary from one time period to another. For these regions a calibration period of about 10 years should result in fairly stable parameter values. In areas where the model results are generally marginal, a longer period of record likely is needed in order to have enough events and to minimize the noise caused by the typical large spatial variability of rainfall that occurs in these regions. This longer period is needed so that at least a reasonable degree of confidence can be assigned to the model parameter values. In regions where model results are typically unsatisfactory, it is unlikely that any length of record will be sufficient to determine parameter values with any significant degree of confidence. For the initial headwater basin to be calibrated (see chapter 7 for more details), it is recommended that besides the period used to calibrate the model parameters, that another period be available to verify the calibration results. This period should ideally be at least as long as the calibration period.

b. The period of record selected for model calibration should contain a variety of hydrologic conditions. There needs to be wet periods with high flows, as well as dry periods with low flows. If snow is a factor, there should be years with below normal snow cover and years with above normal cover, as well as near normal years. In regions where climatic indices are proven to have a significant effect, the calibration period should include a full range of values of the index (e.g. if the Pacific Oscillation is important, years with a strong El Nino effect, as well as years when La Nina dominates should be included). At least for the initial headwater calibration, it may be a good idea to exclude the flood of record and the lowest flow period from the calibration and use these events to verify the extrapolation capabilities of the calibration.

c. In areas where physiographic factors are essentially constant over the period used to generate the input time series, any portion of the period that contains sufficient variability in hydrologic conditions can be used to calibrate the models. However, in areas where there are significant changes in vegetation or land use, the portion of the period of record that should be used to calibrate the models is that which most closely reflects current conditions. This is typically the most recent period though, for example, in the case where a watershed has just recovered from the effects of a large forest fire, the period prior to the fire would better reflect the current state of the drainage. In agricultural areas that have seen large changes in crop type or farming practices or for watersheds near metropolitan areas that have undergone considerable suburbanization, the most recent period of record should be used to calibrate the models.

In many river basins the periods of historical streamflow data vary from one location to the next. Also vegetation or land use changes may only affect certain portions of the basin. The aim is to try to find an appropriate period to calibrate the models that is as common to as many flow points as possible. There are a couple of reasons for this. First, when calibrating downstream locations it is best to have observed data at the immediate upstream sites so that errors in the upstream calibrations are not propagated downstream. Second, having observed flows at each point within the basin during the period used will allow for a comparison with total simulated flows to mimic forecast and extended ESP conditions.

Chapter 6

Step 4 - Historical Data Analysis and Processing

Introduction

This step involves analyzing and processing those data that are not yet in the form needed for model calibration. These primarily are precipitation, temperature, and evaporation data. Lumped hydrologic models require mean areal estimates of these variables, thus this step involves the computation of mean areal values from the station data retrieved in step 1. Even if point model computations are to be done, the station data need to be checked for consistency and any missing data gaps filled in. In addition to the areal estimates of model input variables, mean daily discharge data may need to be checked and modified for the effects of diversions or other control structures. The other data needed for model calibration mentioned in chapter 3 should already be in the form needed for model calibration and do not require further processing. These additional data are typically used to verify or modify simulation results.

This is a very important step in the calibration process. There is a tendency in many cases for people to rush through this step in a mechanical, cookbook fashion without carefully evaluating data consistency, understanding the variability in the data fields, and determining how to properly use the available data to generate physically realistic estimates of these input variables. This can easily result in time series that are inconsistent and biased. This is especially true in areas with significant spatial variability in data values on a seasonal or annual basis such as mountainous regions. The snow and rainfall-runoff models are designed to represent those processes and are not designed to deal with the interpolation and extrapolation of data fields. The models do contain some very simple factors for making minor data adjustments (e.g. the SAC-SMA operation contains a precipitation and evaporation multiplier and the SNOW-17 operation includes a precipitation multiplier and a lapse rate adjustment), but these factors cannot make seasonal modifications or deal with inconsistencies. In order for the models to work properly, the input data should represent as closely as possible the scale and seasonal variations that actually occur in nature.

There is also a tendency for people to immediately start to process precipitation and temperature data after downloading the station information. It is very important to take the time for steps 2 and 3, i.e. assessing spatial variability and selecting flow points and period of records. An understanding of the variability of hydrologic and climatic conditions is essential to choosing the proper data analysis procedure. A careful determination of the flow points to be modeled and the period of record to use will avoid having to regenerate time series for different subdivisions of the river basin and different data periods during the calibration process. By carefully doing steps 2 and 3, a considerable amount of time and effort can be saved in the long run and the entire process made more successful and efficient.

The techniques used for data consistency checks and estimating missing data and the procedures recommended for determining mean areal values and assigning station weights referred to in this chapter are not highly sophisticated. This chapter uses well established techniques and procedures based on engineering judgement. Most of the methods referred to in this chapter were devised by people primarily interested in hydrologic modeling. In order to use the models it is obviously necessary to get the data into the form needed for calibration and operational applications. The procedures described in this chapter for data analysis and processing are an engineering solution to the problem, not a scientific hydro-meteorological solution. The underlying objectives for coming up with these methods for preparing the data were to have estimates that reflect the proper scale of what actually occurs in nature and to be able to reasonably guarantee that there would be minimal bias between historical and operational estimates of data quantities. This last objective is critical to successfully using calibration results for operational applications. There is more discussion of potential sources of bias between historical and real time analyses in chapter 8.

This chapter provides a discussion of general topics and tasks that are important in the analyzing and processing of all types of historical data. Details for performing these tasks and recommendations on the steps to follow and procedures to use when working with individual data types are contained in the subsequent sections.

Precipitation, Temperature, and Evaporation

Effect of Data Bias on Model Results

The Sacramento and snow models are very sensitive to biased data. Thus it is very important to remove as much bias as possible when generating areal estimates of input variables. This not only includes overall bias as reflected in mean annual values, but also seasonal biases that can occur due to such things as variations in the precipitation versus elevation patterns and lapse rates. Again remember that the models are not designed to represent how variables like precipitation and temperature vary over the area. These variations need to be handled by the data analysis procedures.

Table 6-1. Change in runoff based on a change in precipitation

Watershed	Change in Precipitation	Change in Runoff
Leaf R. nr. Collins, MS	+10 %	+24.9 %
Bird Ck. nr. Sperry, OK	+10 %	+28.8 %
Smith R. nr. Bristol, NH	+10 %	+17.8 %
Animas R. at Durango, CO	+5 %	+9.7 %

Table 6-1 shows how a change in the overall amount of precipitation will effect the amount of runoff generated. As can be seen the percentage change in runoff is greater than the relative change in the amount of precipitation. Typically the drier the region the greater the difference. It can be seen that a bias in the amount of precipitation will have a significant effect on the amount of runoff produced by the models. In order to compensate for data bias, either evaporation amounts will have to warped or model parameters, especially ones affecting the water balance such as tension water capacities, will have to be changed. Neither of these adjustments will produce the same results as if the precipitation data were unbiased. Also, evaporation demand curves and tension water capacities that should vary in an understandable pattern over the river basin will vary unrealistically if different amounts of precipitation bias exists from one watershed to another within the basin.

Figure 6-1shows the effect of changing the temperature by only 3°F on the timing of snowmelt for the Animas River at Durango, Colorado. This response is typical of a similar magnitude temperature change on other watersheds where snowmelt is significant. In this case the temperature for both the upper and lower elevation zones were changed by the same amount. As can be seen this relatively small change in temperature causes a fairly large shift in the timing of the snowmelt. If biased temperature data are used in a calibration, the non-rain melt factor parameters and parameters that affect the heat deficit and liquid water storage prior to melt could be changed to partly compensate for the biased temperature input, however, the results would not be nearly as good as if the data were properly corrected. In extreme cases one would be tempted to use a melt base (MBASE parameter) of other than 0°C in order to correct the timing of the snowmelt. The use of a non 0°C MBASE value almost always is an indicator of a bias problem with the temperature time series. Also, as with precipitation, one would find that the pattern of melt factors across the river basin would be unrealistic if temperature inputs were biased by different amounts from watershed to watershed.

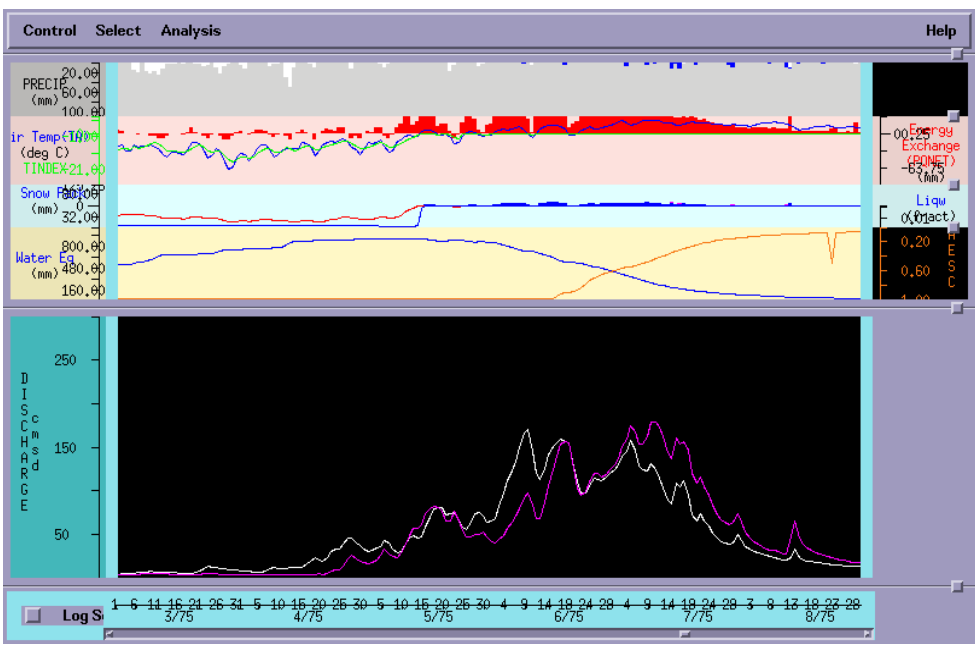


Figure 6-

1. Effect of a 3°F change in temperature - Animas River at Durango, CO

Biased evaporation estimates will also change the amount of runoff computed though the effect is not as great as with precipitation. Model runs on several basins indicated that the change in runoff due to modifying evaporation was about 40% of the change in runoff due to varying precipitation by a given percentage. Again, if such bias exists, it will cause model parameters to be distorted and the variations from watershed to watershed within the river basin will likely not follow expected patterns.

It is very important to carefully analyze the data during this step in the calibration process to minimize any data bias. This is most important in areas where the data values vary from location to location, typically mountainous areas. In such areas it is relatively easy to create biased input time series especially when extrapolating data to ungaged portions, such as high elevation zones.

Mountainous versus Non-Mountainous Area Procedures

Different techniques and procedures are recommended for use in analyzing and processing data based on whether the area is considered to be mountainous or non-mountainous. A non-mountainous area is defined as:

> *An area where the long term average values of the variable being analyzed are essentially the same at all locations within the area. This refers to both annual and seasonal averages.*

Typically for a non-mountainous area the mean values of the variable being considered should be within a range of about ±5% over the entire basin. There can be a general trend of increasing or decreasing average values as one moves across the area, but there should not be any rapid transitions. For non-mountainous areas the recommended techniques and procedures assume that any station can be used to estimate missing data at another station without making any adjustments for differences in magnitude and that areal averages can be computed by weighing stations merely as a function of their x,y plane location (sum of weights will always equal one).

A mountainous area is defined as:

> *An area where there are significant differences in the long term average values of the variable being analyzed over the area. These can be differences in annual or seasonal averages.*

Generally an area that needs to use mountainous area procedures will have terrain differences as these are the most common reason that long term means of a variable will differ from one location to another, however, areas with flat terrain can in some cases require the use of mountainous area methods. For example, long term averages of precipitation, temperature, or evaporation could vary significantly based on the distance from the coast or a large water body even though the terrain is generally level. In the mountainous area procedures, techniques for estimating missing data account for the long term difference in the means between stations. Also, factors other than merely location are used to determine the station weights used to calculate mean areal values (sum of weights do not have to equal one).

It is very important to determine whether mountainous or non-mountainous area procedures should be used prior to analyzing and processing the data for model computations. As far as estimating missing data, if any portion of the river basin conforms to the mountainous area definition, then the entire river basin should use mountainous area techniques. When determining station weights, the use of mountainous versus non-mountainous area methods can vary from one area to another within the basin. To use non-mountainous area methods to determine station weights, all the stations that will be assigned weight for the watershed or subarea should have the same long term average value and all points within the boundaries should have the same mean.

Subdivision of Watersheds

When the flow points to be modeled are chosen, this defines the headwater and local areas for which data estimates need to be provided. However, in some cases these drainages need to be divided into subareas in order to properly model the variations that occur in such quantities as runoff, snow cover, and soil moisture. While areas could be subdivided in many different ways based on such factors as elevation, distance from gage, vegetation cover, soil type, and land use, there are two ways that are commonly used. The first is to divide the drainage into elevation zones and the second is to divide the area based on hydrograph response. Since the conceptual models are being applied in a lumped rather than distributed manner in this manual, the headwaters and local areas are divided into the minimum number of subareas needed to handle the effects of the spatial variability. Typically when subdivision is necessary only 2 zones are required, though in a few cases with extreme variations in conditions, 3 or even 4 zones may be required. From an operational standpoint, it has been found that the fewer the zones, the easier it is to manage real time adjustments to model states and computations.

Elevation zones are used in mountainous areas when the distribution of climatic variables and possibly physiographic factors create significant differences in the amount and timing of runoff. In the United States these differences are almost always related to varying amounts of snow cover and differences in the timing of snowmelt over the drainage. While these differences are not completely based on elevation, elevation is the dominant reason for the variations and elevation zones can easily be delineated. In most of the country when elevation zones are needed, two zones are sufficient with the models used in NWSRFS due to the inclusion of the areal depletion curve concept within the snow model. There are other snow models that divide a mountainous area into many elevation zones. These models don’t use an areal depletion curve, but instead model areal cover based on which zones have snow and which are bare. However, even with the use of the depletion curve there are some areas that will require more than two elevation zones in order to get satisfactory results. These are typically drainages with large elevation variations or watersheds that are partly covered by glaciers. Also, if significant rainfall events are common late in the melt season, additional zones may be needed. Typically there is more snowmelt than ET during much of this period so that the tension water storages in the soil model remain full, even though only a small portion of the area is covered by snow. In reality, when rain occurs late in the melt season, areas that have been bare of snow for some time have dried out and thus, the amount of runoff tends to be over computed. Adding additional zones can reduce this problem. Section 6-1 describes some criteria for determining when elevation zones are needed and guidelines for selecting the elevations between zones.

The second main reason for subdividing a headwater or local area into subareas is based on variations in hydrograph response due primarily to differences in the spatial distribution of rainfall. If the time to peak and/or the shape of the hydrograph can vary significantly based on where most of the rainfall occurs, then the drainage should possibly be subdivided so that these differences can be modeled. Besides differences in response, a precipitation gage network that can adequately define the spatial variation in the rainfall is necessary for the subdivided drainage to produce improved model results. One of the common cases for subdividing based on hydrograph response is when the shape of the drainage is long and narrow. In such a watershed, the response is normally quite different when most of the runoff comes from the upper end of the area as compared to a storm centered just above the gage. In this case the drainage would be subdivided by travel time. In other cases where the shape of the response varies, the subdivision might be based on the configuration of the channel network, e.g. one main branch of the stream network might be separated from another branch.

After making decisions as to whether any of the headwater and local areas need to be subdivided and, if so, delineating subareas based on elevation or drainage boundaries, the areas for which precipitation, temperature, and evaporation estimates must be computed are now defined. Also, at this point it should have been decided whether mountainous or non-mountainous area methods will be used to produce the areal estimates. The next step is to check the consistency of the data prior to computing the mean areal values.

Data Consistency Checks

The station data used to compute areal estimates of precipitation, temperature, and evaporation should first be checked for consistency and adjusted if necessary. By consistency we mean whether the data record is consistent over time, i.e. whether the record at a station maintains the same relationship over time to the other stations in the basin. Station consistency is checked by using a double mass analysis. In this technique the data for each station is plotted against the average of the data for a group of other stations. If the group is reasonably large, the average for the group is not significantly affected by inconsistencies in individual stations, but changes in the record for the station plotted against the group will be revealed. The main problem associated with consistency checks is separating real changes in the stations data record from natural variations that occur. When making consistency checks and adjustments it is very important not to remove the natural variability of the data. The underlying rule when making adjustments should be that if there is any doubt that the correction should be made, then don’t make the adjustment.

Inconsistencies in data records occur primarily for two reasons. First, the station is moved to a new location with a somewhat different climatic regime and a different exposure. This is the most common cause of an inconsistency. Second, there is a change that occurs at the site, such as an equipment change or a change in the exposure of the gage. This can include a new type of gage being installed, a wind shield installed or removed from a precipitation gage, a new building built near the site, or vegetation growing or removed from near the instrumentation. For many of the newer automated networks, moves and site changes are infrequent, thus inconsistencies in the data record are rare. Within the NCDC climatic network there are also stations that have remained in one place with the same equipment for many years, however, there are also stations that are moved periodically due to changes in observers. These are the stations that most frequently require adjustments for inconsistencies. Unfortunately, the records of station moves and equipment changes for the climatological network are not totally reliable. Comparisons made between different sources of station changes such as the Daily Climatological Bulletins, NCDC meta data files, B-44 forms filed by network managers, and records from state climatologists are not always consistent. Thus, changes may have occurred at a station even if the records you have available at the time do not indicate a move or equipment change. However, going along with the underlying rule mentioned earlier, if there is no documentation of a station change, don't make an adjustment unless it is very clear that a correction is needed.

The reason for making adjustments and removing inconsistencies prior to using the data to compute areal estimates of the input variables is to avoid having differences or bias between one portion of the historical record and another. If a reasonably sizeable inconsistency exists and is not removed and that station has a large weight in the computation of an areal estimate, then a significant bias will result from one portion of the areal estimate to another. As we have seen, the hydrologic models are quite sensitive to data bias. Model parameters determined using the record prior to the inconsistency will not be the same as parameters based on the period after. Results obtained using parameters determined from one period will be biased when those parameters are run on the other portion of the period of record. If the model parameters are based on a period that doesn't reflect the current status of the station, then operational results will be biased compared to those obtained during calibration.

Details on the procedures used to make consistency checks and adjustments and guidelines for using these procedures are contained in Section 6-2.

Computation of Mean Areal Values

Once the data have been checked for consistency and any corrections made, it is time to generate mean areal estimates of precipitation, temperature, and evaporation for use in model calibration. The analysis methods and techniques used vary as to whether an area is classified as mountainous or non-mountainous. The objective is the same in all cases, i.e. to obtain an estimate that is as unbiased as possible compared to what occurred in nature and to minimize the random errors in those estimates. For precipitation and temperature the methods used in NWSRFS involve estimating all missing station data and then determining appropriate weights to assign to the stations to compute a mean areal estimate of the variable. This is also true for evaporation in some cases, but more frequently average climatic estimates of evaporation are used when calibrating the models. The recommended procedure for generating mean areal estimates of precipitation are in Section 6-3, temperature is in Section 6-4, and evaporation is discussed in Section 6-5.

Mean Daily Discharge Data

Possible Adjustments

Mean daily discharge data are used primarily to evaluate simulation results by comparing the model computed values to the observed data. For streams that do not have any man-made control structures, the model simulations can be compared directly against the observed natural flow in the river. When control structures exist, there are two options. The first is to model the operations of all of the controls so that a direct comparison can be made between the computed discharge and the observed controlled flow. The second is to adjust the observed daily discharge to remove the effects of the control structures so that these time series now reflect "observed" natural flow conditions. Prior to using the streamflow data, it is probably a good idea to check its consistency. Such a check could uncover variations in measurement techniques, but more likely will provide insight to alterations in runoff produced by such things as forest fires, changes in land use, different agricultural practices, variations in irrigated acreage, and changes to diversions which might otherwise not be noticed. Instantaneous streamflow data, when available, could also be adjusted for control structures, but this is more difficult and is usually not done. Section 6-6 describes possible checks and adjustments to mean daily discharge data.

Extension of Historical Data Record

As time goes by there likely will be a need to extend the historical data record.   Reasons for extending the record were listed in chapter 2. When doing a data extension, it is very important to insure that the additional record is unbiased and consistent with the previous record. Since model parameters are based on the data used in the original historical analysis, the time series extensions must be unbiased as compared with the initial period used for calibration.   When generating extensions, it is critical to do the following:

- New data for stations that were included previously should be checked for consistency with the prior data for these stations and adjusted if necessary (this typically requires that station data for some period prior to the extension, typically about 10 years, be available to use when generating consistency check plots - any consistency adjustments that were used for these stations for this period should be applied before producing the plots). Also, data for any new stations that are being added to the analysis should obviously be check for consistency.

- Station and areal means for precipitation, temperature, and evaporation that were determined for the original complete historical data analysis should continue to be used until another complete data analysis is performed (e.g. if 30 years of data were used when the river basin was first calibrated, and later the record was extended by 10 years, and now it is being extended by another 10 years, the means for the original 30 years of data should be used when processing this latest extension), and

- Mean values for new stations need to be determine based on their relationship to stations with a long historical record that were used in the original analysis using the techniques included in PXPP for precipitation (uses the average ratio of precipitation at each new station to the amount recorded at a well established station) or as outlined in Section 6-4 for temperature data (uses the average difference between each new station and a station with a long record). Typically, based on experience, about 5 years of data are needed at a new station in order to compute a stable estimate of the mean values. Less data can be used, but the estimate of the mean values will not be as reliable.

Historical data extensions are possible when the types of measurements, processing methods, and networks are the same as used in the original analysis. When new types of measurements (e.g. radar based estimates of precipitation), new processing methods (e.g. switching from non-mountainous area to mountainous area procedures), or significant changes in the network (e.g. the addition of a high elevation gage network in an area where previously there were low elevation stations) occur, the historical data analysis should generally be completely redone. In some of these situations it may be possible to produce values that are consistent and unbiased compared to the previous analysis and thus can be used to extend the existing record, but this is difficult to accomplish. In addition, for many of these cases the period of the historical data record that can be used will change since the new measurements or network are only available for a limited time. Unless the new data can be proven to be unbiased and consistent with the previous record, the models must be recalibrated so that the parameters are compatible with the new data. This new historical data period then becomes the base period to use for any future extensions of the record.

Section 6-1

Determination of Elevation Zones

Introduction

Elevation zones are used in mountainous areas primarily to model differences in the amount of snow that occurs and the timing of the resulting snowmelt. A watershed could be divided into elevation zones solely based on variations in the amount of rainfall and resulting runoff, but this seldom is the reason for using elevation zones in the United States. As far as what each elevation zone represents and methods for selecting the separating elevations, the United States can be divided into 2 general regions for discussion purposes. First is the intermountain west, i.e. the area east of the Pacific crest over to the plains, in other words, the Rocky Mountains and the east side of the Sierra Nevada and Cascade ranges. Basins in this region are typically dominated by snowmelt runoff and elevation zones are primarily used to separate the portion of the watershed that contributes significant runoff every year from those that normally don't produce much runoff except during an exceptionally large snow year. Second are mountainous regions where runoff is typically generated at all elevation zones and rainfall is a significant factor in runoff production. This includes a few areas in the eastern U.S., primarily in the northeast, the Pacific coastal drainages, and much of Alaska.

Intermountain West

In much of this region the annual hydrograph, at least from those watersheds that produce enough runoff to generate satisfactory or at least marginal results with a lumped, conceptual model, generally shows a large rise beginning in the spring that is the result of snowmelt and only a few responses at other times of the year caused by rainfall. Most basins in this region produce significant amounts of baseflow, thus there is typically a long recession following the snowmelt period. Rainfall in this region infrequently produces significant amounts of runoff over large areas (as opposed to small scale thunderstorms). Such events occur primarily in the northern part of the region due to moisture coming over the mountains from the Pacific northwest and in the southern part of the region due to moisture moving up from the south into Arizona, New Mexico, and southwestern Colorado. The primary reason for using elevation zones in this region is to separate the portion of each watershed that produces significant runoff every year from the part that generates runoff only during years with large snow accumulations. Throughout this region two elevation zones should be sufficient.

A method for selecting the elevation at which to divide the watersheds in this region is based on areal snow cover information and hydrograph response. The following data are needed:

1. Areal snow cover images at various dates just prior to and throughout the snowmelt period. These images are produced by the NOHRSC from analysis of satellite data. The images should be from a number of years with varying amounts of snow cover, though years with

below normal snow amounts are of most value.

2. Mean daily flow hydrographs for the watershed for the same years as the areal snow cover data.

The steps to follow are:

1. For each date with an areal snow cover image, determine the average snowline elevation over the watershed. Typically this elevation is similar for all watersheds within the river basin, but differences can occur due to factors that affect the accumulation and melt processes, such as slope, aspect, vegetative cover, and prevailing storm direction. The CAP should contain a method to access these images and determine the snowline elevation.

2. Tabulate the snowline elevations on the hydrograph plots for the watershed for each date. The snowline will typically be lowest prior to the onset of melt, but will also move down the mountains after periods of snowfall during the melt season

3. By examining all the years, select the elevation above which snow exists just prior to the beginning of significant runoff during almost all years. This is the elevation to use to separate the zones for modeling. During years with considerable snow and above normal runoff, the snowline at the onset of significant runoff will be lower than that during below normal runoff years. What one is looking for is the highest snowline elevation just prior to the beginning of significant runoff during all the years or, in other words, the elevation above which snowmelt always produces a rise in the hydrograph. This elevation is usually determined by looking at some of the below normal runoff years and possibly averaging the snowline elevations prior to significant runoff for these years. If there is a very low snow year, i.e. runoff far below normal, it is probably best to ignore that year. When later modeling such a low snow year hopefully the snowmelt runoff volume will be reasonable, though the timing of melt will be too early since the snow during that year is really only in the upper part of the upper zone.

Figure 6-1-1 shows an example of a below normal runoff year for the Animas River above Durango, Colorado which could be used to determine the elevation separating the upper and lower zones. In this case, the snowline was at about 10,000 feet just prior to the onset of significant runoff. The use of this zonal split elevation resulted in good simulation results. Figure 6-1-2 shows the snowline elevations for an above average snow year for the same basin. It can be seen that significant runoff was generated due to snowmelt at elevations below 10,000 feet. By splitting the watershed at 10,000 enabled the models to properly simulate both of these years. In water year 1981 very little runoff was generated from snowmelt in the lower zone while in 1985 this zone produced significant runoff. The upper zone produced runoff during both years. Figure 6-1-3 shows simulation results for the lowest snow year on record, 1977. The snowline elevation prior to melt during this year was over 11,000 feet and was significantly higher than for other low snow years and thus not used when deciding where to

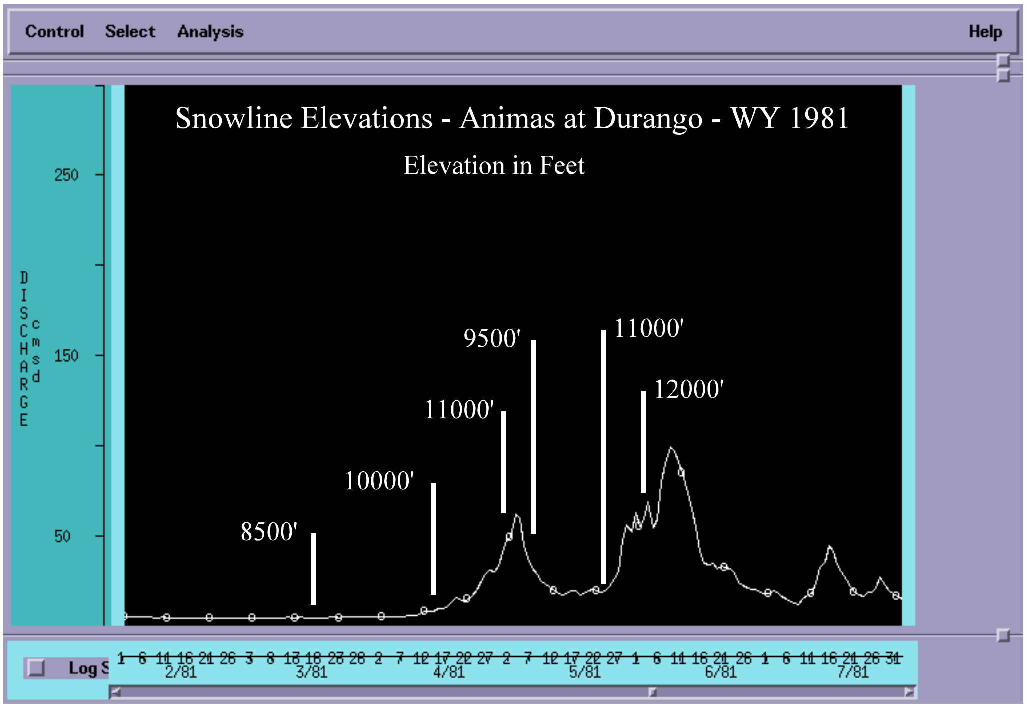


Figure 6-1-1. Snowline elevations during a below normal runoff year.

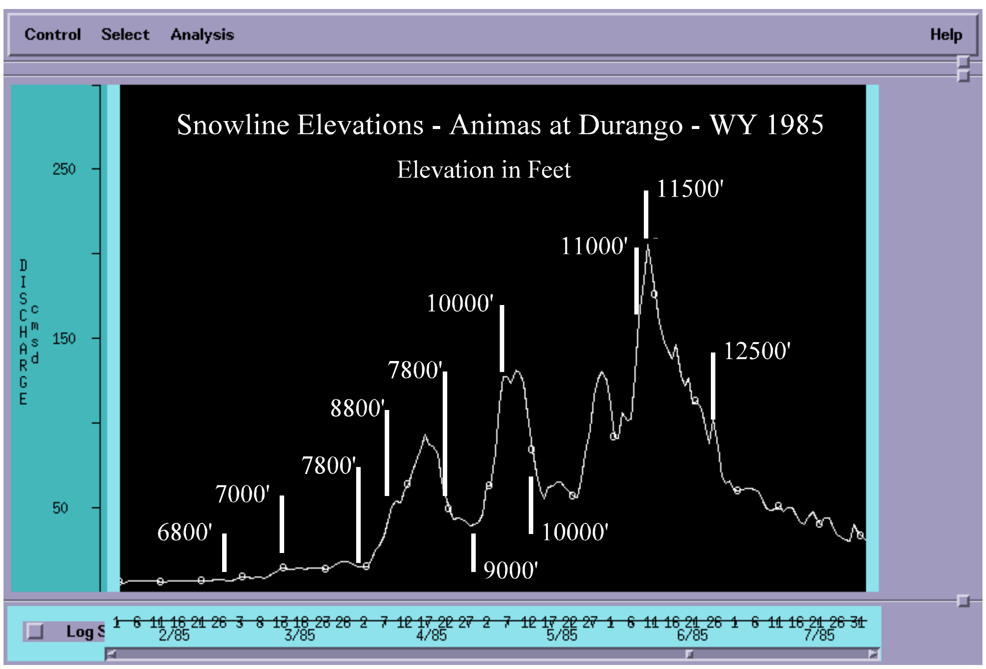


Figure 6-1-2. Snowline elevations during an above normal runoff year.

divide the two zones. The snowmelt runoff volume for this year was simulated quite reasonably, but as expected the timing of the melt is early. Three elevation zones could be used to better simulate such a small year, but generally the added benefits don't justify the added work of operationally maintaining the state variables for an extra zone.

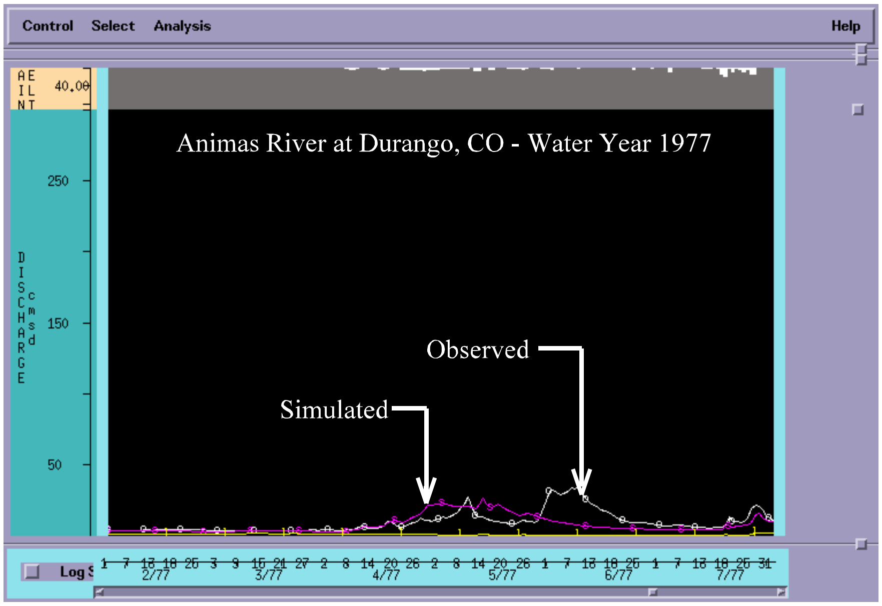


Figure 6-1-3. Typical response during the simulation of a very low snow year.

In addition to areal snow cover data and the response of the hydrograph, vegetation information can be very helpful in selecting the elevation separating the 2 elevation zones in the intermountain west. The type of vegetation that grows at a particular location is highly dependent on the prevailing moisture supply. Thus, in many cases there will be a transition from one type of vegetation to another at the elevation separating where runoff occurs almost every year and where it only occurs during very wet years. In much of the intermountain west this is the elevation where the transition from pines to a predominately fir-spruce forest occurs. In the southern part of the region, e.g. the Mogollon Rim area of Arizona, there is only a small portion of the area that produces significant snow runoff every year and has predominately fir-spruce forests, thus it may be better to split the watersheds at a slightly lower elevation where the transition from pinon pine-juniper to ponderosa pine forests occur. CAP should contain information on the types of forest cover and the distribution of vegetative types with elevation.

Northeast, Pacific Coast, and Alaska

In the northeastern part of the United States, the Pacific Coast drainages which primarily involve the west side of the Sierra Nevada and Cascade ranges, and Alaska, significant runoff is generated at all elevations, but the amount and timing of snowmelt runoff varies considerably with elevation. During most storm events precipitation occurs at all elevations, but in many cases there is a transition from rain at the lower elevations to snow at the higher locations. Thus, in these regions elevation zones are needed to properly model the accumulation and ablation of the snow cover throughout the watersheds. The general breakdown in zones that you are trying to achieve in these regions are:

- zone where there is a significant snow cover during all years,
- zone where a significant snow cover exists only during substantial parts of some years,
- zone where snow seldom occurs and any snow cover exists for only short periods,
- zone that is permanently covered by snow and ice, i.e. glaciated areas which occur in some Pacific northwest basins and frequently in Alaska.

In the northeastern United States there are only a few areas with a significant range in elevation to justify using multiple zones. This primarily occurs in the White Mountain region of New Hampshire and possibly in a few watersheds in Maine, the Andirondack region in New York, and the Allegany highlands of West Virginia. In the southern Appalachian Mountains there are significant elevation differences, but snow is typically hydrologically unimportant. In the northeast 2 zones are sufficient when they are needed at all. Along the Pacific Coast and over portions of Alaska only 2 of these elevation zones comprise the vast majority of the drainage area and thus are sufficient for modeling. In glaciated basins in Alaska and fairly frequently in other parts of these regions, however, 3 or even all 4 zones exist and need to be included. In some of the watersheds a snow cover exists over the entire drainage every winter, but there is still a significant difference in the amount and timing of snowmelt with elevation. This is especially true in Alaska. In these cases, 2 elevation zones are still needed to model the seasonal snow cover and its contribution to runoff. If glaciers are present in these watersheds, then a third zone would be required.

The elevations used to separate the elevation zones in this region are primarily determined by examining areal snow cover information from NOHRSC and snow depth and water equivalent data at various locations. These data can be examined for a number of years and a subjective determination made as to what elevations to use to separate the zones. The elevations selected should be able to be used over a fairly wide area. Along the Pacific Coast the elevations separating the zones should likely decrease as one goes further north as average temperatures generally decrease and thus snow is more likely to accumulate at lower elevations. In Alaskan basins where there is substantial snow cover over the entire drainage every year, the tree line elevation may be a reasonable place to separate the zones.

Section 6-2

Consistency Checks for Precipitation, Temperature, and Evaporation

Basic Method

Consistency of precipitation, temperature, and evaporation data from individual stations is checked using a double mass analysis. NWSRFS contains consistency check options within each of the programs that are available for processing these data types, i.e. the PXPP and MAP programs for precipitation, the MAT program for temperature, and the MAPE program for evaporation. In addition a graphical user interface program, IDMA (Interactive Double Mass Analysis), is available to display the consistency plots generated by the processing programs and to interactively make consistency corrections. When using these processing programs the first step is to check the consistency of the data and make any adjustments needed prior to computing mean areal values for use in model calibration.

When using a double mass analysis technique it is essential to include enough stations so that inconsistencies in individual stations can't have a significant effect on the consistency of the computed group average. Typically when performing the data analysis for an entire river basin or on a regional basis, there are more than enough stations, however, in case the technique is being applied to a smaller network it is recommended that at least a minimum of 10 stations be included.

For precipitation and evaporation the consistency checks involve plotting the data for one station against the average of the data values from a large group of stations. This is because the relationship between precipitation and evaporation stations is normally expressed as a ratio, i.e. it is said that one station typically has a certain fraction of the value observed at another station, the average of a group of stations, or an areal averaged value. The accumulated value for the station is plotted against the accumulated value of the group average. In NWSRFS in order to more clearly see changes in the relationship between one station and the group, the deviation of the accumulated station average from the accumulated group average is plotted against the accumulation of the group average. The group average is computed based on all the stations in the group minus the station being plotted against the group. Thus, the accumulated group average generally changes slightly from one station to another and therefore there is not a direct relationship between the accumulated group average and a specific date in time.

For temperature the consistency check involves plotting the deviation between the accumulated average temperature for a single station and the accumulated average temperature for a large group of stations against time. This is because the relationship between temperature stations is normally expressed as a difference, i.e. it is said that one location is a certain amount colder or warmer than other locations on the average. Separate plots are generated for maximum and minimum temperatures.

For all these data types the record for the individual station is consistent over time if the relationship between it and the group plots generally as a straight line. However, there is a lot of variability in nature such that the relationship between an single station and a group of stations will not be perfectly straight. These random variations in the relationship will cause the plotted lines for each station to wobble. As long as the general trend of line is straight and there are not significant deviations from the general trend line, the data are consistent. Inconsistencies are indicated by changes in the slope of the line that are of a significant magnitude and last for a reasonably long period of time to be caused by something other than the natural variability in the data fields. The trick is to be able to recognize inconsistencies and adjust the appropriate data periods without removing the natural variations that exist in the data. Precipitation data typically are much more spatially variable than temperature and evaporation, thus consistency plots for precipitation generally exhibit more wobble than plots for the other variables.

NWSRFS Program Options

The NWSRFS programs with consistency checks contain options for specifying the number of groups, the stations assigned to each group, the stations to be included on each plot, and whether to do precipitation checks on a seasonal basis.

Generally all the available stations within the river basin are included in a single group. In this case each station is then plotted against the average for all the other stations. NWSRFS does contain the option to have multiple groups. It was initially thought that it would be better in mountainous areas not to put all the stations in one group, but instead group the data by some factor such as elevation or mean annual value. This feature still exists, but experience has shown that typically nothing is really gained by trying to use multiple groups when making consistency checks. Also, generally all the stations in the group are used to compute the group average even though the option exists to remove some stations from this calculation (option not in PXPP). This option is seldom needed since normally there are enough stations involved in the group that the effect of any one station is minimal. If the data for a station are so questionable that it should not be part of the group average, the station probably shouldn't be included in the analysis in the first place.

The consistency plots generated by the NWSRFS data processing programs display a maximum of 5 stations per plot. When a large number of stations are being included for a river basin, it is very important as to how the stations are grouped for plotting, especially in the case of precipitation. As indicated earlier, inconsistencies typically show as a change in the slope of the double mass plot that persists for a reasonably long period of time. For precipitation data such changes in slope can also occur due to shifts in storm tracks or storm types over an area like a river basin and can persist for a number of years. For example, changes in storm tracks can cause one side of the basin to catch more precipitation relative to the other side than normal for a period of several years or changes in prevailing storm types can change the relationship between high and low elevation stations for a period of time. Thus, the selection of which stations are included on each plot is important. Selection should be made so that stations in the same geographical part of the basin or with similar elevations are displayed together. When this is done, then real shifts that occur over the basin due to climatic changes can be recognized and not inferred to be inconsistencies in the data. When many of the stations in the same portion of the basin or at similar elevations exhibit a change in the slope of their consistency plots at the same point in time, this is an indication that this is a real shift that occurred in nature and should not be adjusted. When only a single station exhibits a change in slope, then it may indicate an inconsistency. Temperature and evaporation stations should also be grouped by location or elevation for plotting purposes though such pattern shifts are less likely to occur with these data.

With precipitation data the option exists to perform consistency checks on a seasonal rather than an annual basis, i.e. separate plots are generated for the winter and summer seasons. The decision to do consistency checks on a seasonal basis is independent of whether station weights are specified on a seasonal basis though the NWSRFS programs do force one to use the same definition of the seasons for both options. Consistency checks for precipitation should be done on a seasonal basis when snowfall dominates some months during the winter. This is because the effect of gage exposure or equipment changes is generally much larger when the precipitation is in the form of snow rather than rain. Thus, if a station is moved or a wind shield added, the existence and magnitude of an inconsistency are highly dependent on the form of the precipitation. The NWSRFS programs allow only for the separation of precipitation into different consistency plots based on month of the year, not on an event or time interval basis. Thus, the winter season should include those months when snowfall predominates and the summer season when the majority of the precipitation is rain. Seasonal precipitation consistency plots should be used whenever snowfall is significant over the river basin.

Guidelines for Making Consistency Corrections

There are a number of factors to consider when analyzing the consistency plots and making corrections for apparent inconsistencies in the data.

- Consistency corrections can be applied only to periods with observed data, not to periods of estimated values. Thus, it is first important to delineate those periods that contain missing values and are thus estimated from those periods with observed data. The PXPP program works only with monthly precipitation totals. A month is treated as missing and thus estimated whenever any data are missing during the month. The other programs estimate only those days or hours that are missing, thus a month can contain a mix of observed and estimated data. The IDMA program tries to designate when data are observed and when the values are estimated by changes in the color of the plotted line. Estimated data periods may not be consistent with the observed data periods for some stations, i.e. the slopes of the plots during these periods may vary. However, once the inconsistencies have been corrected for all the stations, the estimated data periods for all stations should plot at the same slope as the observed data periods, i.e. the trend of the entire plot should be straight.

- Inconsistencies should occur only when a station is moved or there is an equipment change that can affect the measurement. Thus, it is important to have the meta data that indicates the type and time of modifications to a station. Actual moves and equipment changes, such as adding a wind shield or converting from a weighing gage to a heated tipping bucket gage at a precipitation observation site, should be marked on the plots as possible times when inconsistencies can occur. Inconsistencies seldom occur in any network that is stable, i.e. there are no site relocations or equipment changes. The network that is most susceptible to inconsistencies is the national climatological network maintained by NCDC. This network relies on volunteer observers for the most part and station relocations occur quite frequently. In some cases when a station is relocated, a new station number and name are assigned and thus you have a new record. In other cases when a move occurs, the station number remains the same, though the name will be modified by changing the distance and direction from the nearest town, e.g. ANYTOWN 1N may be changed to ANYTOWN 5SW. When a move occurs there are not clear rules as to when a new station is established and when the number remains the same and just the name is modified. Sometimes a site can be moved only a couple miles and a new number is assigned, while in other cases a station can be moved 15-20 miles and the number remains the same. In one case a station was not moved at all, but the number was changed when the two word name was reversed thus changing is alphabetical position. Frequently when a station is discontinued and a new station is established just a short distance away, the records are merged prior to being used in the data analysis programs. Obviously the time of this move should be examined for a possible inconsistency in the record.

• Data should generally be made consistent with the current location of the instrumentation. This is especially true for a real time reporting site. However, if the data for the current location seems unreasonable when compared to nearby gages, then either the data should be made consistent with another portion of the period of record or the data for the current location should be ignored by setting it to missing. When using climatic stations that have been discontinued and are no longer in use, the data can be made consistent with any portion of the period of record that you choose. If a correction is applied to the current location of a real time reporting station, this correction should also be applied in OFS.

• For temperature data the mean monthly max and min temperatures at each station are used to estimate missing data. These mean monthly values are computed from the observed data for the period of record being used. When corrections are applied to portions of the observed record, the mean monthly values for that station are altered. For precipitation the computation of monthly means is done automatically within the PXPP program, however, no preliminary processing program currently exists for temperature, thus the mean monthly temperatures must be manually adjusted whenever a consistency correction is applied to a station. The MAT program contains the option to compute and output the new monthly means, but the user must manually take this output and use it to edit the input file. This should be done after every run that involves new consistency corrections. Since the revised monthly means are not computed until after the corrections are input, the program is typically using the monthly means from the previous run which are not correct whenever new adjustments have been entered. Thus, it is necessary at the end to make one final run with no new adjustments

• Consistency plots will show random wobbles due to the natural variability of the data. Precipitation data will generally show more of this variability than temperature or evaporation. Consistency plots can also exhibit a seasonal wobble caused by variations in the relationships between stations, especially due to elevation. Especially in the intermountain west the precipitation relationship between high and low elevation sites varies considerably from one time of the year to another. There is also typically a seasonal variation in lapse rates for temperature. The extreme case is in portions of Alaska where temperature decreases with elevation generally in the summer, but in the winter inversion conditions can persist even for maximum temperatures at interior locations during the months with the least sunlight. These effects can cause natural seasonal wobbles in the consistency plots.

• Sudden jumps in a consistency plot for a station indicate that there may be some bad data in the record. In the case of precipitation, the jump could occur because that station received much more precipitation during a given month than any of the other stations, typically from an intense thunderstorm directly over the gage. However, in most cases, discontinuities in the plots are due to improper values being entered into the data record for a station. The bad data at one station can cause bad estimates at nearby stations therefore causing jumps in their plots also. A little detective work should find the culprit. There have been some problems, at least in the past, with hourly precipitation data not being able to be decoded properly, resulting in a number of months of data that should be missing being set to all zeros. If the problem period is long enough, this should cause a shift in the slope of the consistency plot. Such a period will not respond to a correction factor since zero times any factor is still zero.

• There is a greater chance of inconsistencies occurring in mountainous areas than in flat terrain. This is because in mountainous areas the amount of normal precipitation can vary by a considerable amount over a fairly small area due to orographic effects. Thus, when a station is relocated there is good chance that the average amount of precipitation being caught will change. There is also a greater chance for inconsistencies to occur in regions with substantial snowfall than in regions where most or all of the precipitation is rain. This is because snowfall catch is greatly affected by the exposure of the gage to wind. Station relocations will frequently change the exposure of the gage. In general, one will find a greater need to make consistency corrections in mountainous areas with substantial snowfall where there are periodic site relocations. In a region of flat terrain with only rainfall, inconsistencies should seldom occur.

• The aim is not to see how many “inconsistencies” one can find, but to preserve the variability that occurs in nature and correct only those periods that clearly need to be corrected. It is also not rational to go to the other extreme and assume that consistency adjustments will just distort the observed data and therefore avoid making consistency checks. There are clearly times when the measurements at a station are modified by a relocation, equipment change, or alteration of the site surroundings. These changes to the observed data need to be adjusted so that model parameters can be reliably determined during calibration and that these parameters will be applicable for forecast applications. One should adjust those periods that clearly need to be corrected, but if there is any doubt as to whether an adjustment is needed, it is best to not make that correction.

By taking all of these factors into account, one should be able to adjust the data record for any significant inconsistencies without removing the variability that occurs in nature.

Mechanics of Computing Consistency Corrections

Even though the IDMA program will compute consistency corrections for you, it is a good idea to understand how the corrections are calculated. The calculations can be done in several ways. Following is one method.

1. For each station determine the line segment that the data should be made consistent with. As mentioned earlier this generally corresponds to the most recent location of the gage.

2. Draw a line that is parallel to the line segment from step1 that originates at the beginning of the period of observed data for the station. This is referred to as the “Corrected Line”. Note that this line will start after the beginning of the period being analyzed when measurements aren’t initiated for a given station until a later date, thus the data for the first part of the analysis period are estimated.

3. Compute corrections as:

Precipitation or evaporation:

$$A_{t,t'} = \frac{\left(S_t - S_{t'}\right) + \left(C_t - C_{t'}\right)}{\left(S_t - S_{t'}\right)} \qquad (6\text{-}2\text{-}1)$$

Temperature:

$$A_{t,t'} = \frac{\left(C_t - C_{t'}\right)}{\Delta N_{t,t'}} \qquad (6\text{-}2\text{-}2)$$

where: A = Adjustment, precipitation or evaporation (multiplying factor), temperature (degrees/month)
S = Accumulated precipitation or evaporation
C = Magnitude of correction (difference between current location and Corrected Line; positive if increase, negative if decrease)
ΔN = number of months

t' = start time of adjustment
t = end time of adjustment

Figures 6-2-1 and 6-2-2 illustrate the computation of the consistency factors. These figures show how all the corrections for the stations can be computed at one time, however, when first learning to adjust data for inconsistencies, it is probably easiest to work with one station at a time. It is probably also best in this situation to make and verify one correction at a time, beginning with the earliest.

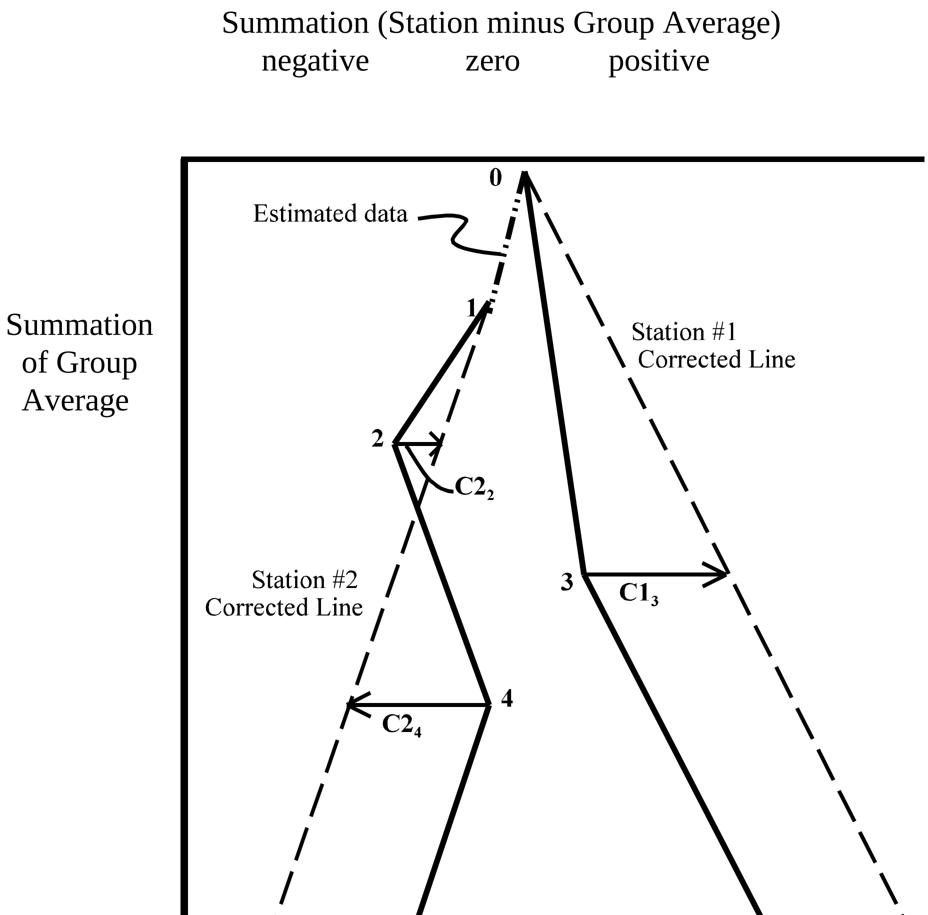


Figure 6-2-1.
Illustration of precipitation or evaporation consistency adjustments

For figure 6-2-1 the adjustments would be computed as:

For station 1:

$$A1_{3,0} = \frac{S1_3 + C1_3}{S1_3}$$ (greater than 1.0 since $C1_3$ is positive)

If the data record begins with October 1948 and the inconsistency for station 1 occurs in May 1975 and if $S1_3$ = 860 inches (i.e. accumulated precipitation for station 1, not the group average -- when using the PXPP, MAP, or MAPE programs this value is obtained from the tables that accompany the consistency plots using the date corresponding to when the inconsistency occurred) and $C1_3$ = 260 inches (computed from the plots using the station minus group average summation scale), then the adjustment is 1.30. This adjustment is applied starting in October 1948 and remains in effect through April 1975. In May 1975 the adjustment factor needs to be set back to 1.0 since the remaining data plot parallel to the Corrected Line.

For station 2:

$$A2_{2,1} = \frac{\left(S2_2 - S2_1\right) + C2_2}{S2_2 - S2_1}$$ (greater than 1.0 since $C2_2$ is positive)

$$A2_{4,2} = \frac{\left(S2_4 - S2_2\right) + \left(C2_4 - C2_2\right)}{S2_4 - S2_2}$$ (less than 1.0 since $C2_4$ and $-C2_2$ are both negative)

For figure 6-2-2 the adjustments would be computed as:

For station 1:

$$A1_{2,0} = \frac{C1_2}{N_2 - N_0}$$ (adjustment is negative since $C1_2$ is negative)

If the data record begins in October 1977 and the inconsistency for station 1 occurs in June 1984 (i.e. 80 months after the start of the observed record) and if $C1_2$ = -120 °F (computed from the plot using the deviation of accumulated means scale), then $A1_{2,0}$ = -1.5 °F/month. This adjustment is applied beginning in October 1977. The adjustment is then set back to 0.0 in June 1984.

For station 2:

$$A2_{3,1} = \frac{C2_3}{N_3 - N_1}$$ (adjustment is positive since $C2_3$ is positive)

$$A2_{4,3} = \frac{C2_4 - C2_3}{N_4 - N_3}$$ (adjustment is negative since $C2_4$ and $-C2_3$ are both negative)

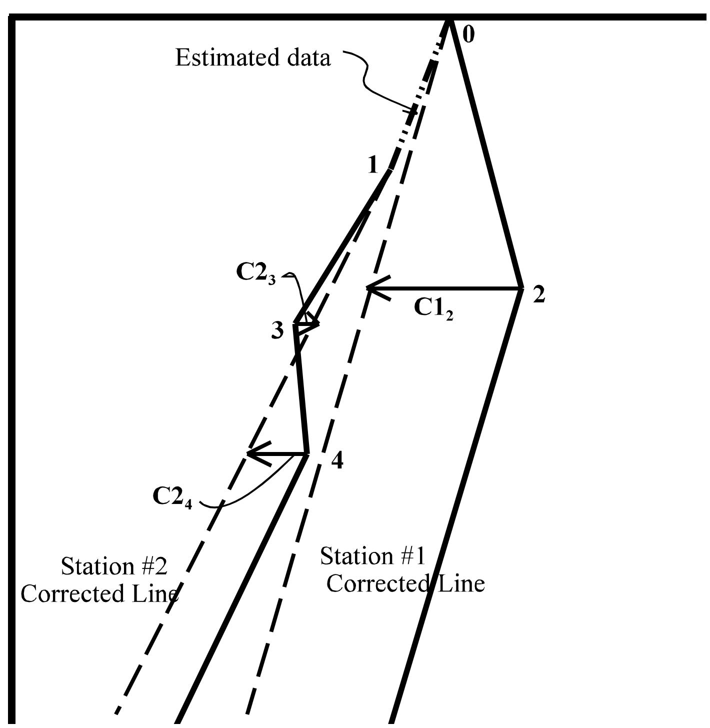


Figure 6-2-2. Illustration of consistency adjustments for temperature

Section 6-3

Computation of Mean Areal Precipitation

Introduction

Good estimates of precipitation are critical to the successful use of conceptual models. The precipitation estimates should first of all conform to the physical scale of what actually occurs in nature, i.e. the estimates should be unbiased compared to what actually occurs. Second, other statistical properties of the estimates, such as frequency of occurrence of various amounts and seasonal variability, should also be as realistic as possible. Third, the amount of random error in the estimates should be as small as possible. The random error is controlled to a large degree by the data network and spatial variability of precipitation over the region. In sections of the country where there is a high spatial correlation between precipitation amounts the typical climatological network can produce a fairly reliable areal estimates, whereas in areas with little spatial correlation the estimates will contain a large amount of random error. A large amount of noise in the precipitation input makes it very difficult to determine model parameters and obtain good simulation results. The quality of the areal precipitation estimates largely determines where lumped, conceptual models can be applied with satisfactory results (see Figure 1-1 in chapter 1).

Prior to doing the steps discussed in this section it is assumed that all the precipitation data are available in the proper form and that the data have been checked for consistency and adjusted if necessary. It is also assumed that the areas where MAP estimates are to be generated have been determined based on the definition of the flow points needed for calibration and the possible subdivision of the drainage areas into elevation zones or subareas specified by other means. It is also assumed that it has been determined as to whether mountainous or non-mountainous area procedures should be used to compute areal estimates.

Ideally precipitation data should be corrected for gage catch deficiencies prior to computing areal estimates for use in conceptual models. Catch deficiencies are a function of the type of precipitation, the type of gage, and the amount of wind at the orifice of the gage. The catch deficiencies for snow are much greater than for rain. The wind speed at the gage orifice is controlled by the current atmospheric wind speed and direction, the gage exposure, and the type of wind shield, if any. The catch deficiency varies throughout an event as meteorological conditions change. Some techniques have been proposed for applying monthly adjustments to precipitation data at a given station based on wind and temperature data from nearby synoptic sites and a general classification of the gage exposure including whether a wind shield is installed. Whether the application of such techniques would improve model simulation results has not be shown. In non-mountainous areas gage catch deficiencies are typically ignored when computing MAP. An average catch deficiency for snow events is later incorporated in the snow model computations (e.g. the SCF parameter in the SNOW-17 model). In mountainous areas some adjustment for the average catch deficiency can be implicitly included when water balance computations are used to obtain average areal precipitation estimates. Further adjustment is likely when the models are calibrated (see discussions under the SCF parameter in sections 7-4 and 7-7).

Time Interval for Precipitation Computations

The Mean Areal Precipitation (MAP) processing program in NWSRFS used for calibration will allow for the generation of time series at a 1,3, and 6 hour interval. In most cases a 6 hour interval should be used. There are several reasons for using a 6 hour time interval when generating MAP time series from historical raingage data. First, the program used operationally in NWSRFS to generate MAP time series from raingage reports currently will only generate time series at a 6 hour time interval. Second, in most regions there is not a dense enough historical hourly raingage network to produce reliable areal estimates at less than a 6 hour interval. Third, since some of the models, especially the Sacramento Model, will produce different results depending on the time scale that they are applied, the calibration of the model and the operational application should use the same time interval.

Historically for river forecasting at an RFC a 6 hour time interval has been used for model computations. This has typically been the case for several reasons. First, real time data, especially precipitation, was only available on a 6 hour basis at a reasonable network density. Second, the time needed operationally to obtain and process data, perform model computations and make manual adjustments, and get the forecasts to the users limited the time between forecast updates to around 6 hours. Third, RFCs were not opened on a 24 hour basis except during times of significant flooding potential. Thus, when the current OFS MAP program was coded in the 1980's a 6 hour time interval was specified. The use of a 6 hour computational interval has also tended to limit the size of the basins that are modeled by the RFCs to those that can be modeled successfully at a 6 hour interval, i.e. basins that typically peak in 12 or more hours. Drainages with faster response times have been handled using site specific and regional flash flood procedures by the WFO or via local flood warning systems such as ALERT and IFLOWS. The WFO and local flood warning procedures seldom involve continuous modeling and rely on previously prepared guidance material.

With the automation of more data networks, there now are considerable data available operationally at intervals of 1 hour or less in some parts of the United States, however, the availability of hourly data from the climatological network is still limited and the OFS MAP program still produces time series at only a 6 hour interval. Techniques are now available in OFS to use gridded hourly precipitation estimates generated by merging radar, raingage, and other data, however, studies have shown that these estimates in most cases are biased as compared to MAP values generated from historical raingage data. There is of course also the scale effects of the models which must be accounted for prior to using hourly precipitation estimates operationally with models that are calibrated at a 6 hour time interval. A further discussion of historical versus operational bias and scale effects is included in chapter 8 of this manual.

If there are sufficient historical hourly stations, a 1 or 3 hour MAP time series could be generated and used for calibration. If snow is also a factor, the SNOW-17 model allows for the generation of the rain plus melt time series at the same interval as the precipitation time series even if temperature data are only at a multiple of the precipitation data time interval. Thus, for example, SNOW-17 will produce hourly rain plus melt from hourly MAP data and 6 hour temperature estimates (the NWSRFS historical temperature processing program only produces 6 hour mean areal estimates). In order to then use such calibration results for operational forecasting would require a procedure that would produce real time hourly estimates of precipitation from raingage data or the assurance that there was no bias between the historical MAP values and hourly radar based estimates available operationally.

Non-Mountainous Area Precipitation Estimates

Introduction

Even though it has been previously decided by looking at the station data and other factors that the non-mountainous area procedure can be used to generate MAP estimates, it is probably a good idea to reexamine the station data after the consistency checks and adjustments have been completed to make sure that the variation in average station precipitation over the river basin conforms to the definition of a non-mountainous area. If so, the computation of the MAP time series is quite straight forward.

Background

The MAP program of NWSRFS uses the following sequence when completing the data record by estimating all missing data values and time distributing accumulated amounts.

1. Estimate all missing hourly station values using only other hourly stations since these are the only data that always correspond exactly to the time period of the missing record. Also time distribute any accumulated amounts at hourly stations based on the other stations in the hourly data network. If there are no estimator stations available for certain periods, i.e. all hourly stations have missing data, then the estimates are set to zero for all the hourly stations for these periods. The program lists the number of hours that this occurs. If the number of hours that precipitation is set to zero is significant (something like more than 0.1% of the period of record), more hourly stations should be added to the analysis if possible. This is most important when some of the hourly stations are assigned weight for computing MAP values.

2. Time distribute all observed values at daily reporting stations into hourly estimates based on the observation time of the daily report and the stations in the hourly network. If no hourly data are available to time distribute a daily value, i.e. all hourly stations were missing or recorded no precipitation, the daily total is currently assigned to the hour of the observation time and the other hours in the day are set to zero. The program tabulates the

number of days for each station when the daily total can't be distributed for amounts greater and less than 0.5 inches. The maximum daily amount that couldn't be distributed is also tabulated for each station. If the number of cases for some stations are much larger than for the majority, this may indicate a problem with the observation times specified for those stations. Such discrepancies can also occur for daily stations that are not in the vicinity of any hourly stations or for high elevation daily reporting stations when all the closest hourly stations are at much lower elevations. Correcting the observation time histories and adding additional hourly stations, if available, are the only ways to reduce the number of days when the distribution of daily amounts is not possible. However, even in the best of cases there will always be many days when isolated storms effect only daily stations.

3. Estimate the missing values at daily reporting stations based on the observation time of the report and all available hourly estimates from both the hourly network and daily stations that were time distributed in step 2. The missing daily totals are then time distributed into hourly amounts just like the observed daily data.

After this process is complete, all of the stations have a complete record, i.e. no missing or accumulated data, and the data for each station are defined at an hourly time interval. Station weights can then be multiplied times the data values and the results summed up over the specified time interval to generate the MAP time series for each subarea.

The equation used for estimating missing precipitation data in non-mountainous areas is:

$$P_x = \frac{\sum_{i=1}^{i=n} \left\{ P_i \cdot \left(1.0 / d_{x,i}^2 \right) \right\}}{\sum_{i=1}^{i=n} \left(1.0 / d_{x,i}^2 \right)} \qquad (6\text{-}3\text{-}1)$$

where: P = precipitation amount
x = station being estimated
i = estimator station
n = number of estimator stations, and
d = distance

The estimator stations are the closest stations with available data in each quadrant surrounding the station being estimated. The quadrants are based on the roughly 4 km HRAP grid system. Estimated amounts are not used to estimate other amounts. The same weights, i.e. $1/d^2$, are also used to time distribute accumulated amounts. Equation 6-3-1 assumes that the mean precipitation at all the estimator stations can be assumed to be the same as the station being estimated, which is the basic assumption of the non-mountainous area procedure.

<u>Station Weights</u>

The assumption for a non-mountainous area is that the mean precipitation is essentially the same at all locations with the basin, not only where there are stations, but also at all points in between. Thus, station weights can be determined merely by the location of the gages within the boundaries of the area. This requires that basin boundaries, i.e. latitude, longitude points that define the outline of the basin, are available. There are two methods in the MAP program for calculating station weights using gage and boundary locations, Thiessen weights and grid point weights. Both are generated within the program by overlaying the HRAP grid over the area. For Thiessen weights, the weight for each HRAP grid point is assigned to the closest station. For the grid point method, the weight for each grid point is divided based on the $1/d^2$ technique to the closest station in each quadrant. For both methods, the weight assigned to each station from all grid points is then summed and normalized to obtain the station weights. These weights will always sum to 1.0. Both methods produce fairly similar weights, though the grid point method assigns some weight to stations outside the boundaries that will not receive any weight with the Thiessen method. The Thiessen method is the preferred way to compute station weights in most cases.

Mountainous Area Precipitation Estimates

Introduction

As discussed earlier, in a mountainous area the mean precipitation is spatially variable. Thus, the estimation of missing data must account for the fact that the precipitation catch at the estimator stations may be different than at the station being estimated. Also, station weights cannot be computed based on the location of the gages with the boundaries of the area. The procedure outlined in this section was primarily developed to make it relatively easy to minimize bias between historical (calibration) estimates of MAP and subsequent operational estimates. For model parameters determined during calibration to perform in a similar manner during operational use, it is imperative that there is not a bias between the precipitation values used as input to the two applications of the model. The procedure relies heavily on isohyetal analyses of long-term precipitation patterns. Good isohyetal maps are essential to the success of the method. By using an isohyetal analysis as the basis for computing areal estimates, the typical precipitation pattern defined by the isohyetal maps is used to interpolate between station values and used to extrapolate into ungaged portions of the area. In many mountainous watersheds there are no stations at the highest elevations, thus the relationships defined by the isohyetal maps are used to estimate the amount of precipitation falling above the highest gages. This works well over the long term, but can result in errors for individual storms due to changing dynamics from one storm to the next. Since model parameters are based on the simulation of many events, these random errors for individual events should not affect the determination of parameter values during calibration. Operationally it would be beneficial to have a procedure that would account for the changing storm dynamics and still maintain the same long term pattern defined by the isohyetal maps used during calibration.

The suggested steps for computing MAP in mountainous areas is as follows:

1. Determine mean monthly precipitation for each station for the period of record,

2. Determine if station weighting should be done on an annual or seasonal basis,

3. Determine the mean seasonal or annual precipitation for the historical data period for each area within the river basin where MAP time series are to be generated after checking the isohyetal maps to determine if adjustments are needed for incompatibilities in the periods of record, differences between station data and isohyetal map estimates, or disparities based on a water balance analysis,

4. Determine annual or seasonal station weights for each MAP area by adjusting subjectively determined relative weights so that the correct areal average precipitation for the historical period of record will be generated, and

5. Compute MAP time series for each area within the river basin for the period of record using the predetermined station weights determined in step 4.

The remainder of this section describes recommended procedures for each of these steps.

Determining Mean Monthly Precipitation for Each Station

If all stations had complete data for the entire period of record, monthly, seasonal, and annual mean values could be computed directly from the observed data. However, in most cases the periods of observed data vary from station to station and when data are collected, there are times when the values are missing. Since the amount of precipitation can vary considerably from one time period to another, mean values need to be computed for all stations for the same period. This is the main function of the Precipitation Preliminary Processing (PXPP) program of NWSRFS. PXPP runs on a monthly basis. If any data for a station are missing for a given month, the data value for the month is estimated. When missing values have been estimated for all months with missing data, PXPP computes mean precipitation values for each station for the entire period of record from the observed and estimated monthly values.

The basic equation for estimating missing precipitation data in mountainous areas is:

$$P_x = \frac{\sum_{i=1}^{i=n} \left[\left(\overline{P_x} / \overline{P_i} \right) \cdot P_i \right] \cdot w_{x,i}}{\sum_{i=1}^{i=n} w_{x,i}} \qquad \text{(6-3-2)}$$

where: P = precipitation amount ($\overline{P}$ signifies mean value)

x = station being estimated
i = estimator station
n = number of estimator stations
w = weight applied to each estimator, usually $1.0/d^2_{x,i}$ and,
d = distance

PXPP solves this equation by establishing a base station and then computing the ratio of precipitation at each station to that caught by the base station for each month of the year. The base station must be a station with very little missing data during the period of record and should be a station that is naturally consistent (i.e. consistency corrections are not needed). A station with a low catch, as compared to the other stations, should not be used as the base station. The base station should be one with a moderate to high catch to avoid very high ratios being computed during months with little or no precipitation. The location of the base station within the region being used in the analysis is not critical. The ratio of precipitation at a given station to that caught at the base station for each month is computed using all years for which both stations have complete data for the month. If both stations have overlapping data for about 5 or more years, a fairly stable relationship can be determined. PXPP then substitutes the ratio to base for the appropriate month for station x and station i in place of the mean precipitation values into Eq. 6-3-2 in order to determine the average ratio of station x to station i. In this way Eq. 6-3-2 is used to compute precipitation for months with missing data.

Reasonable estimates of mean monthly precipitation cannot be computed by PXPP for stations with little or no overlapping data with the base station. Since the base station is usually selected partly because it has data for essentially the entire period of record, these are usually stations with very short records or with frequent missing data such that monthly totals seldom can be calculated. Typically such stations are not adding much information to the precipitation analysis and thus would be discarded. The only other option is to remove such stations from the PXPP runs and then estimate their mean monthly values based on other stations and monthly averages derived from the isohyetal maps so that they can be included in the MAP program.

Within the PXPP program, determining mean values over the period of record and making consistency checks and corrections is an iterative process. Consistency corrections will increase or decrease the observed values for some portion of the period of record and thus change not only the computed mean values for the station being corrected, but also the mean values for stations using the corrected data to estimate missing months.

After consistency corrections and mean monthly values (referred to as characteristics in some cases) have been computed using PXPP, the MAP program should be run to verify that the consistency plots are similar between the two programs. Typically the plots look basically the same, but sometimes the plots are slightly different for one or two of the stations, generally hourly stations, due to differences in the computational sequence in the two programs. In MAP, as mentioned in the non-mountainous area section of this section, hourly stations can only be estimated from other hourly stations, whereas in PXPP each station can be estimated from all the others. If inconsistencies show up in MAP that were not present in the final PXPP run, these can sometimes be removed by changing or adding consistency corrections to the affected stations in the MAP run. Changing consistency corrections in the MAP program will not automatically change the mean monthly values (characteristics) being used by the program (adjustments to the mean monthly values could be made by the user if the change in the consistency correction is significant).

In Alaska there is very little hourly precipitation data available from the NCDC climatological network. In fact only a handful of stations are available over the entire state and most of these have a short period of record. Even those with the longest record, Anchorage and Fairbanks, don't go back to when many of the daily digital records began in water year 1949. Some hourly data can be obtained from real time stations for use in the historical analysis, but these are generally very short records and many of the sites have considerable missing data. The result is that only a few of the hourly stations have sufficient data for use in PXPP and in many cases these gages are located far from the river basin being processed. However, the MAP program requires that hourly stations be available. One solution to this problem is to remove any hourly stations that don't have sufficient data overlapping with that of the base station from the PXPP runs. Then estimate the mean monthly values for these stations based on nearby stations and the isohyetal maps so that they can be included in the MAP program. However, rather than locating the stations at their actual location which can cause problems when estimating missing data, position the stations at locations surrounding, but far outside, the other stations being used for the river basin. These hourly stations will then be used for time distribution of daily amounts whenever they have observed data, but their $1/d^2$ values will be very small and will not affect the estimation of missing data for the daily stations being used.

Annual versus Seasonal Station Weights

The MAP program allows for station weights (predetermined) in mountainous areas to be specified on an annual or seasonal basis. Seasonal weights are beneficial in regions where the spatial pattern of precipitation is greatly different in one season than in another. This is typically caused by different types of storms predominating at different times of the year. The region where seasonal weights are typically needed is the intermountain west. In this region large scale storms with significant orographic effects dominate during the winter, while small scale convective events cause most of the summer precipitation. In most other regions of the United States the precipitation patterns do not vary sufficiently enough from one season to the other to justify the use of seasonal weights. In these regions annual weights are generally fully adequate.

Since the MAP program allows for only a single definition of the winter and summer seasons, the seasons used for station weighting and for consistency checks must be the same. In most cases, especially in the intermountain west, the seasons to use for these two features are the same for all practical purposes so this doesn't present a problem.

There are two types of plots that can be constructed to help in deciding whether seasonal station weights need to be used. The first, is to plot the seasonal relationship between a high elevation station and a nearby low elevation station. Ideally the two stations selected should have the same orographic exposure, i.e. both on the same side of a major divide and not one on the windward side and the other on the leeward side. This high-low precipitation plot is generated by plotting the monthly ratio of the average catch based on the PXPP program results at the two stations. If the monthly ratio of precipitation from the two stations is quite similar throughout the year, there is little benefit to be gained by using seasonal station weights, whereas if there is a significant variation and a distinct seasonal pattern in the ratio, then seasonal weights should be used.

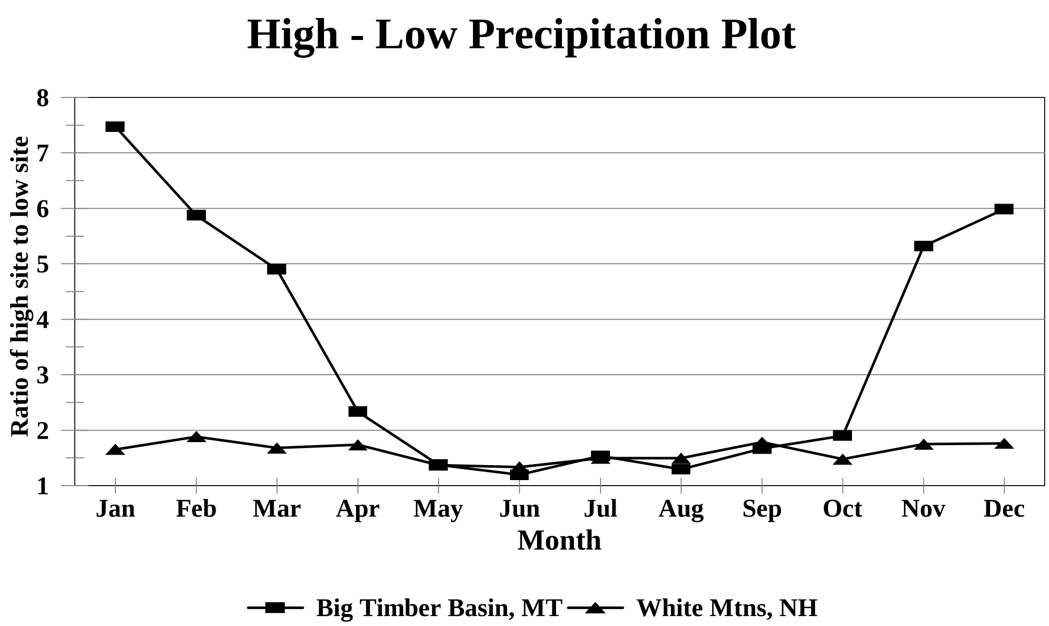


Figure 6-3-1. High-low precipitation plots for locations in the intermountain west and New England. (The Big Timber watershed plot is based on the Monument Peak SNOTEL site at 8850 feet and the Big Timber climatological station at 4100 feet. The White Mountain plot is based on climatological stations at Mount Washington (elev. 6262 feet) and Bretton Woods (elev. 1621 feet).)

Figure 6-3-1 shows such plots for two gages within the Big Timber watershed just north of Yellowstone National Park in Montana and for two gages in the White Mountains of New Hampshire. In the Big Timber case there is a very large difference in ratios from mid-winter when large orographic storms dominate to mid-summer when most of the precipitation is produced by small scale convective events. Seasonal weights are certainly justified in this region. The typical winter season in the intermountain west is from October to April and the summer season from May to September. Based on the Big Timber plot a winter season from November through March might be better for station weights, though the October to April season is probably more appropriate as far as when snowfall predominates for making consistency adjustments. For the White Mountains annual station weights can be used since the variation in the high-low precipitation ratio is similar throughout the year.

The idea for using plots of high elevation to low elevation precipitation stations to get an insight into seasonal changes in precipitation patterns was introduced by Eugene Peck, former Director of the NWS Hydrologic Research Laboratory, [1964]. By examining pairs of high and low elevation stations scattered throughout the western mountains he showed that there were significant seasonal variations over much of the intermountain west, but little seasonal change in the ratios west of the Pacific Crest.

The second type of plot that is helpful in deciding whether to use seasonal station weights is a plot of precipitation versus elevation for each season. If the plots for the two seasons are dissimilar, this would indicate that the types of storms producing the precipitation are different and thus, seasonal station weighting would be appropriate, whereas if the relationship between precipitation and elevation is similar throughout the year, annual station weighting is sufficient. The high - low plot is best for defining the seasons to use for station weighting, but it only shows the relationship between two stations in the basin. The precipitation versus elevation plots are used to confirm whether the precipitation patterns are different for the entire network.   Figure 6-3-2 shows precipitation versus elevation plots for an area in the upper Yellowstone River basin.

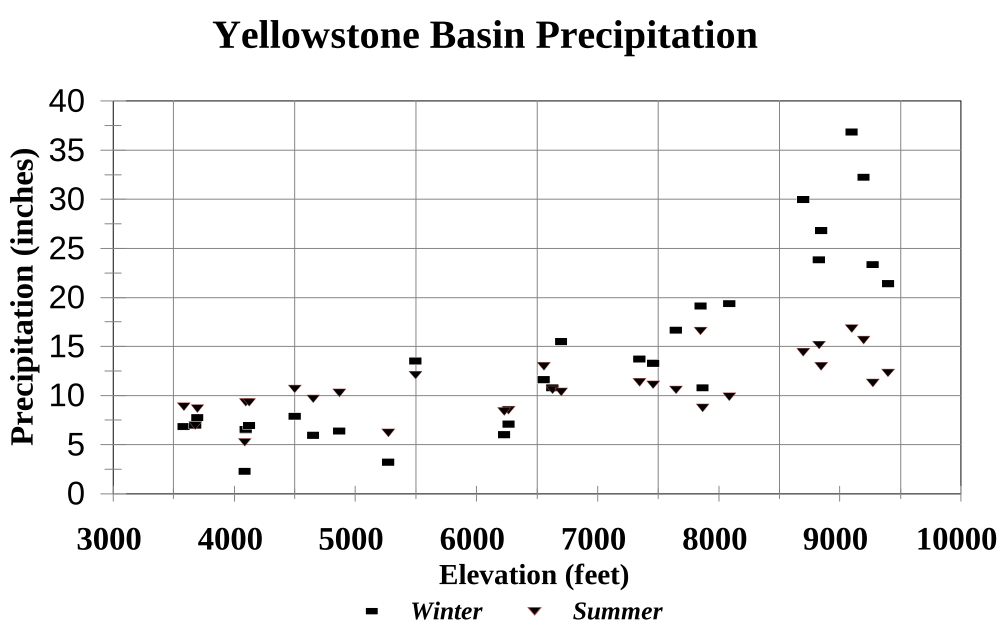


Figure 6-3-2. Precipitation versus elevation plots for the Upper Yellowstone River basin in Montana and Wyoming. Winter season is October through April, summer season is May through September.

This plot shows much more variation in precipitation with elevation, especially at the higher elevations, in the winter season than during the summer, i.e. the orographic effects are much larger during the winter months. This clearly suggests that seasonal station weighting would be appropriate. Such differences in the precipitation versus elevation relationships are common throughout the intermountain west.

<u>Determination of Average Mean Areal Precipitation for Each MAP Area</u>

The next step for computing MAP in mountainous areas is to determine the average mean areal precipitation on a seasonal or annual basis for the historical period of record for each of the MAP areas within the river basin. This is done by averaging the precipitation shown on the isohyetal maps over each of the MAP areas either on an annual or seasonal basis and then applying any necessary adjustments to the result. Adjustments can be needed for several reasons.
First, if the period used to produce the isohyetal map differs from the period of historical record being used, an adjustment may be needed. Second, the mean precipitation values determined for the stations being used to compute the MAP time series should be compared against the estimate for these sites from the isohyetal maps to determine if adjustments are needed to portions of the isohyetal analysis and whether the station data makes sense. Third, water balance computations need to be made to determine if runoff information suggests adjustments to the areal mean derived from the isohyetal maps.

The first check to perform is whether the periods of record used to produce the isohyetal maps are the same as the period of record being used for the historical analysis. It is most likely that they are not the same. In that case, one needs to determine if adjustments need to be applied to the isohyetal analysis so that it reflects the historical period. The most straight forward way to do this is to take a number of the stations with long data records and compute the ratio of the average annual precipitation over the historical data period to the same value for the isohyetal map period of record. The average station precipitation determined by the PXPP program would be used to compute these ratios. If these ratios differ significantly from 1.0, then an adjustment is needed. If the ratios for all stations are fairly similar in magnitude, then the average ratio can be used to adjust the isohyetal maps. If there is a pattern to the ratios over the river basin, a different adjustment could be used for different parts of the basin. While annual precipitation should be sufficient for computing this adjustment, one could compare seasonal ratios if the MAP analysis was being done on a seasonal basis to confirm if the adjustment is similar for each season.

The second check is to compare the mean values for the stations being used for calibration as determined by the PXPP program with the mean values for these sites from the isohyetal analysis (any period of record adjustment determined in the first check should be applied to the station values picked off the isohyetal maps). This should be done on a seasonal basis for those river basins where it has been determined that seasonal station weights are appropriate for computing MAP. While the isohyetal analyses have generally been done in a careful manner with proven techniques, the results cannot be treated as the ‘true’ definition of what actually occurred. The data being used for calibration are typically more complete than the data used to generate the isohyetal maps. Generally the isohyetal maps use only stations with a long period of record, whereas in calibration we also use stations with shorter records to better define the spatial variability. Also all the calibration stations should have been checked for consistency and adjusted if needed, whereas, this is probably not the case for all the stations used to generate the isohyetal maps. The best way to visualize differences between the station data and the isohyetal analysis is to plot the ratio of the value picked off the isohyetal map at each station location divided by the PXPP value for the station on a map of the river basin. Ideally the ratios should vary around 1.0. Isolated values that differ significantly from 1.0 could represent a small scale problem with the isohyetal analysis or could indicate a problem with the data for that station. If there are portions of the river basin where the ratios are quite different from 1.0 and exhibit a definite pattern, this most likely indicates that the isohyetal maps are over or under estimating the amount of precipitation in these areas; thus the long-term average values for the affected MAP areas derived from the isohyetal analysis will need to be adjusted. Before making any corrections it is best to do a water balance analysis to confirm that adjustments are needed for watersheds in these portions of the river basin.

Most isohyetal analyses are done using only station precipitation data. The techniques being used then interpolate and extrapolate these station data using elevation, aspect, prevailing storm direction, and other factors to estimate the average precipitation pattern over the region being studied. One way to determine if the average volume of precipitation shown on an isohyetal map is realistic is to do a water balance analysis. The water balance equation for a watershed can be expressed as:

$$P - R - \Delta S - L = ET \qquad (6\text{-}3\text{-}3)$$

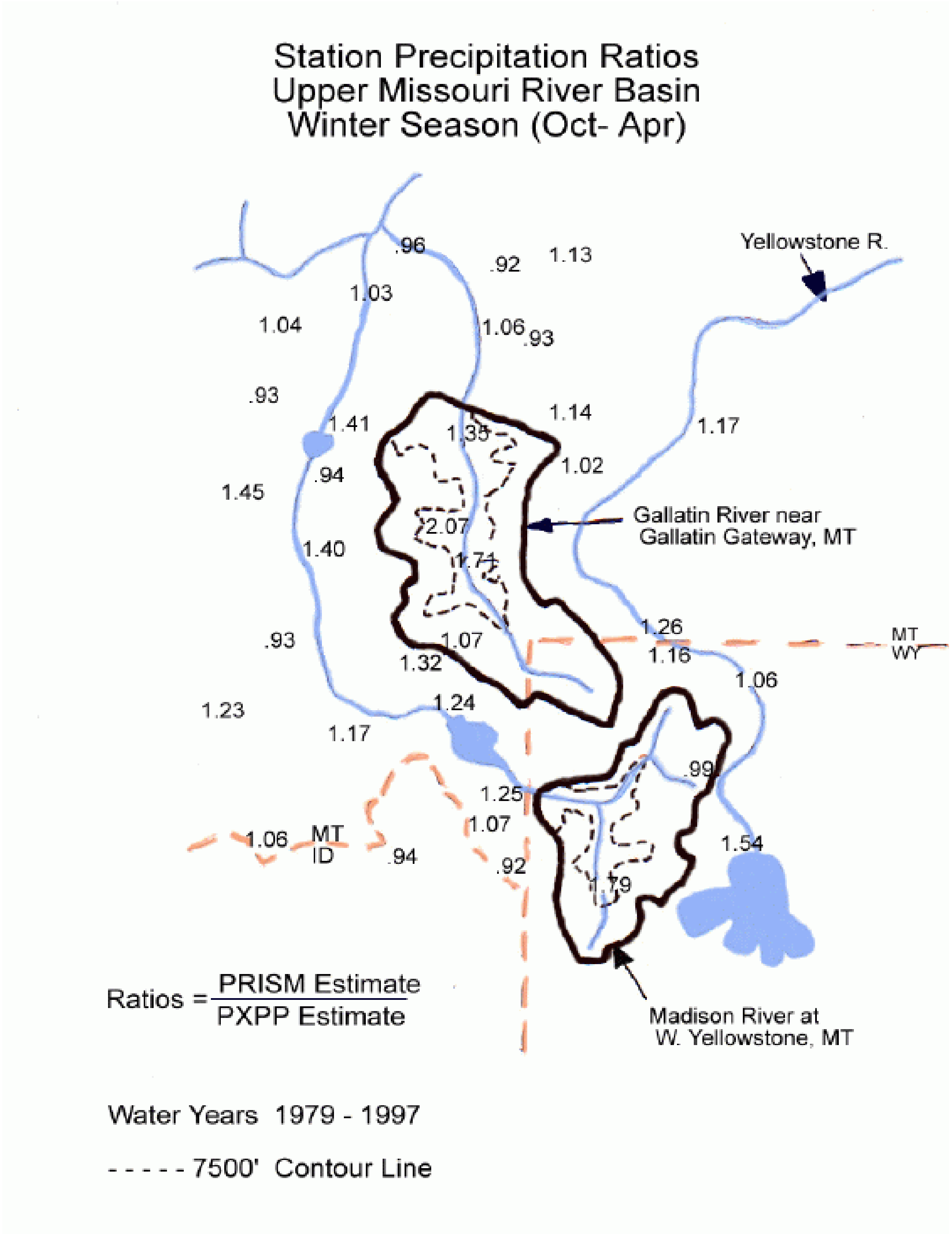
where: P = average annual precipitation,
R = average annual runoff,
ΔS = average annual change in storage,
L = average annual losses or gains due to transfers across watershed boundaries or losses to deep groundwater aquifers, and
ET = average annual evapotranspiration.

Over a sufficiently long period the change in storage term should be essentially zero except for watersheds with a significant glaciated area. The watersheds used for a water balance analysis would be headwater areas with a value of the L term equal to zero and few complications such as large reservoirs or substantial irrigated acreage. Local areas could also be included as long as the area is relatively large enough so that a reliable estimate of the local runoff can be determined by subtracting upstream flows from downstream flows. The precipitation used would be that derived from the isohyetal analysis adjusted to the historical period of record. The runoff would be the mean annual runoff for this same period. In many cases the period of record of the streamflow data used to compute average annual runoff is less than the period of record being used for historical data analysis. For these watersheds MAP time series should be generated for all subareas using the mean areal average computed directly from the isohyetal analysis (adjusted for calibration period of record). Then the average annual precipitation for use in the water balance computation can be calculated for the same years as the runoff data. In these cases, which is typical for many watersheds, one would complete the remaining steps in the MAP computational procedure so that time series would be available to determine the proper annual precipitation to use in the water balance equation and then if further isohyetal map adjustments were needed, the steps would be repeated using adjusted values of the mean areal averages.

The average annual ET determined from the water balance computations for as many watersheds as possible over the river basin should be tabulated for comparison. Another good way to see if the computed ET values make sense is to plot them against elevation. The variation in ET over the basin and with elevation should make sense. If there are watersheds that deviate significantly from a reasonable variation of ET over the basin, it is likely that the isohyetal map needs to be adjusted for these areas. If these watersheds correspond to the portions of the basin where the ratio of the station data to the isohyetal map estimate for the station were substantially different from 1.0, this further indicates that there are problems with the isohyetal estimates of precipitation over those areas. Adjustments should then be determined so that a more reasonable estimate of the average mean areal precipitation, annual or seasonal, can be used for computing each of the MAP time series. For watersheds included in the water balance analysis, the adjustments are based on both the water balance and patterns in the plots of the ratios of observed station data to the isohyetal estimates. For other drainages in the river basin, the adjustments are based on the patterns shown in the ratio plots.

Water balance computations in regions with large glaciated areas is more complex. In these cases, one needs to have a general idea as to whether there was a significant gain or loss of ice stored in the glaciers over the period being analyzed. Then either an attempt can be made to estimate the ΔS term in Eq. 6-3-3 so that ET variations could be computed directly or the value of ET + ΔS can be computed. Then ideally one could compare the ET + ΔS values for watersheds with and without glaciers, or at least with different amounts of glacial coverage, to see if the variation makes sense.

To illustrate these last two checks, we will look at a portion of the Upper Missouri River basin near Yellowstone National Park. Figures 6-3-3 and 6-3-4 show plots for both the winter and summer seasons of the ratio of the estimate picked off the isohyetal maps at each station location divided by the PXPP precipitation estimate for each station. For illustration purposes two watersheds, as well as their two elevation zones, are outlined on these plots; the Gallatin River near Gallatin Gateway, Montana and the Madison River near West Yellowstone, Montana. While the ratios tend to scatter around 1.0 over much of this region, there are definite places where there is a pattern of values greater than 1.0. Ratios greater than 1.0 appear over the drainage area of both of the outlined watersheds suggesting that the PRISM precipitation estimate is likely too large. Table 6-3-1 shows the results of water balance computations for a number of watersheds in this region. The ET values from Table 6-3-1 are plotted against the the mean elevation of each watershed in Figure 6-3-5. This plot shows a reasonable variation in ET versus elevation for most of the watersheds, however, the values for the Gallatin and



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igure 6-3-3. Winter season precipitation ratios for the Upper Missouri River basin.

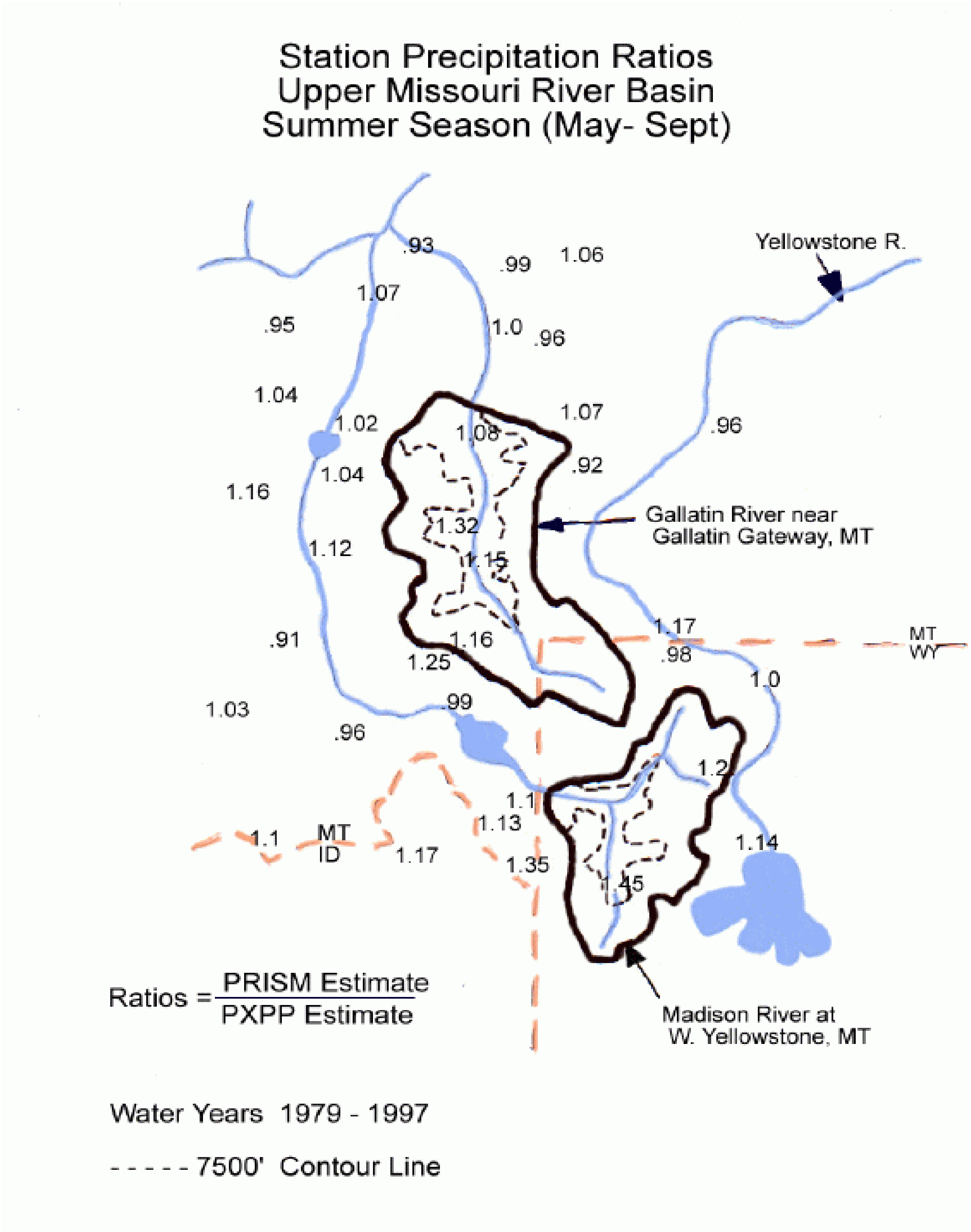


Figure 6-3-4. Summer season precipitation ratios for the Upper Missouri River basin.

Watershed	Period	Elevation	Pcpn	Runoff	ET
Stillwater R. nr. Absarokee,MT	wy 79-95	7186.	29.5	12.2	17.3
Clark Fk. nr. Belfry, MT	wy 79-97	7463.	27.7	9.5	18.2
Big Hole R. nr. Wisdom, MT	wy 89-97	7373.	24.8	4.5	20.3
Boulder R. nr. Boulder, MT	wy 85-97	6661.	22.6	4.0	18.6
Boulder R. nr. Big Timber, MT	wy 79-97	7533.	32.0	13.2	18.8
Gallatin R. nr. Gallatin Gateway, MT	wy 85-97	7880.	37.0	13.8	23.2
Madison R. nr. W. Yellowstone, MT	wy 90-97	7884.	44.3	16.8	27.5
Ruby R. ab. Ruby Reservoir, MT	wy 80-97	7247.	23.6	4.7	18.9
Lamar R. nr. Tower Falls, WY	wy 89-97	8366.	36.2	20.2	16.0

Table 6-3-1. Water balance for watersheds in the Upper Missouri and Upper Yellowstone River basins (Units for elevation are feet and for precipitation, runoff, and ET are inches).

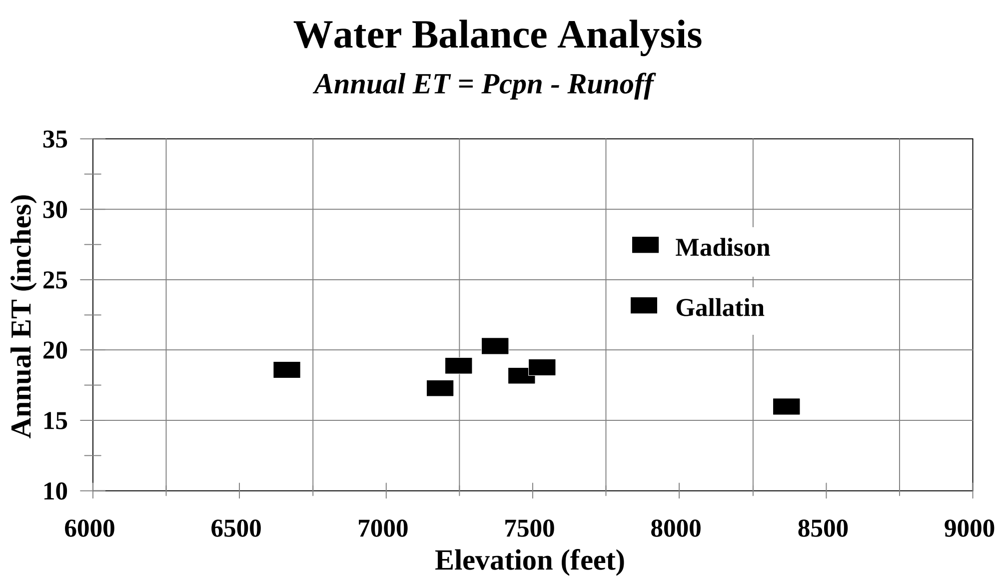


Figure 6-3-5. Annual ET derived from water balance computations versus elevation for watersheds shown in Table 6-3-1.

Madison Rivers do not conform to the relationship defined by the other watersheds. Thus, the water balance computations confirm that the PRISM precipitation estimates are too high in the portions of the river basin where these watersheds are located. For the Gallatin River, based on these 3 plots, adjustments of 0.625 and 0.87 (correspond to average precipitation ratios of 1.6 and 1.15) were applied to the winter and summer seasons, respectively, for the lower elevation zone (below 7500 feet) and an adjustment of 0.91 (corresponds to an average precipitation ratio of 1.1) was applied to both winter and summer for the upper elevation zone. These adjustments are applied to the average mean areal precipitation for each zone derived from the isohyetal maps after any corrections for differences in the period of record were applied. This resulted in an average annual precipitation of 31.9 inches for the water year 1985-1997 period and an annual ET of 18.1 inches which appears quite reasonable. Similarly adjustments to the Madison River PRISM estimates of precipitation could be computed so that a reasonable water balance estimate of annual ET could be generated. The precipitation ratio patterns would also be used to compute adjustments for areas not included in the water balance analysis, such as downstream locals on the Gallatin and Madison Rivers.

Determination of the Average Mean Areal Precipitation in Data Sparse Regions

In some areas the historical precipitation gage network is so sparse that it is very unlikely that isohyetal maps generated from these very limited data will indicate the true magnitude of the average precipitation over the region. This is generally the case with much of Alaska. The best that can be hoped for in such an area is that the PRISM analysis will reflect a reasonable relative distribution of the average precipitation pattern over the region. In most of Alaska a different approach must be taken to determine the average mean areal precipitation over each MAP area for the historical period of record, since it is highly unlikely that averaging the values from the isohyetal maps over each MAP area will provide a usable value. The suggested approach for these extremely data sparse areas involves starting with the runoff data which integrates the volume of water being produced by a watershed. Then the average amount of annual ET is estimated and added to the runoff to get an estimate of the average mean areal precipitation for the watershed. If multiple subareas are being used for the watershed, the average mean areal value for the watershed can be distributed into each subarea based on the pattern suggested by the isohyetal maps. This approach requires that the runoff data are corrected for any diversions across the boundaries of the watershed and complications such as irrigation or deep recharge are not affecting the water balance.

Suggestions for estimating the annual ET for use in such computations are included in Section 6-5 in the section "Determining Precipitation and Actual ET from Runoff, Evaporation, and Vegetation Information." It is very important in this approach that ET estimates are done in a consistent manner from one watershed to another so that the resulting pattern of actual annual ET values makes sense when taking into account differences in climatic conditions, elevation, and vegetation cover. This approach may require a number of iterations since the initial guess at the ratio of actual ET to ET Demand may not turn out to be what actually occurs when the models are run. Also certain changes to model parameters can change this ratio and thus, alter the water balance. It may also turn out that the relative distribution of precipitation between the subareas suggested by the isohyetal analysis may not give reasonable results when subarea variables such as the amount of snow cover or change in glacier volume are compared to observations of these variables. This will require modifications to the assumed distribution of precipitation over the watershed. Differences in the period of record of the runoff data and the historical data period being used for calibration can be adjusted for by comparing the ratio of the catch at precipitation stations with long records for the two periods.

After this procedure is applied to several watersheds in a region, the ratios of the precipitation amounts actually used to produce reasonable simulation and water balance results to the isohyetal map amounts can be calculated. These ratios can then be used to adjust the isohyetal map values for nearby local drainages or for watersheds with complications that don't allow the runoff data to be used to derive the areal average precipitation. The end result should be a more realistic estimate of the amount of precipitation than can be determined from isohyetal estimates derived from a very sparse precipitation network.

Determining Station Weights

The last step before computing the time series for each MAP area within the river basin is to determine the weight to be applied to each station. For most MAP areas within a mountainous region predetermined station weights should be used. As opposed to Thiessen or grid point weights which always sum to 1.0, predetermined weights generally will not sum to 1.0 because the precipitation pattern is not uniform over the area. Thiessen or grid point weights can sometimes be used for a few MAP areas in a mountainous region. These weights are appropriate in a flat portion of a mountainous river basin where the average precipitation is basically uniform over the area and all the stations that will receive weight have the same average precipitation as the MAP area. Predetermined station weights can be applied on an annual or seasonal basis as discussed earlier in this section. The recommended procedure for deriving station weights involves first subjectively assigning relative weights that sum to 1.0 to the appropriate stations and then adjusting the relative weights such that the summation of the final weight times the average precipitation for the each station will equal the average mean areal precipitation for the MAP area as determined from the isohyetal analysis and any needed adjustments.

The selection of which stations should be weighted for each MAP area and the assigning of relative weights to each of these stations is currently a subjective process. Hopefully in the future some objective techniques can be developed to assist in this process. The primary factors to consider when selecting the stations to be weighted and assigning relative weights is where the station is located relative to the MAP area and how representative is the catch at the station to other portions of the area. The location is a function of latitude, longitude, and elevation. In general, stations within or close to the area should be given most, if not all, the weight. This is especially true in regions or seasons when there is significant spatial variation in the amount of precipitation during storm events. If the region or season can be characterized by large scale storms with substantial orographic components and thus the typical spatial variation in precipitation amounts follows a fairly well defined orographic pattern, then stations further outside the MAP area that reflect the orographic exposure of portions of the area can be given some weight. One needs to be careful not to give weight to stations too far outside the MAP area such that the resulting time series represents the precipitation over an area much larger than the area that you are trying to represent. Assigning weight to stations a considerable distance outside the MAP area will tend to cause the model response to individual storms to be damped out. This is more of a concern in basins where there are significant runoff events caused by rainfall than in basins where almost all the runoff comes from the melting of the seasonal snow cover, though even in snowmelt dominant basins variations in the amount of snow accumulation could be damped out by assigning weights to stations far outside the MAP area.

There are several displays that can be examined to help in determining which stations to weight and what relative weight to assign to each station in addition to the users knowledge of the climatic conditions in the region. An option in the PXPP program will generate tables which show the correlation of monthly precipitation at each site to all the other sites on a seasonal or annual basis. In these tables known seasonal patterns as reflected by variations in each stations monthly ratios to the base station are removed prior to computing the correlation. For a given station the correlation coefficients for all other stations relative to that station can be plotted on a topographic map. This map can then be examined to see if the correlations are primarily based on distance, elevation, prevailing storm pattern, or some other factor. Figures 6-3-6 and 6-3-7 show correlation plots for portions of the Yellowstone River basin for the winter and summer season. These figures tend to show that the correlation pattern in the winter season is related to both elevation and distance while the summer pattern appears to be primarily related to distance. This is typical of the intermountain west where large scale storms with substantial orographic components dominate in the winter and small scale convective storms cause most of the summer precipitation. This would suggest that stations further outside the MAP areas that reflect the orographic pattern of portions of the areas could given some weight in the winter (e.g. high elevation stations some distance outside the upper elevation zone could be weighted), but that in the summer the weights should be assigned to stations within or near the boundaries of the each area.

Another display that can be helpful when deciding on which stations to weight and assigning relative weights is an anomaly map. This map is created by drawing a line on the precipitation elevation plot (plots like figure 6-3-2) and then computing and plotting the deviation of each station from that line. The line should represent the general trend of how precipitation varies with elevation, but it doesn’t precisely matter where the line is drawn. Positive deviations indicate areas where the precipitation is greater than what is expected for a given elevation and negative deviations show areas that are sheltered from the prevailing orographic pattern. Anomaly maps are primarily of value for understanding the orographic pattern over the basin produced by large scale storms, thus either the winter season is typically examined in the intermountain west or an annual anomaly map is generated in other areas where storms with substantial orographic components predominate. An understanding of the typical orographic pattern should help in selecting which stations should represent various portions of an MAP area.

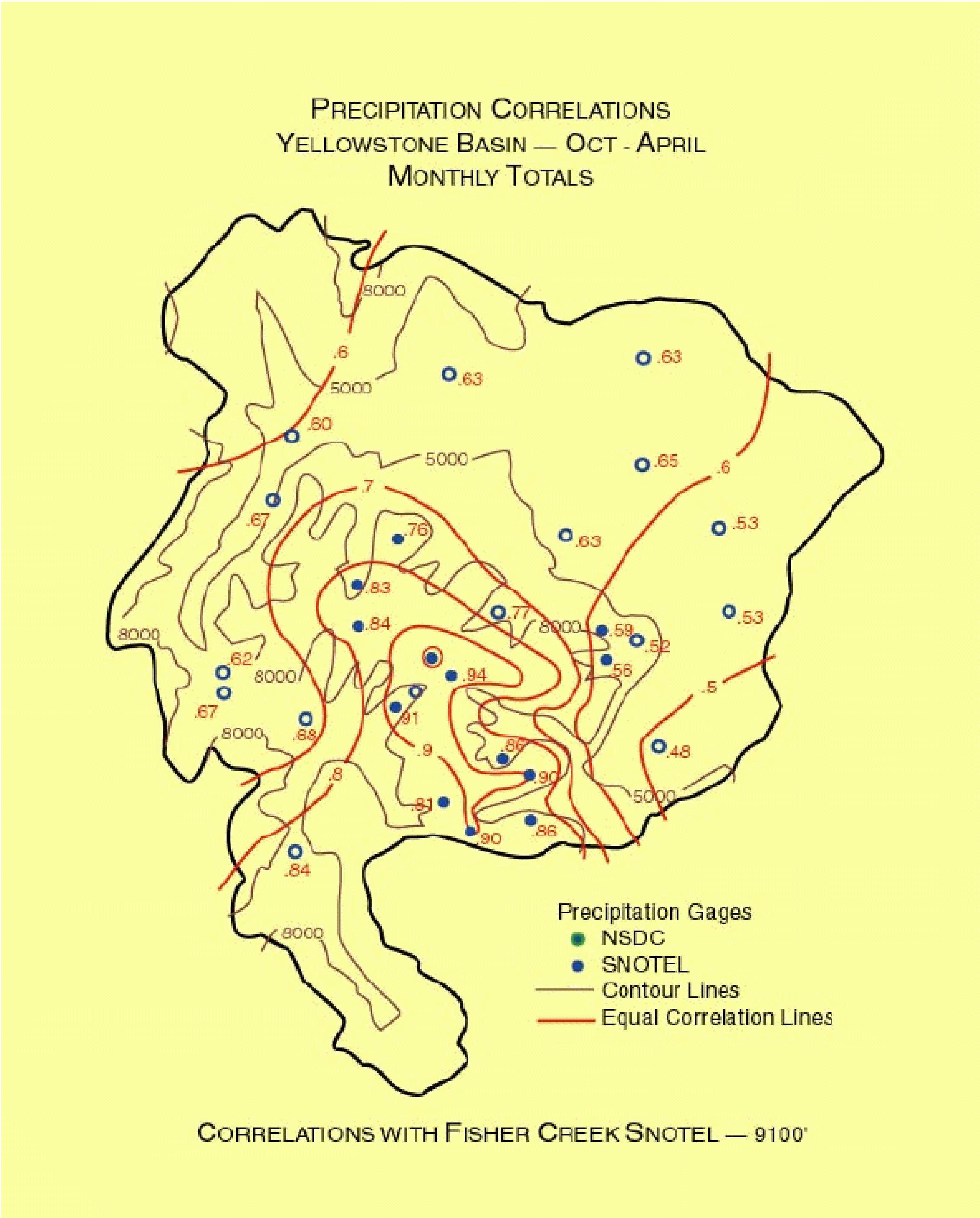


Figure 6-3-6. Winter season correlation pattern for Upper Yellowstone River basin around the Fisher Creek SNOTEL station

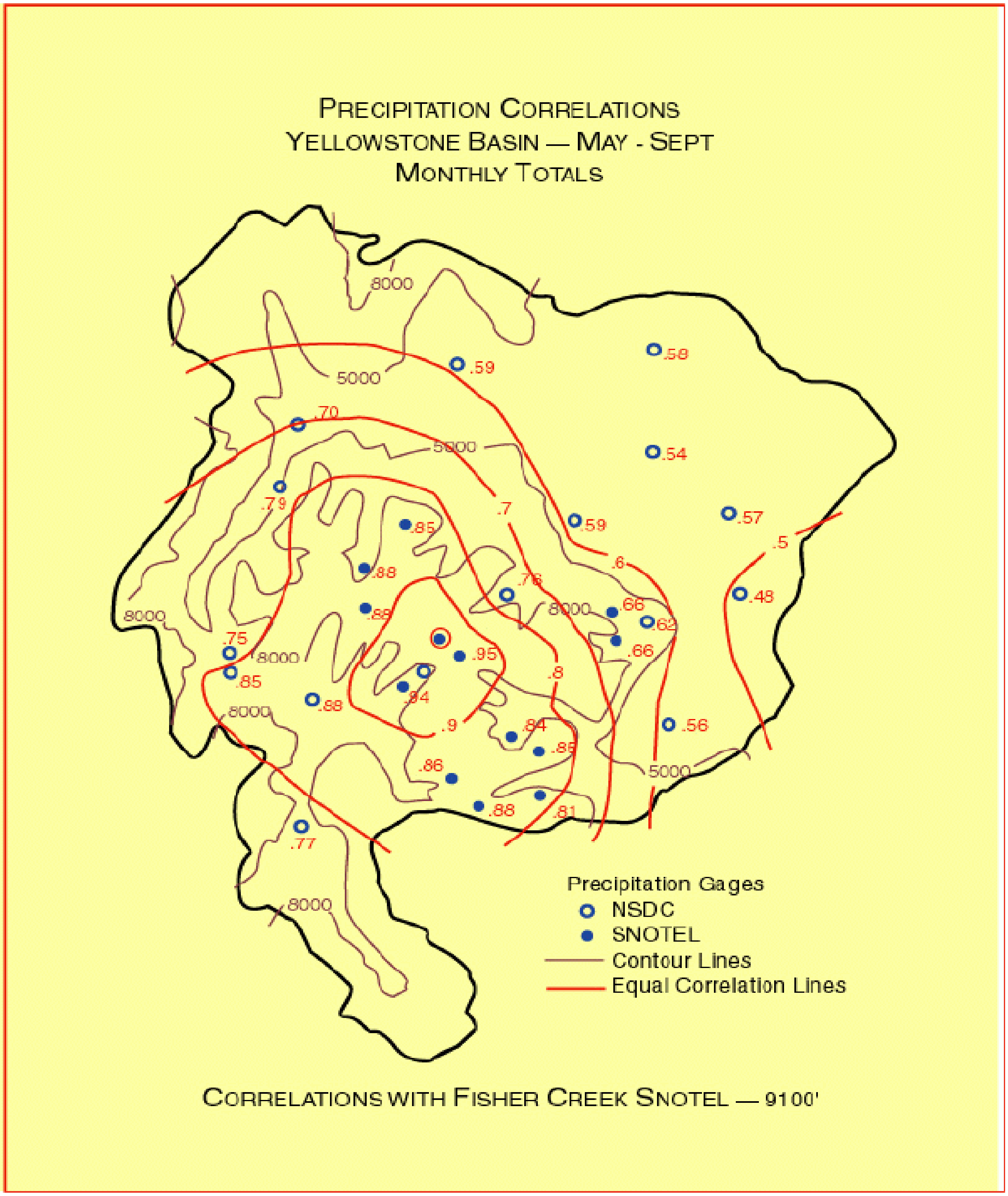


Figure 6-3-7. Summer season correlation pattern for Upper Yellowstone River basin around the Fisher Creek SNOTEL station

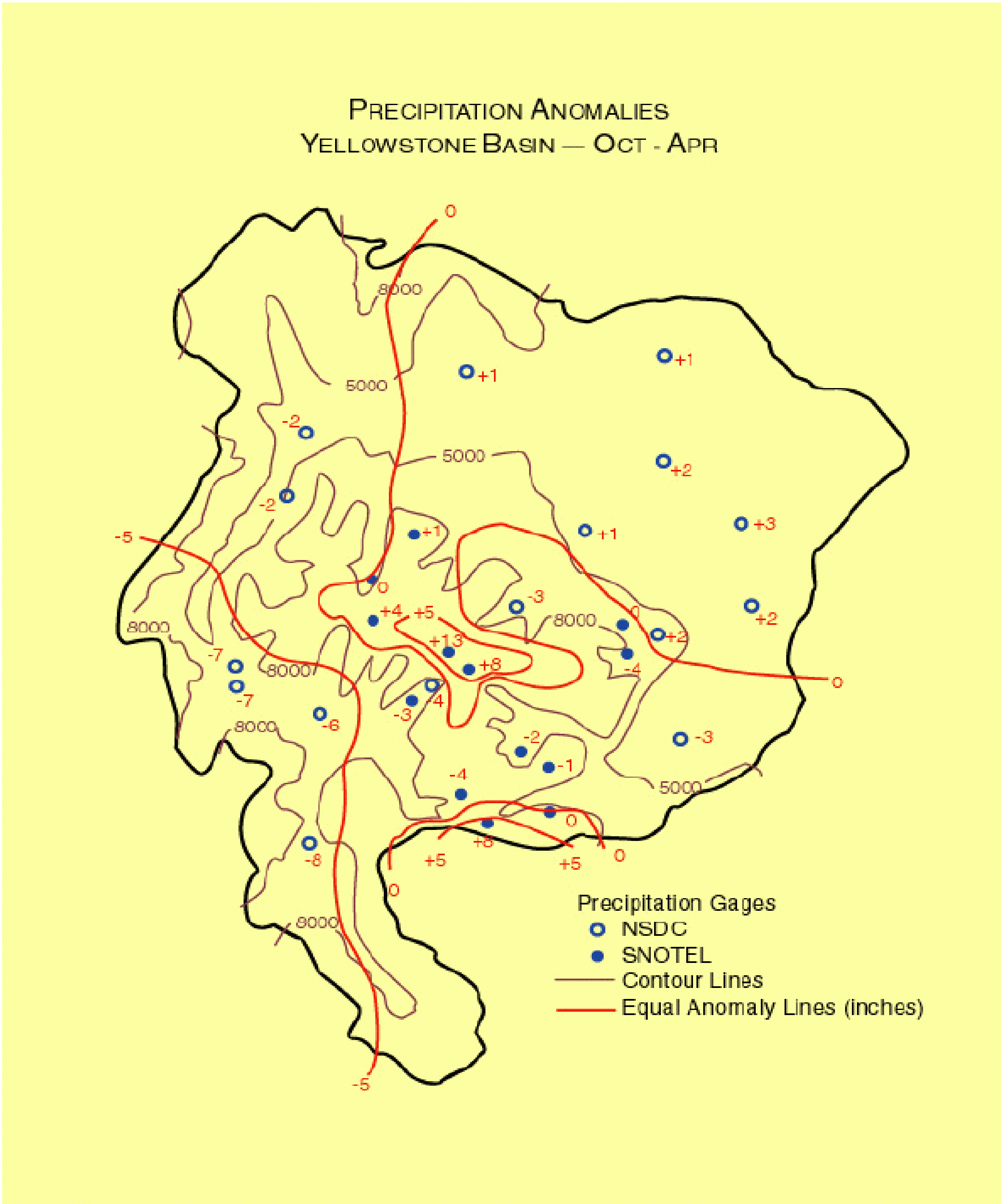


Figure 6-3-8. Winter season precipitation anomaly map for the Upper Yellowstone River basin.

Figure 6-3-8 shows an anomaly map for the winter season for the Upper Yellowstone River basin (Figure 6-3-2 shows the variation in precipitation versus elevation for this basin). This plot shows positive deviations in the northeast quadrant of the basin with the largest orographic effects at higher elevations of the Beartooth Range.

Once the stations to be weighted are selected and the relative weights chosen, then the relative weights are adjusted using Equation 6-3-4 for each MAP area to get station weights that will generate the average mean areal precipitation that has been determined to be the most likely estimate for the historical period of record. These are the predetermined weights used to compute the MAP time series for each area.

$$W_{i,s} = \frac{\overline{A}_s}{\sum_{i=1}^{i=N} \left(\overline{S}_{i,s} \cdot R_{i,s} \right)} \qquad (6\text{-}3\text{-}4)$$

where: i = station whose weight is being computed
s = season of the year
N = total number of stations with weight
W = station weight
R = relative station weight
$\overline{A}$ = average mean areal precipitation
$\overline{S}$ = station mean precipitation

Computation of the MAP Time Series

The final step in the historical precipitation analysis process for mountainous areas is to run the MAP program and compute the mean areal precipitation time series for each MAP area within the river basin for the period of record being used. The sequence used when estimating missing values and distributing accumulated amounts is the same described in the Background section under Non-Mountainous Area Precipitation Estimates in this chapter except that Eq. 6-3-2 is used to estimate missing data. The MAP program will generate summary tables for each area that show the total precipitation for each month, as well as the annual and seasonal mean values over the run period. The mean values computed should agree with the annual or seasonal averages determined from the adjusted isohyetal analysis. If not, the station weights were not computed correctly and need to be corrected.

Section 6-4

Computation of Mean Areal Temperature

Introduction

Temperature time series are needed for model calibration whenever snow is to be included in the computations. Temperature time series are also needed when the frozen ground options are to be used in the Sacramento Model and possibly for some of the other NWSRFS operations such as the Consumptive Use irrigation model to estimate evaporation. As was pointed out in chapter 6, the snow model is very sensitive to temperature. Small differences in temperatures can have a significant effect on the timing of snowmelt and will alter the model's determination of whether precipitation is in the form of rain or snow. Thus, it is very important that the MAT estimates are as unbiased as possible with regard to what actually occurred in nature. Bias can easily occur if one is not careful when extrapolating low elevation temperature measurements to high elevation portions of the basin. Such bias can seriously affect the simulation results and the proper determination of snow model parameter values.

At this stage of the process it is assumed that all the temperature data are available in the proper form and that the data have been checked for consistency and adjusted if necessary. It is also assumed that the areas where MAT estimates are to be generated have been determined based on the definition of the flow points needed for calibration and the possible subdivision of the drainage areas into elevation zones or subareas specified by other means. It is also assumed that it has been determined as to whether mountainous or non-mountainous area procedures should be used to compute areal estimates. Generally the mountainous area procedures need to be used for temperature only when there are definite variations in elevation over the river basin.

Limitation of Current NWSRFS Historical MAT Program

The current NWSRFS historical data MAT program uses only daily maximum and minimum temperature data to compute 6 hour mean areal values. In order to generate 6 hour estimates from daily max/min data, the program must make assumptions as to when during the day the max and min values occur and the shape of the diurnal variation in temperature. The program assumes that the max temperature occurs in the early afternoon and the min temperature occurs around 6 a.m.. The observation time of the max/min values is used to determine the day to which each value is assigned. If a station has a p.m. observation time, it is assumed that the max and min occur on the day that the observation is taken. If a station has an a.m. observation time, it is assumed that the recorded max temperature occurred the previous day and the min temperature occurred that morning. Thus, it is important to specify changes in observation time whenever there is a change from afternoon to morning or vice-versa for a station. The diurnal temperature pattern that is used in the MAT program is based on typical spring time patterns at the Central Sierra Snow Laboratory near Donner Pass in California and the NOAA/ARS snow research station near Danville, Vermont.

As would be expected, the daily temperature pattern produced by the MAT program is in error whenever the actual max and min temperatures occur at times considerably different from those assumed. However, errors also occur just due to the use of daily max/min values. For an a.m. observing station, rather than the recorded minimum temperature occurring that morning as assumed by the program, the recorded value could have occurred the previous morning. For a p.m. observing station, rather than the recorded maximum temperature occurring that afternoon as assumed by the program, it could have occurred the previous afternoon. Thus, even though the max and min values occur at the times assumed by the program, they may be assigned to the wrong day. Both of these problems, i.e. values occurring at times other than assumed and values being assigned to the wrong day, are illustrated in Figures 6-4-1 and 6-4-2. In Figure 6-4-1 not only are the 6 hour temperatures in error on days 5 and 6 due to the max actually occurring in the early morning hours, but some of the 6 hour values on days 2 and 3 are also off because the min recorded on the 3rd actually occurred on the morning of the 2nd. Similarly in Figure 6-4-2, the 6 hour MAT values on days 5 and 6 are in error for the same reason as the previous figure and some of the 6-hour values on day 4 are off because the max recorded on the afternoon of the 4th actually occurred on the afternoon of the 3rd. Both these problems could be eliminated by using instantaneous temperature data to determine the diurnal pattern and the time of occurrence of the max and min values. Such an enhancement would significantly reduce problems of mistyping the form of precipitation and would improve computations of the timing of snowmelt in many regions of the country. Instantaneous temperatures are used in the operational MAT program.

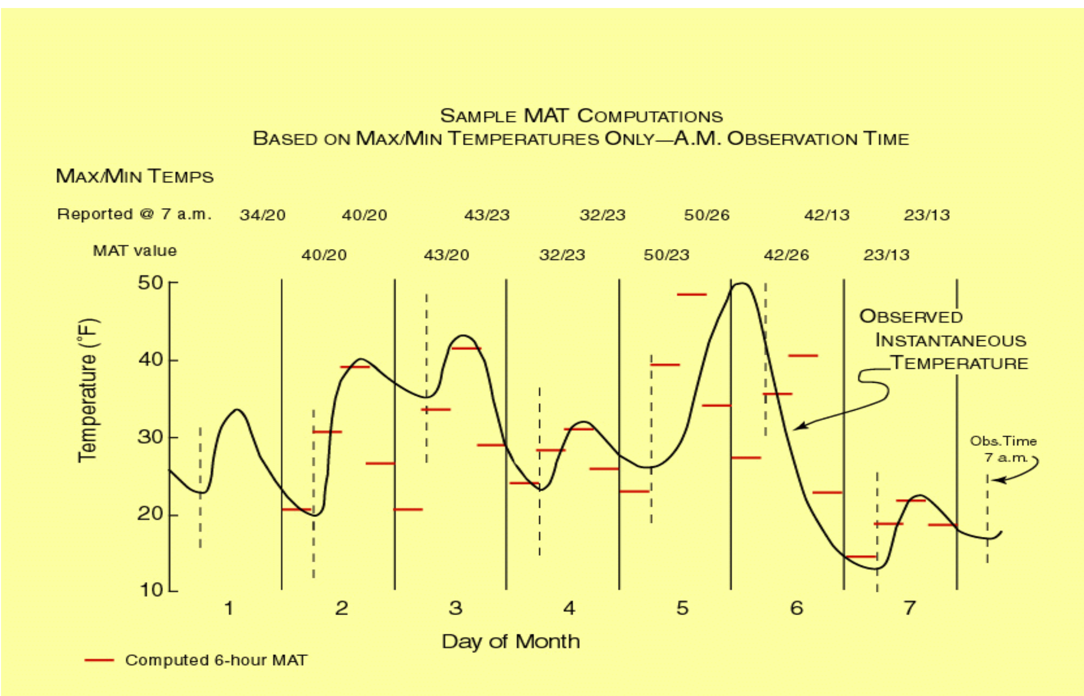


Figure 6-4-1. Sample MAT computations using only max and min temperatures and an a.m. observation time.

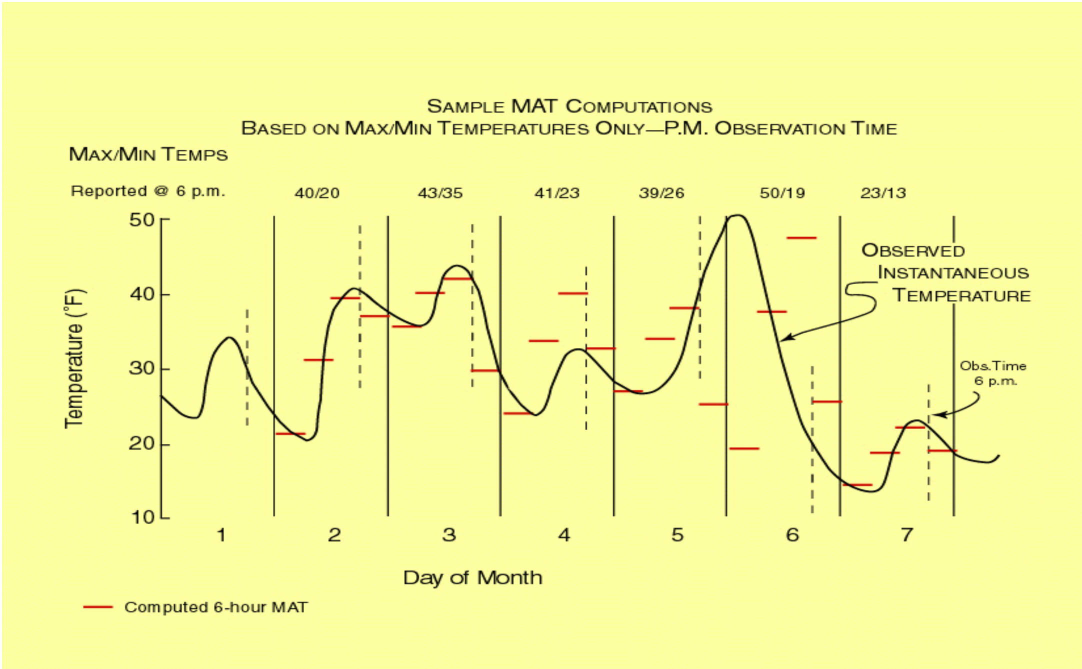


Figure 6-4-2. Sample MAT computations using only max and min temperatures and a p.m. observation time.

<u>Estimation of Missing Max/Min Temperatures</u>

Unlike with precipitation, mean monthly temperatures are used to adjust estimator stations to be consistent with the station with the missing values in non-mountainous, as well as mountainous areas. Missing temperature values, either maximum or minimum, are estimated in NWSRFS by the equation:

$$T_x = \frac{\sum_{i=1}^{i=n}\left[\left(\overline{T}_x - \overline{T}_i\right) + T_i\right] \cdot w_{x,i}}{\sum_{i=1}^{i=n} w_{x,i}} \qquad (6\text{-}4\text{-}1)$$

where: T = max or min temperature value ($\overline{T}$ signifies mean value),
x = station being estimated,
i = estimator station,
n = number of estimator stations, and
w = weight applied to each estimator; computed as:

$$w_{x,i} = \frac{1.0}{d_{x,i} + F_e \cdot \Delta E_{x,i}} \qquad (6\text{-}4\text{-}2)$$

where: d = distance,
ΔE = elevation difference, and
F_e = elevation weighting factor.

In non-mountainous areas the elevation weighting factor is zero. In mountainous areas F_e is used so that elevation, as well as distance, is used to determine which estimator stations are used. This is important since elevation has such a dominant effect on temperature in the mountains. The "TEMPCK" option in the MAT program can be used to investigate the effect of different F_e values on the accuracy of the estimates for a selected station. Normally, default values of F_e are used. The default values suggested are 20 (miles/1000 feet) for English units and 100 (kilometers/1000 meters) for metric units. As with precipitation, the station with the largest weight and an observed data value in each quadrant is used as an estimator. The quadrants are again based on the HRAP 4 kilometer grid system. Also, as with precipitation, estimated values are not used to determine missing values.

The TEMPCK option in the MAT program allows the user to select various values of F_e to estimate all the maximum and minimum temperatures at a specified station and then statistically compare the estimated and observed values. The TEMPCK option was used in the White Mountains of New Hampshire and the Mogollan Rim area of Arizona to investigate how the accuracy of the estimates varied with F_e. A value of F_e that gave nearly the best statistical result in both regions was selected as the default. It should be noted that for any given station the optimal value of F_e depends on the locations and elevations of the surrounding stations in the network. The most significant changes in the accuracy of the estimates occur when the use of a different F_e causes a change in the estimator station in one or more quadrants. If the closest stations in terms of distance are also the nearest in elevation, changing F_e doesn’t have much affect on the accuracy of the estimates. It is recommended that the default value of F_e be used unless the TEMPCK option clearly shows that another value would improve the estimation of missing data. It is likely that the TEMPCK option would only be worthwhile trying for a station with a lot of missing data that had a large weight for an important area..

Once all the missing max and min values have been estimated for all stations, then the assumed typical diurnal temperature variation is applied in order to compute 6 hour mean temperature values at all the stations. If all stations have missing values for max or min temperatures on a given day, several resulting MAT values will be set to missing.

Computation of Station Mean Temperature

Unlike precipitation, where the PXPP program computes monthly mean values in a consistent manner for the entire period of record, there currently is no preliminary processing program for temperature in NWSRFS. The initial mean monthly max and min values are generally computed directly from the observed data for the station and then altered when consistency corrections are applied as mentioned in Section 6-2 (under the section titled "Guidelines for Making Consistency Corrections"), however, the mean values are still based only on the period of observed data for the station. Inconsistencies exist when different stations use different periods of record to compute the mean monthly values. Since there is no preliminary processing program for temperature, the stations used should have relatively long periods of record (at least 70% of the historical data period as mentioned in Chapter 3) so that the means computed from the data are close to the mean for the entire MAT computational period. However, in mountainous areas there are situations when parts of the region, especially high elevation areas, do not have any stations with that length of data and thus, stations with relatively short periods of record need to be included in the analysis. For stations with relatively short periods of record, the monthly means should be computed in a manner similar to that used by the PXPP program for precipitation. This procedure involves the use of a base station with a long, consistent record. The elevation of the base station should also be as close as possible to the elevations of the stations with short periods of record. For temperature data this procedure must be done manually. The steps in the process are as follows:

1. Select a base station and get its mean monthly max and min values for the MAT computational period from a MAT run for the entire period.

2. For each station with a short period of record, make an MAT run for the period that the station has data and get the mean monthly values for both that station and the base station for this shorter period. Compute the difference in mean monthly max and min temperatures between each station and the base station for the period when both stations have data.

3. For each station with a short record, apply the difference computed from the period when both it and the base station have data to the mean values obtained in step 1 for the base station. This results in an estimate of the mean values for the entire period for the stations with short records. These estimates will be the initial mean monthly max and min values to use for these stations.

4. As consistency corrections are applied and new mean values are computed, do <u>not</u> substitute the updated means computed by the MAT program for the stations with short records as the updated mean values computed by the program are based solely on the period of observed data for each station. If consistency corrections are applied to the stations with short records, the mean monthly values for those stations will need to be manually adjusted based on the magnitude of the correction and the portion of the observed data period over which it is applied.

Table 6-4-1 contains an example of the process for computing the appropriate means for a station with a short record. In this example MAT values are to be generated for the historical period from 1949 to 1998. Station B has a consistent and essentially complete (i.e. very little missing data) record for the entire historical period. The table shows the mean monthly max and min values computed for this station for the 1949-1998 period. Station X is a high elevation station that was not available until 1985. Station B is the highest elevation station with a long record in the vicinity of Station X. By running the MAT program for the 1985-1998 period, mean monthly values can be generated for both stations for this portion of the historical record. These values are shown in the table (note that the means for Station B for 1985-1998 are generally higher than those for the entire historical period indicating that the later years were somewhat warmer). The average difference in temperatures between Stations X and B are then computed based on the period when both had data (note that in order to get a good estimate of the average difference between the stations, the record for both stations should be as complete as possible during the overlapping period -- the program computes the mean of all observed values for each station, whereas in reality the difference should be computed using only those months when both stations have no missing data) . These differences are then added to the means for Station B for the entire historical period in order to estimate the means for Station X that are appropriate for use during the 1949-1998 period.

Sta./Yrs.	value	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sta. B 49-98	max	30.3	31.7	38.4	45.7	52.5	60.3	68.7	69.4	54.8	42.9	35.6	31.3
	min	2.8	5.6	11.2	21.7	28.6	31.7	35.7	36.2	30.6	20.4	10.9	6.4
Sta. B 85-98	max	33.6	34.8	41.3	47.7	54.3	63.7	70.4	70.2	57.1	45.8	38.2	33.8
	min	5.8	9.5	12.8	24.1	30.8	33.6	37.6	35.8	33.4	24.1	14.2	8.9
Sta. X 85-98	max	26.8	27.6	34.1	39.3	45.1	53.9	60.0	60.1	47.5	37.4	30.9	27.4
	min	9.5	13.7	15.4	25.3	30.4	31.2	34.2	32.6	31.5	23.8	16.0	12.3
Diff. (X-B) 85-98	max	-6.8	-7.4	-7.2	-8.4	-9.2	-9.8	-10.4	-10.1	-9.6	-8.4	-7.3	-6.4
	min	3.7	4.2	2.6	1.2	-0.4	-2.4	-3.4	-3.2	-1.9	-0.3	1.8	3.4
Sta. X 49-98	max	23.5	24.3	31.2	37.3	43.3	50.5	58.3	59.3	45.2	34.5	28.3	24.9
	min	6.5	9.8	13.8	22.9	28.2	29.3	32.3	33.0	28.7	20.1	12.7	9.8

Table 6-4-1. Example of Computing Mean Temperatures for a Station with a Short Record.

This procedure should certainly be used for any stations with data for less than 25 percent of the computational period. It should be considered for all stations with data for less than about 70% of the computational period. Ideally a preliminary processing program should be written for temperature data so that the proper means for all stations for the entire historical period will be computed correctly and automatically.

Non-Mountainous Areas

Determination of Station Weights and Generation of MAT Time Series

For non-mountainous areas the stations to be weighted and the weight assigned to each station are based on the location of the station relative to the boundaries of the area for which MAT is being computed. In the NWSRFS historical data MAT program, grid point weighting is used in non-mountainous areas. Basin boundaries are specified by latitude/longitude points. The 4 km HRAP grid is overlain over each MAT area and 1.0/d weights are determined for each grid point within the area based on the closest station in each quadrant around the point. The weights for all the grid points in the area are then normalized so that the sum of the station weights is 1.0. These weights are then applied to the 6 hour mean temperature values that have been computed for each station to get the 6 hour MAT time series for each area.

Mountainous Areas

Introduction

In a mountainous area the average temperatures vary considerably over each MAT area with most of the variation due to differences in elevation. Thus, the estimation of the mean areal temperature in mountainous regions is based on the typical relationship between temperature and elevation. The temperature-elevation relationship serves the same function for the recommended mountainous area temperature procedure as an isohyetal analysis does for the precipitation procedure. Such relationships are generally regional in nature, thus one relationship can be used for a number of MAT areas to estimate the average temperature at the mean elevation of the area.

Temperature-Elevation Analysis

The temperature-elevation analysis should be done on a regional basis, not for individual watersheds. The regions for which temperature-elevation relationships are developed need to be carefully selected based on climatic factors. Typically for temperature the major factors are latitude and distance from major water bodies, especially oceans. Other climatic factors may also need to be considered. It is up to the user to determine the regions over which the relationship of temperature with elevation can be considered the same.

The typical relationship between temperature and elevation varies seasonally due to differences in heating caused primarily by differences in the length of days and the amount of solar energy. Also the variations of maximum and minimum temperature with elevation are not typically the same. The lapse rate during the middle of the day when the max temperature generally occurs is generally steeper than the lapse rate in the early morning when temperatures are typically at the minimum values. Thus separate temperature-elevation relationships are developed for max and min temperatures on a monthly basis to reflect these variations.

In order to develop the relationships, the mean max and min temperatures for all stations in the region (after consistency corrections have been made) are plotted versus elevation for each month of the year. In NWSRFS, the TAPLOT program can be used to generate these plots. TAPLOT uses the letters of the alphabet to plot each station, thus a maximum of 26 stations are allowed. If there are more than 26 stations in a region, some of the stations that represent similar elevations can be removed before generating the plots. Once the plots are generated, lines can be drawn for each month to represent how max and min temperatures typically vary with elevation. When drawing the lines there are several factors that should be considered:

1. Though one straight line is normally drawn, the rate of change of temperature with elevation can vary in some regions. Also during certain months in some areas, lapse conditions may persist at higher elevations, while there is an inversion at the lower elevations. This is especially true during winter months in interior Alaska where even max temperatures can show inversions at low elevations during months with little or no sunlight.

2. There may be some stations that experience local effects, like cold air drainage, and are thus not representative of the elevation where they are located

3. The lines drawn should represent physically realistic lapse and inversion conditions. For example, lapse rates are typically in the range of about 0.3 to 0.9 °C/100 m for most areas, though they can be less, especially for min temperatures, in the winter at northern latitudes. A typical lapse rate used in many snowmelt modeling studies throughout the world is 0.6°C/100 m (3.3°F/1000 ft) for mean daily temperature (the max temperature lapse rate would be greater than this value and the min temperature lapse rate would be smaller). It can be helpful to draw a 0.6°C/100m lapse rate line on each plot to assist in making sure that the relationship selected is physically realistic.

4. The seasonal variation in lapse rates should exhibit a smooth transition from month to month. Typically lapse rates are greatest in the summer and smallest in the winter. In some regions minimum temperature lapse rates will show a double peak. In such regions the min lapse rate will peak in the spring and again in the fall when humidity is lower and it is easier to cool the atmosphere and decrease during the humid summer months. It is a good idea to compute the lapse rates from the temperature versus elevation relationships that are developed and plot the rates on a monthly basis to make sure the seasonal changes are reasonable and that there are not abrupt variations from one month to the next.

The temperature versus elevation relationships are primarily used to extrapolate temperatures from lower to higher elevations due to a lack of high elevation data in most basins. Since most snow accumulation, and thus the majority of the runoff, comes from higher elevations, it is critical that the extrapolation is physically realistic. Improper lapse rates can result in biased MAT values being generated at higher elevations. Biased temperatures will result in unreasonable snow model parameter values and poor simulations of the snow accumulation and ablation process.

Figure 6-4-3 shows max and min temperature versus elevation plots for the month of March for the Merrimack River basin in Massachusetts and New Hampshire. This river basin was divided into 2 regions as far as temperature versus elevation relationships. This was partly due to differences in latitude from south to north in the basin and partly due to the influence of the ocean on the southern portion of the basin. During the summer months the relationships were essentially the same, as the cooling effects of the ocean in the south offset the increased latitude of the northern portion. In the winter, temperatures were significantly cooler at a given elevation in the north than in the south where the ocean had a moderating effect. The lapse rates for max and min temperatures for each month were the same for both regions, only the intercepts varied. It should be noted that in addition to the max and min temperature versus elevation lines for the two regions, a line showing the 0.6°C/100m lapse rate is also drawn on the plots to assist in making sure that the lapse rates are realistic.

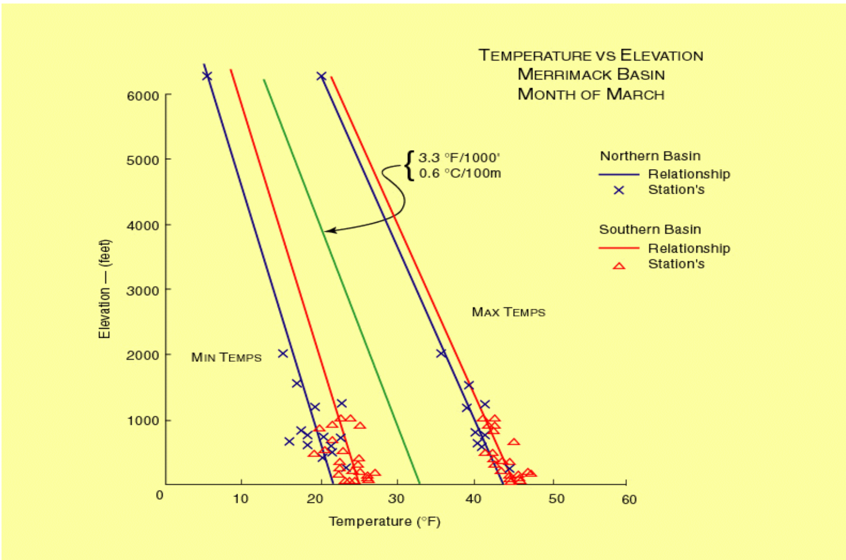


Figure 6-4-3. Temperature-elevation plots for March for the Merimack River basin.

Figure 6-4-4 shows a plot of the seasonal variation in lapse rates for the Upper Missouri River basin. This figure shows the lapse rates computed from the initially drawn temperature versus elevation lines and adjusted lapse rates. These adjustments were made so that the seasonal lapse rate pattern made a reasonably smooth transition from one month to the next. The adjusted lapse rates were used to slightly modify the initial temperature versus elevation lines. It is very important to compute and plot the lapse rates for each month as a check that the values are realistic and that the transition from month to month is reasonable.

Determination of Station Weights

The procedure recommended for temperature computations in mountainous areas for use with

NWSRFS involves establishing a synthetic or "dummy" station at the mean elevation of each MAT area and giving all the weight to the synthetic station. A synthetic station is one with no observed data; i.e. all the data values are estimated from surrounding real stations. In order to define a synthetic station, mean monthly max and min temperatures and a location are needed. The mean monthly max and min temperatures are picked off the regional temperature versus elevation plots for the mean elevation of the MAT area that the synthetic station represents. The location of the synthetic station is subjective, but should be selected so that the best possible estimator stations will be used to generate the synthetic data values. The location, elevation, and completeness of data for potential estimator stations are the major factors to consider when locating the synthetic station. Ideally the elevation of the estimator stations should be as similar as possible to the elevation of the synthetic station. Typically the synthetic station should be located so that several good estimators will be used to generate the data values.

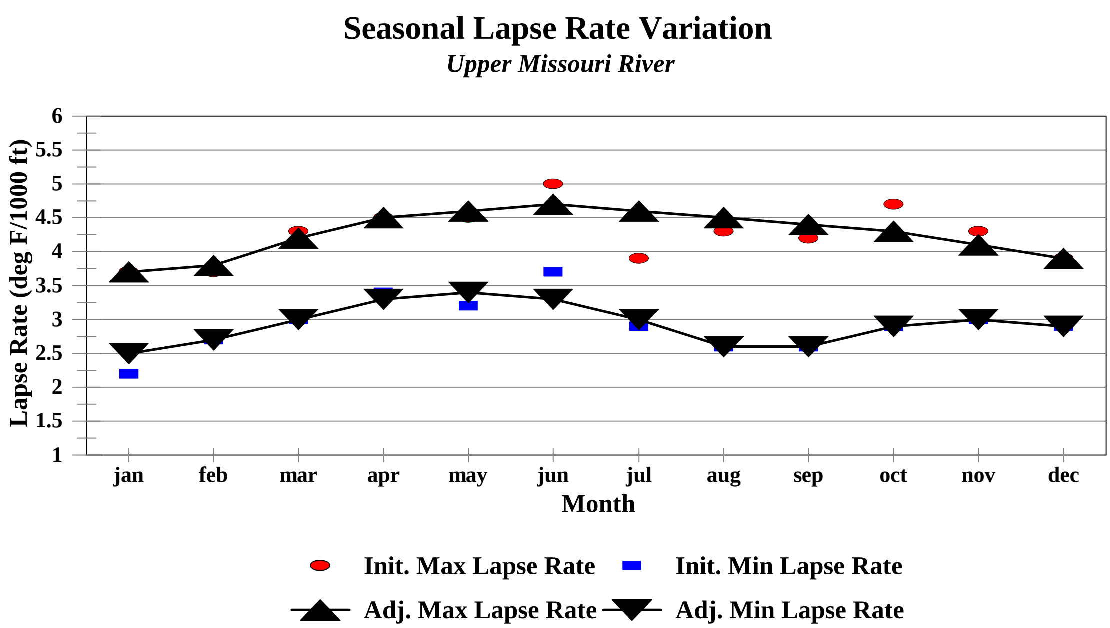


Figure 6-4-4. Seasonal variation in lapse rates for the Upper Missouri River basin.

Computation of MAT

The final step in the historical temperature analysis process in a mountainous area is to input the synthetic station information and the station weights and run the calibration MAT program to compute the time series for each MAT area for the entire period of record. For each MAT area, the synthetic station associated with that area is given a predetermined weight of 1.0 and all other stations, real and synthetic, are given zero weight. Besides generating 6-hour MAT time series, the program will produce summary tables for each zone showing the mean temperatures for each month and year, as well as the overall mean for the period of record.

Section 6-5

Evaporation Estimates for Conceptual Modeling

Introduction

In order to produce a proper water balance, conceptual models require realistic and consistent estimates of evaporation as well as precipitation. Although evaporation data will generally not affect the simulation accuracy of individual storm events nearly as much as precipitation data, good evaporation estimates are critical to producing a reasonable seasonal and annual water balance. Like the other input data used to drive the models, evaporation estimates should correspond as closely as possible to what actually occurs in nature. Biased estimates of evaporation will cause model parameters to take on unrealistic values and will deteriorate the quality of the simulations.

At this stage of the process it is assumed that all the data needed to determine evaporation estimates for use by the models are available in the proper form and that the data have been checked for consistency and adjusted if necessary. It is also assumed that the areas where evaporation estimates are to be generated have been determined based on the definition of the flow points needed for calibration and the possible subdivision of the drainage areas into elevation zones or subareas has been specified by other means. It is also assumed that it has been determined whether mountainous or non-mountainous area procedures should be used to compute the estimates. As with temperature, generally the mountainous area procedures only need to be used for evaporation when there are definite variations in elevation over the river basin.

Terminology

There are a number of terms that are used in conjunction with evaporation that sometimes take on different meanings to different people, thus, these terms need to be clearly defined as to how they are used in this manual.

- Potential Evaporation - Potential Evaporation (PE) is defined as the evaporation from a well wetted (i.e. the moisture supply is not limiting the evaporation), actively growing grass surface. The PE rate for grass under these conditions is calculated from the current meteorological conditions, i.e. temperature, humidity, wind, radiation, atmospheric stability, etc..

- Free Water Surface Evaporation - Free Water Surface (FWS) evaporation is the evaporation from a water surface with no heat storage. Evaporation from lakes and reservoirs involves some energy being used to warm the water body or being released as the water body cools and thus differs from FWS evaporation. Studies have shown that FWS evaporation is essentially the same as PE from a grass surface.

• Evapotranspiration (ET) Demand - ET Demand is the term used in the Sacramento Model to specify the evaporation that occurs when the moisture supply is not limiting given the type of vegetation that exists and the activity level of that vegetation. Thus while PE is defined for an actively growing grass surface, ET Demand is based on the actual vegetation in the area and how active that vegetation is given the time of the year and other factors.

• Seasonal PE Adjustment Curve - The PE adjustment curve modifies PE values on a seasonal basis for both the type of vegetation and the activity level of the vegetation. Thus, it is the seasonally varying ratio of ET Demand to PE or expressed in another way, ET Demand is equal to PE times the seasonal PE adjustment curve.

• Actual ET - Actual ET is the amount of evaporation loss from a watershed or subarea given the ET Demand and the current moisture conditions and snow cover. The actual amount of ET is limited by the amount of moisture in the soil and the evaporation rate is generally suppressed when snow covers the vegetation. Actual ET is less than or equal to ET Demand.

• Pan Evaporation - Pan evaporation is the amount of evaporation as measured with an evaporation pan. Pan evaporation differs from FWS evaporation in that there is some change in heat storage due to changes in the temperature of the water in the pan and because energy transfer occurs through the sides and bottom of a pan. The evaporation pan used most commonly in the United States is called a Class A pan.

• Pan Coefficient - The pan coefficient is the average ratio of FWS evaporation to the evaporation measured by a pan. Pan coefficients are less than 1.0 since the evaporation measured by the pan is greater than FWS evaporation over the long-term. The pan coefficient for a Class A pan is generally said to be about 0.7. The May-October pan coefficient actually varies from 0.66 to 0.88 over the contiguous United States as shown on map 4 in NOAA Technical Report NWS 33 [*Farnsworth and Peck*, 1982].

It is important to clearly understand these terms before reading the rest of this section and in order to properly prepare and use evaporation data with conceptual models. The Sacramento Model computes actual ET starting with an ET-Demand that is derived from PE and a seasonal PE adjustment curve. The ET-Demand values input to the model can either be in the form of climatological averages (defined at the mid-point of each month) or daily estimates (calculated by applying an average seasonal PE adjustment curve to a daily PE time series).

Determination of PE

For use in deriving evaporation estimates for application with conceptual models, PE can be in the form of daily time series or average monthly values.

• Daily PE is generally computed from meteorological factors using a Penman type equation. The most common equations use air temperature, dew-point, wind speed, and solar radiation to compute a daily value of PE since atmospheric radiation and the data to derive stability are seldom available. If direct measurements of solar radiation are not available, the amount of solar energy can be estimated from percent sunshine using the method of Hamon, Weiss, and Wilson [1954] or sky cover using the method of Thompson [1976]. Values can be computed only at synoptic stations or at other climate stations that include instrumentation to measure these variables. Temperature, dew-point, and especially wind data must be adjusted to a specified instrument height. Lindsey and Farnsworth [1992] reported that using percent sunshine to estimate the amount of solar radiation produces a reasonably unbiased estimate of PE. This study also indicated that using sky cover to get solar radiation will result in a biased estimate of evaporation. The NWSRFS synoptic data program includes a correction for removing this bias. It should also be noted that with the introduction of ASOS the sky cover data are no longer the same as the manual observations of sky cover that the Thompson method uses to compute solar radiation.

Daily values of PE could also be obtained from daily pan evaporation measurements using the appropriate pan coefficient to adjust the measured values. To be more precise the measured pan values should be adjusted for changes in heat storage using daily measurements of the water temperature in the pan. Even then the pan coefficient is only the average relationship between pan evaporation and FWS evaporation and actually varies somewhat from day to day based on meteorological conditions.

• Monthly average PE can be obtained from computations using meteorological factors or from average monthly pan evaporation adjusted by the appropriate pan coefficient. NOAA Technical Report NWS 34 [*Farnsworth and Thompson*, 1982] gives monthly average pan evaporation computed from meteorological stations for selected stations in each state. These values need to be adjusted by the appropriate pan coefficient to get average monthly PE. Technical Report 34 also contains tables of monthly average evaporation from pan data for the period 1956 to 1970. Averages of pan evaporation for other periods can be gotten directly from daily climatological stations that have pan measurements. Again the pan data need to be adjusted by the appropriate pan coefficient in order to get average monthly PE. In addition, in many parts of the country pan data are not available in the winter since the water in the pans will freeze. For these stations the ratio of annual FWS evaporation to May-October FWS values as determined from Technical Report NWS 33 can be used to determine the average amount of evaporation from November through April. Then a nearby meteorological station from report 34 can be used to prorate this total into monthly values.

Seasonal PE Adjustment Curves

The seasonal PE adjustment curve accounts for the type of vegetation in the area and the activity level of that vegetation. The curve is defined at the mid point of each month. When used with daily estimates of PE, linear interpolation is used between each point on the curve to determine the proper adjustment for each day. When monthly ET Demand is being input to the Sacramento Model, then the average monthly PE is multiplied by the PE adjustment for that month to get the

ET Demand at the mid point of the month. Again linear interpolation is used to determine the ET Demand for a given day.

Studies have shown that the evaporation rates from most actively growing vegetation differs from the rate for grass on which PE computations are based. In addition, the evaporation rates can vary considerably throughout the year as the vegetation goes through various stages from dormancy to active growth. A number of studies have shown that the total evaporation loss from a forest subjected to frequent rain, i.e. with leaves kept wet much of the time, can be 50% or more larger than the evaporation rate from grass (e.g. [*Calder, 1976]*. Under dry conditions the losses from a forest are much less due to stomatal control of water loss. For agricultural areas estimates of the seasonal PE adjustment curve can be computed for various crops using an FAO report [*Doorenbos and Pruitt*, 1977]. This report gives coefficients for various crops and climatic conditions that can be used to construct the seasonal adjustment curve based on the times of germination, attainment of full ground cover, start of maturing, and full maturity or harvest. For the crops listed, the PE adjustment during the active growing period varies from 0.8 to 1.25. There is also evidence that moss and lichen plants in tundra regions, such as Alaska and high elevations in the lower 48, use water at slower rates than does vegetation in warmer regions [*Patric and Black, 1968]*. Tundra plants function more like mulch than like transpiring vegetation. In such areas, evaporative demand, as specified by PE, can considerably exceed precipitation, but the soil almost always remains wet, even saturated, throughout the short summer season.

The PE adjustment curve used with the Sacramento Model is based solely on the time of the year and doesn't include any dynamics that account for differences in past and current climatic conditions from one year to another. For example, the activity level of vegetation in June could vary from a year with plenty of moisture and thus lush, green vegetation to a drought year when the vegetation has turned brown. The shape of the curve is also the same from year to year and thus any variations in the time when leaves come out in the spring or begin to turn colors in the fall are not taken into account. The PE adjustment curve used for hydrologic modeling is an integration of all the vegetation types and activity levels that exist over a watershed, elevation zone, or other area definition. Thus, some the information in the literature can serve as a guideline when coming up with a PE adjustment curve, but much of the process is subjectively based on a general knowledge of the type of vegetation in the area and the timing of changes in the activity levels.

Figures 6-5-1, 6-5-2, and 6-5-3 show seasonal PE adjustment curves that have been used for watershed calibrations at various locations around the country. Most of the curves in these figures exhibit a seasonal pattern of activity levels. This is because most of the watersheds contain considerable deciduous vegetation or crops that have a seasonal growth pattern. The curve for the watershed in western Washington shows essentially no seasonal variation. This watershed is covered predominantly with conifers, and the climatic conditions are such that the vegetation should be able to transpire throughout the year.

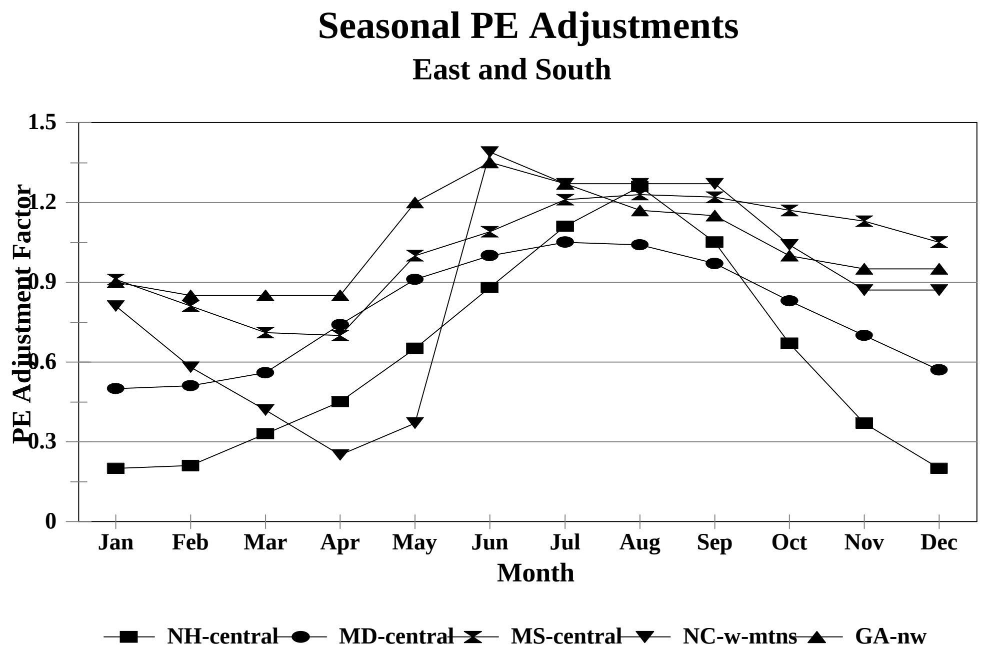


Figure 6-5-1. PE adjustment curves for watersheds in the east and south.

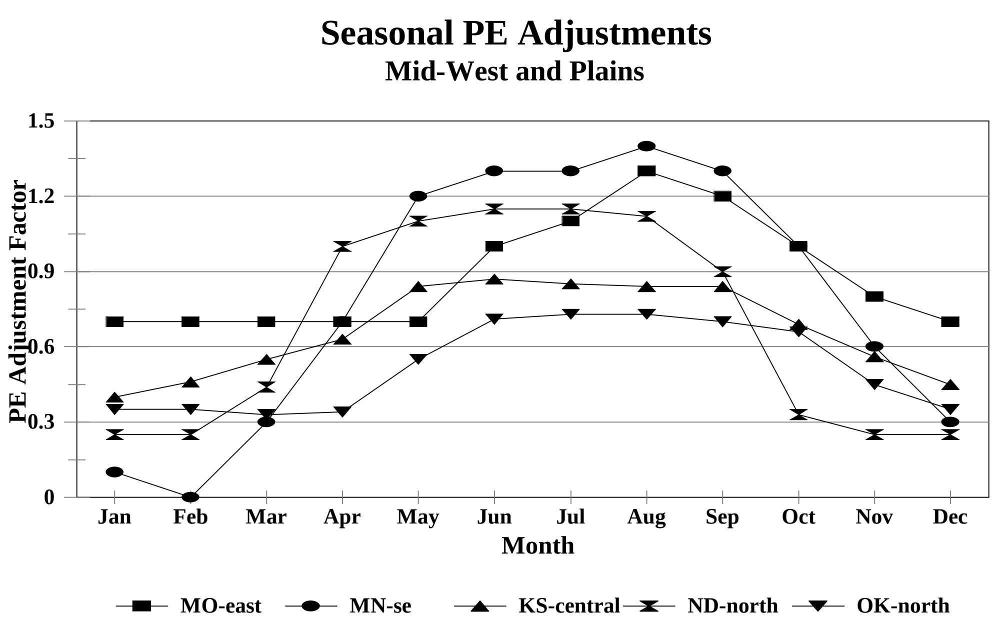


Figure 6-5-2. PE adjustment curves for watersheds in the mid-west and plains.

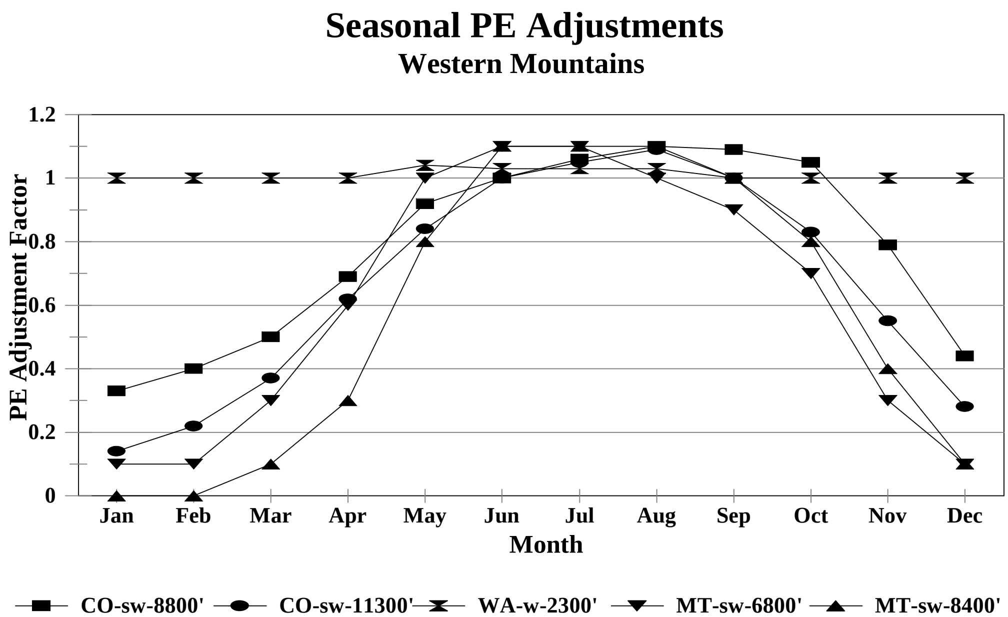


Figure 6-5-3. PE adjustments curves for watersheds in the western mountains.

Koren et al. [1998] compared NDVI green vegetation fraction values extracted from NCEP global data sets to PE adjustment curves from watersheds representing a northern mixed forest, southern mixed forest, southern Appalachian highlands, and the southwest (these curves were included in a 1970's prepared handout on deriving initial parameter values for the Sacramento Model). A reasonable correlation was found between the green vegetation fraction and the PE adjustment factors. This resulted in an equation for estimating the PE adjustment factors from the NDVI green fractions. This method can be used to derive a seasonal PE adjustment curve, but the method may not be applicable to the whole country. This method is included in CAP.

Non-Mountainous Area ET Demand Estimates

<u>Procedure</u>

For non-mountainous areas of the United States the map of annual FWS evaporation (map 3) in NOAA Technical Report NWS 33 has been adopted as the standard for long-term average PE values. The annual FWS evaporation values from this map provide an estimate of annual PE which when properly prorated to monthly values and combined with a reasonable seasonal adjustment curve gives ET Demand estimates that generally produce a realistic water balance. Thus, all PE estimates used in non-mountainous areas should first be adjusted to conform to the annual FWS values given in Technical Report 33.

The steps to follow for determining initial ET Demand values for each modeling area in a non-mountainous region are:

1. Obtain monthly estimates of PE as described earlier in this section based on meteorological variables or pan data and adjust the annual total to correspond to the value picked off map 3 of Technical Report 33. The PE may be in the form of daily values or monthly averages. The PE estimate can be based on a single station, a weighted average of several stations, or computed by using the MAPE program. The MAPE program can combine daily PE computed from meteorological variables and adjusted daily pan measurements to get a mean areal value. The MAPE program contains the option to make consistency checks and corrections.

2. Determine a seasonal PE adjustment curve as described earlier in this section. This curve is always defined at the mid point of each month.

3. Compute ET Demand. If climatological average values of ET Demand are to be used, the average PE for each month is multiplied by the PE adjustment for the month to get values of ET Demand that are assigned to the mid point of each month. If daily estimates of ET Demand are to be used by the model, the input is a daily time series of PE and the seasonal PE adjustment curve defined at the mid point of each month.

The only available guidance regarding the use of daily PE values as opposed to mean monthly estimates comes from a brief HRL study [*Anderson and Farnsworth*, 1981]. In this study simulations from three watersheds using both daily PE values with a seasonal PE adjustment curve and mean monthly ET Demand estimates were compared. The average monthly ET Demand values in both cases were kept exactly the same. The results are shown in Table 6-5-1. There was very little difference in simulation results in North Carolina, a little improvement when using daily PE values in Mississippi, and more improvement, especially in regard to monthly volume errors, for the Oklahoma watershed. In general, two conclusions can be made from this study. First, PE data has more effect on volume computations than on daily flow calculations. Second, the use of daily PE data improves simulation results more in areas where there is a significant variation in PE amounts from one year to another. The greatest variability in annual PE values in the United States is in the southern plains.

During calibration the amount of ET Demand may need to be adjusted in order to obtain a good water balance. Estimates of long-term average precipitation should be quite reliable in a non-mountainous region, thus variations in ET Demand from one watershed to another should be related to differences in vegetation, as long as one doesn’t neglect water balance terms such as diversions and deep aquifer recharge. When making adjustments in ET Demand, it is best to monitor how the seasonal PE adjustment curve is changing to make sure the transition from one month to another is realistic and that the differences in relationships from one watershed to another make sense.

	Daily RMS error (cms)		Monthly Vol. RMS error (mm)		
Watershed	Daily PE	Monthly Means	Daily PE	Monthly Means	Standard Deviation of Annual PE (mm)
Bird Ck. nr Sperry, OK	18.02	18.97	3.97	5.13	131.3
Leaf R. nr Collins, MS	15.76	16.02	7.54	7.91	89.3
Neuse R. nr Northside, NC	6.73	6.74	5.61	5.71	23.1

Table 6-5-1. Statistical comparison of streamflow simulations using computed daily PE values versus simulations using mean ET Demand estimates.

Mountainous Area ET Demand Estimates

Introduction

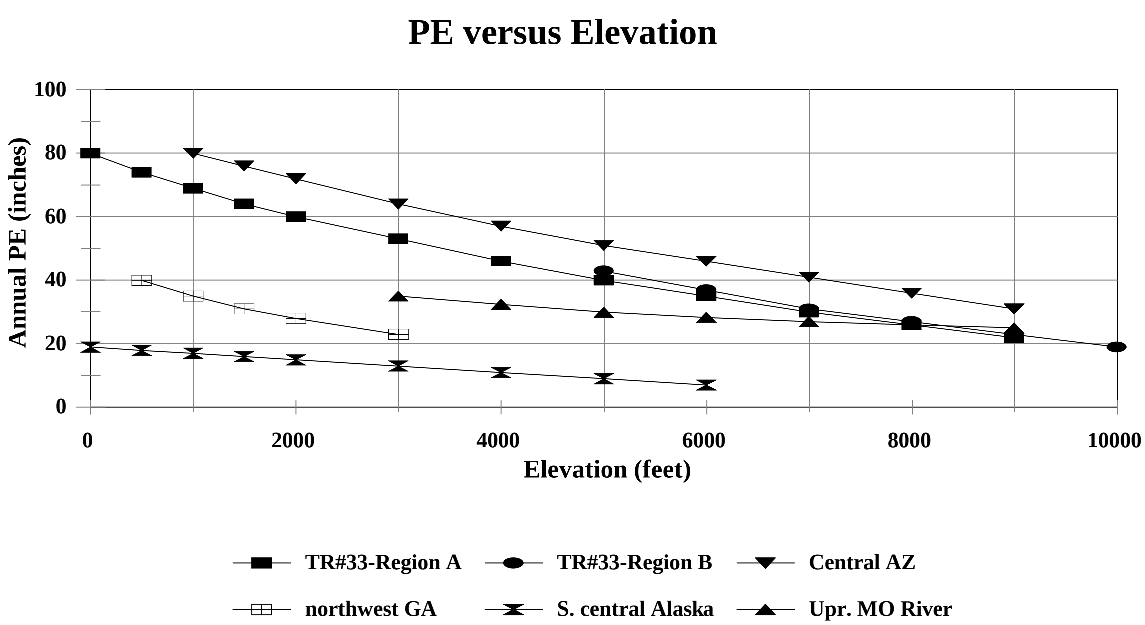
In mountainous regions the areal estimates of average precipitation are more likely to be in error than in non-mountainous areas. The isohyetal analysis used may reflect the general trend in how precipitation varies over the region, but at the watershed scale there can easily be random errors. Thus, if one treats the precipitation derived from the isohyetal maps as "true" and forces ET Demand adjustments to create a good water balance, it very likely that the resulting ET Demand variation over the region will not make physical sense. There should be a reasonable variation in ET Demand with elevation since PE and vegetation are highly correlated with elevation. Thus the underlying assumption for the recommended procedure for determining evaporation in mountainous areas is:

> *ET Demand variations are more spatially predictable and contain less error than precipitation variations, thus it is more logical to determine a reasonable ET Demand versus elevation relationship and then adjust MAP if needed than to assume MAP is correct and adjust ET Demand to obtain the correct water balance.*

Two approaches are given in this manual for determining the relationship between ET Demand and elevation. Which approach is used depends on whether the precipitation amounts from the available isohyetal analysis can be used to generate a reasonable water balance over most watersheds in the region. If so, water balance computations can be used to determine how actual ET varies with elevation and can serve as a basis for determining an ET Demand versus elevation relationship. If areal precipitation estimates derived from the available isohyetal maps do not produce a reasonable water balance over most watersheds in the region, then it is best to derive the variation in ET Demand with elevation from information on the variation of evaporation and vegetation over the region and combine this with runoff data to determine the amount of precipitation needed to produce the proper water balance. One way to judge the quality of the precipitation estimates from an isohyetal map is to compare the resulting actual ET values to PE estimates for the region. Actual ET is generally less than PE in most regions, though the ratio will vary depending on climate. The ratio of actual ET to PE is lowest in an arid region. In a forested area with frequent rains, actual ET could be greater than PE as mentioned earlier in this section. A snow cover over substantial portions of the year will tend to suppress ET, thus reducing the ratio.

Before describing methods of obtaining an ET Demand versus elevation relationship, we should first look at how PE can vary with elevation as a guide. In mountainous areas the annual FWS map in Technical Report 33 is not drawn to a sufficiently small spatial scale to define PE at the watershed level. That map shows the general trend of PE variations in mountainous areas, but not at the detailed level needed for hydrologic modeling. The amount of PE at a given location is affected by the climate of that location. In the mountains there can be small scale variations in PE due to terrain effects on radiation and wind, however, at the watershed scale much of the variation in PE can be explained by elevation differences. PE decreases with elevation with the rate of decrease becoming less as elevation increases. Figure 6-5-4 shows the variation in PE with elevation for several regions of the United States. The two relationships from Technical Report 33 were produced by plotting pan measurements at various elevations over the regions and then using the average pan coefficient for the region to convert the values to FWS evaporation. The Alaska relationship was generated from values computed by the Thornthwaite method for stations in south central Alaska by Patric and Black [1968]. The Upper Missouri River basin relationship was determined from a few pan sites and values picked off map 3 of Technical Report 33. The other two relationships were determined by plotting PE derived from

Figure 6-5-4. PE versus elevation for various regions of the United States.



pan measurements and meteorological variables. The magnitude of PE varies from one region to another due to climatic differences, but the general shape of the curves are similar.

In many regions the shape of the ET Demand versus elevation relationship should be somewhat similar to the shape of a plot of PE versus elevation. This will occur in regions where there is significant vegetation at all elevations and the transition from one type of vegetation to another is not dramatic. Such regions are those in the eastern part of the country and west of the Pacific crest. In other regions the variation in vegetation types and thus PE adjustments are so great that the shape of a ET Demand versus elevation plot may not be similar to the PE versus elevation relationship. Watersheds in such regions may include various subsets of transitions from arid climate vegetation such as cactus and sagebrush to forested zones to alpine tundra to extremely high elevations with no vegetation at all. Such variations can occur in the intermountain west and Alaska. In the northern portions of the intermountain west, the ET Demand versus elevation relationship is likely similar to a PE versus elevation plot over the range in elevations where most of the runoff is generated. In addition to being difficult to determine, it probably is not that important to know the exact ET Demand versus elevation relationship over elevation ranges where little or no runoff is generated.

<u>Determining ET Demand from a Water Balance Analysis</u>

In order to use this approach to determine a ET Demand versus elevation relationship for a river basin, water balance computations for drainages within the basin should produce a plot of actual ET versus elevation that shows a clear relationship. There may be a few watersheds within the basin that deviate from the relationship defined by the others due to possible errors in the isohyetal analysis (as in Figure 6-3-5), but the results from most of the drainages should show a clear and realistic relationship. If there is no clear relationship or if the resulting actual ET values are not reasonable, then the second approach (i.e. using evaporation, vegetation, and runoff data) should be tried. The water balance approach works best for relatively wet regions where the ratio of actual ET to ET Demand is greater than about 0.75 or if the ratio is less, it is due to a long period of snow cover. In semi-arid regions where this ratio is lower, it is more likely that there will be considerable scatter in the actual ET values derived from water balance computations.

The steps to follow when trying to derive a ET Demand versus elevation relationship from the results of water balance computations are as follows:

1. Perform water balance computations for appropriate headwater and local drainages within the river basin to determine estimates of actual annual ET. Guidelines for water balance computations are in Section 6-3 under the section "Determination of Average Mean Areal Precipitation for Each MAP Area."

2. Plot actual annual ET values derived from the water balance computations in step 1against the mean elevation of each drainage area (Figures 6-3-5 and 6-5-5 are examples of such

plots). If most of the points define a clear relationship that is physically realistic, then draw a line that defines the actual annual ET versus elevation relationship for the basin. If the plot exhibits a lot of scatter or the values are physically unreasonable, then try the second approach to determining an ET Demand versus elevation relationship.

3. If possible, use pan data or estimates based on meteorological variables to determine annual PE values for sites at different elevations in the vicinity of the basin. Plot these points and draw a PE versus elevation line. This step is optional, but can be helpful as a guide for determining the shape of the ET Demand versus elevation relationship.

4. Obtain a point on the ET Demand versus elevation relationship by calibrating the initial headwater basin (recommended strategy for calibrating the drainages in a river basin is discussed in chapter 7) to determine the average annual ratio of actual ET to ET Demand. This is done through an iterative process.

   a. Make an assumption as to the average annual ratio of actual ET to ET Demand to determine an initial estimate of the annual ET Demand for the watershed. If the headwater has multiple elevation zones, the ratio generally increases with elevation when the typical length of snow on the ground is not substantially different between zones. When one zone has snow for a much longer period than others, its ratio will typically be smaller due to suppression of evaporation when a snow cover exists.
   b. Using estimates of monthly PE and the seasonal PE adjustment curve generate monthly ET Demand values (could use daily PE data, if available) for this drainage.
   c. Adjust the seasonal PE adjustment curve until the resulting annual ET Demand is the same as the ET Demand which was based on the assumed ratio of actual ET to ET Demand. Spreadsheets are an ideal tool for these calculations.
   d. Calibrate the headwater area using these monthly ET Demand values. As the calibration proceeds, check the resulting average annual ratio of actual ET to ET Demand and revise the estimates of ET Demand based on the actual value of the ratio. This will typically have to be done once or twice.
   e. Finally, take the resulting annual ET Demand value and plot it versus elevation on the graph produced in step 2.

5. Using the value of annual ET Demand from the initial headwater area, draw an initial estimate of the curve showing how ET Demand should vary with elevation over the river basin. The actual annual ET and PE versus elevation plots can be helpful in drawing this curve. Also how the ratio of actual ET to ET Demand likely varies with elevation should be taken into account.

6. Verify the ET Demand versus elevation curve by using annual ET Demand from this relationship to calibrate other headwater areas at different elevations. Adjust annual ET Demand and thus the curve if the resulting ratio of actual ET to ET Demand is unrealistic.

7. Use the resulting annual ET Demand versus elevation relationship when calibrating all of

the other drainages within the river basin. Seasonal PE adjustment curves used to prorate the annual ET Demand into monthly values should reflect changes in the vegetation types and activity patterns with elevation. Some scatter about the defined relationship is allowed based on the location of the drainage within the basin (e.g. areas in the northern part of a river basin might be assigned a slightly lower annual ET Demand for a given elevation than an area in the southern part of the basin). During the calibrations, corrections to the long-term water balance should be made by adjusting the amount of precipitation rather than changing the ET Demand curve.

This procedure may be somewhat difficult to follow, thus it will be illustrated step by step using the Merrimack River Basin in New Hampshire and Massachusetts.

Step 1 – Water balance values were computed for all appropriate headwater areas and a couple of local areas within the Merrimack Basin. The WATERBAL operation was used to calculate the water balance components (requires the inclusion of the SNOW-17 and SAC-SMA operations -- nominal parameter values were specified). The MAP time series were based on the PRISM estimates of annual precipitation. The PXADJ and SCF model parameters were set to 1.0 so that there would be no changes made to the MAP values. The water balance values are shown in Table 6-5-2.

Step 2 – The actual ET values generated by the water balance analysis were plotted against the mean elevation of each watershed as shown in Figure 6-5-5. There is a reasonable relationship between actual ET and elevation. Some of the scatter is undoubtedly caused by climate differences resulting from variations in latitude and distance from the coast and some is due to sight variations in vegetation from one area to the next, however, a major portion of the scatter could be caused by inaccuracies in the PRISM isohyetal analysis.

Step 3 – There were two pan evaporation sites and two locations with evaporation computed from meteorological factors within the basin. All the sites were at similar elevations, thus it was not possible to construct a PE versus elevation relationship. The available data were used to derive an estimate of mean monthly PE that was thought to be realistic for a 500-1000 foot elevation in the central part of the basin. This seasonal variation in PE is shown in Figure 6-5-6. This PE corresponds to an annual total of 27.3 inches.

Step 4 – The Smith River near Bristol, NH (BRSN3 - mean elevation of 1117 feet) was chosen as the initial headwater area to be calibrated for the Merrimack Basin. This watershed has a single elevation zone. As far as arriving at a final ET Demand estimate for BRSN3, the steps were as follows:

4.a – A value of 0.75 was used as the initial estimate of the ratio of actual ET to ET Demand for BRSN3. This was just a guess.

4.b& c – An initial guess of the shape for the seasonal PE adjustment curve was made for BRSN3. This curve was then adjusted so that when the values were multiplied by the monthly PE shown in Figure 6-5-6 to get ET Demand, the resulting annual ratio of actual ET to ET Demand was about 0.75. This initial PE adjustment curve is shown in Figure 6-5-7. The resulting monthly ET Demand values are shown in Figure 6-5-6 and represent an annual total of about 25.2 inches.

Watershed	Period(WY)	Pcpn	Runoff	ET
BRSN3	49-77 49-93	41.6 41.9	23.1 23.2	18.5 18.7
PTRN3	49-77	43.8	23.4	20.8
DVSN3	49-78	42.9	22.6	20.3
SOUN3	52-77 52-87	39.7 40.4	19.5 20.0	20.2 20.4
SOHN3	49-76	44.0	23.0	21.0
WGTM3	49-77 49-92	43.8 44.8	22.4 23.4	21.4 21.4
GFFN3	49-78	42.3	21.0	21.3
NCIN3	49-70	42.5	20.6	21.9
FBGM3	73-93	48.4	26.3	22.1
SAXM3	81-93	47.1	25.0	22.1
MAYM3	49-77 49-93	45.0 45.7	22.1 22.5	22.9 23.2
WLMM3	65-93	44.7	21.8	22.9
RUMN3	49-77	39.0	24.2	14.8
WOON3	49-77	49.7	36.5	13.2
HENN3(local)	49-77	42.0	23.8	18.2
PLMN3(local)	49-77	45.2	28.1	17.1

Table 6-5-2. Water Balance Analysis for the Merrimack Basin (values are in inches).

4.d – The BRSN3 watershed was calibrated following the guidelines given in chapter 7. Early on in the calibration it became clear that the ratio of actual ET to ET Demand for this watershed had been underestimated. It was evident that the ratio was more in the range of 0.85-0.9 rather than the initial guess of 0.75. Thus, the PE adjustment curve was altered and new ET Demand values computed. When the calibration was completed, the ratio of actual ET to ET Demand was 0.87. The final PE adjustment curve is shown in Figure 6-5-6. The final monthly ET Demand values, which resulted in an annual total of 21.7 inches, are shown in Figure 6-5-7.

4.e – The annual ET Demand for BRSN3 was plotted versus elevation on the plot produced in step 2 as shown in Figure 6-5-5.

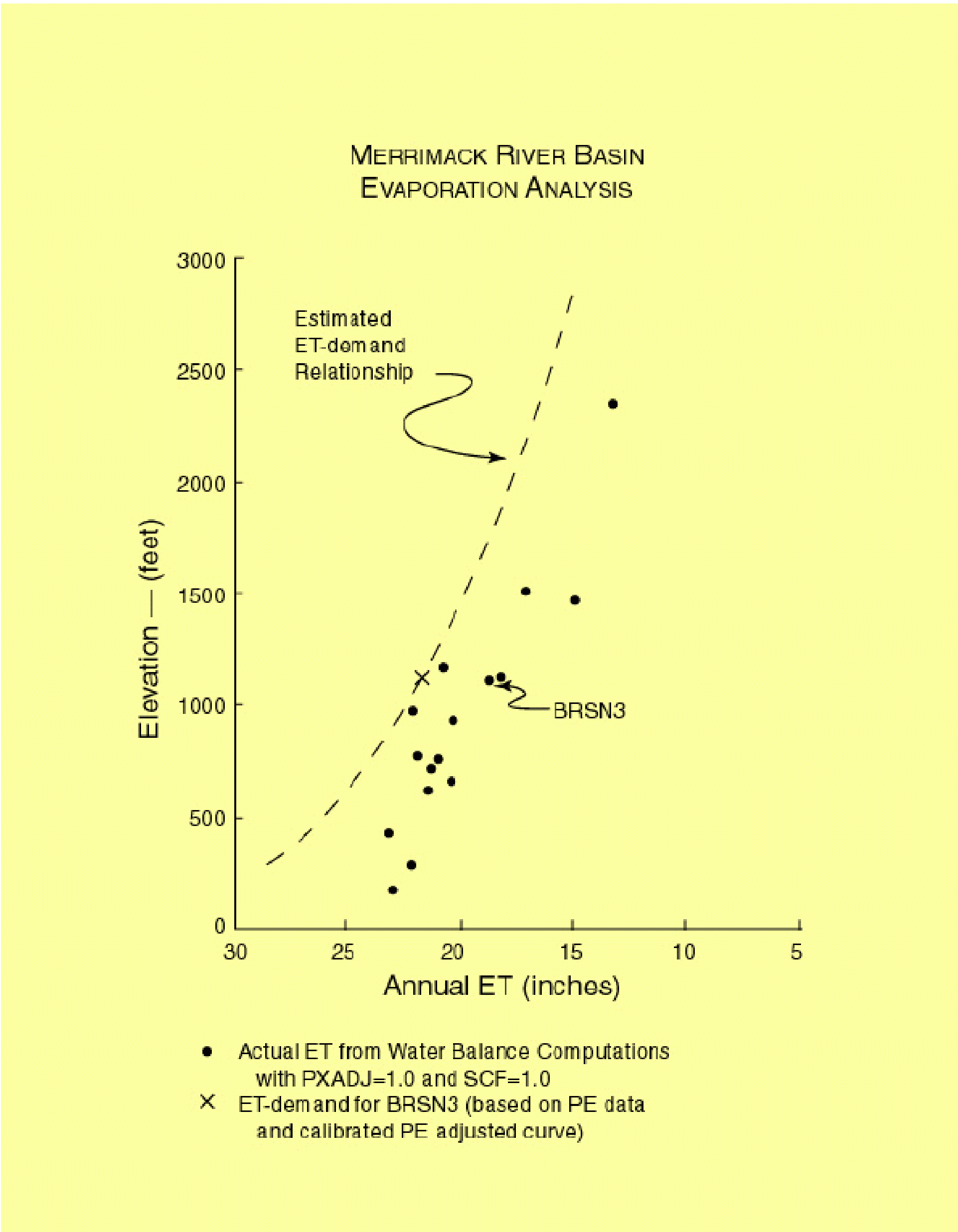
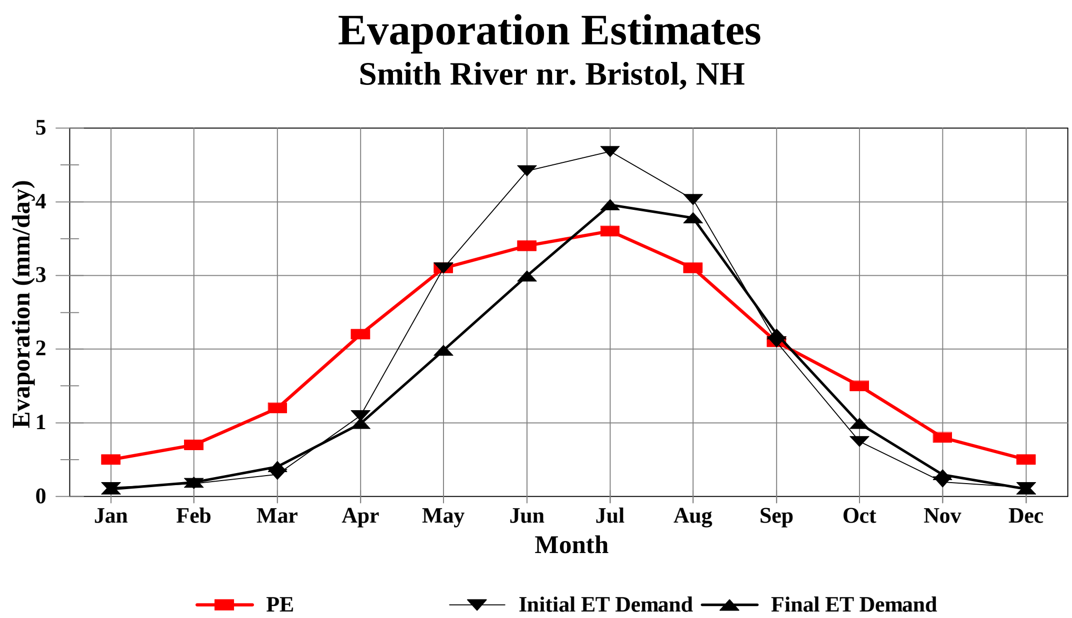
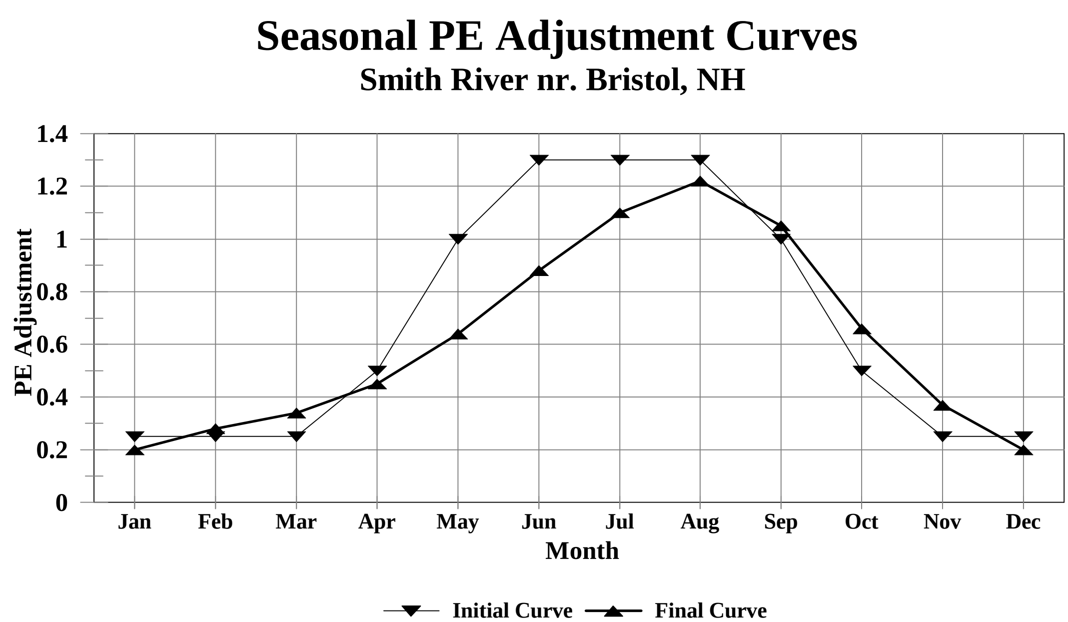


Figure 6-5-5. Evapor





ation versus elevation relationships for the Merrimack River basin.

Figure 6-5-6. Evaporation Values for the Smith River near Bristol, NH (BRSN3).

Figure 6-5-7. Season PE Adjustment Curves for BRSN3.

Step 5 – An estimate of the relationship between ET Demand and elevation was drawn for the Merrimack Basin using the trend in the actual ET versus elevation plot as a guide. This relationship is shown in Figure 6-5-5.

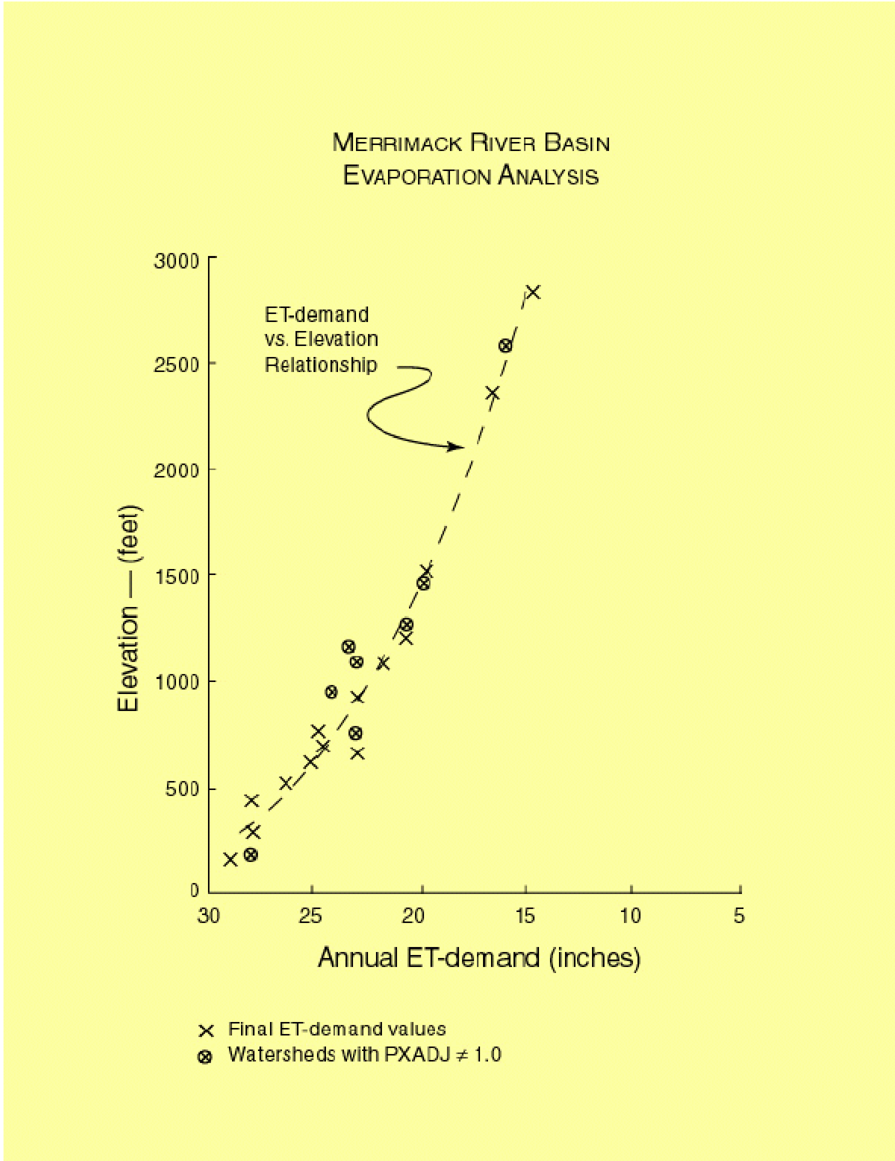
Step 6 – To test the validity of the estimated relationship between ET Demand and elevation derived in step 5, model simulation runs were made for two other headwater areas at different elevations. These were the Pemigewasset River near Woodstock, NH (two subareas with mean elevations of 1465 and 2846 feet) and the Assabet River near Maynard, MA (mean elevation of 448 feet). Annual ET Demand values for these watersheds were picked off the curve shown in Figure 6-5-5 and prorated to monthly values. The proration was based on modifying the shape of the seasonal PE adjustment curve for BRSN3 for perceived variations in vegetation activity and type from one area to another and adjusting the values so that when multiplied by the monthly PE shown in Figure 6-5-6, the resulting ET Demand had the correct annual total (variations of PE with elevation are implicitly absorbed into the seasonal adjustments). In deciding whether the estimated relationship between ET Demand and elevation was realistic, the higher and lower elevation watersheds were not calibrated, but instead the parameters determine for BRSN3 were used for the simulations. This seemed reasonable at this point in the calibration process since an assessment of hydrologic variability had suggested that model parameters should be quite similar over the entire Merrimack Basin (see Figure 4.2). These simulations resulted in variations in the ratio of actual ET to ET Demand to vary from around 0.85 at the lowest elevation to slightly over 0.9 at the highest elevation. This seemed quite realistic.

Step 7 – The annual ET Demand versus elevation relationship shown in Figure 6-5-5 was used to calibrate the other watersheds within the Merrimack Basin. Some slight deviations off this relationship were made to account for the location of each watershed within the basin (e.g. slightly different ET Demand values were used when watersheds at similar elevations were located at different latitudes). Figure 6-5-8 shows the actual annual ET Demand values used in the final calibration of each watershed. The figure also indicates those watersheds for which precipitation values needed to be adjusted in order to obtain the proper water balance (this was done by using PXADJ in the SNOW-17 operation). As mention previously it is more reasonable to establish a realistic relationship between ET Demand and elevation and then adjust precipitation if needed than to treat the isohyetal map as the truth and alter the ET Demand to get the proper water balance. The isohyetal analysis was quite good for this river basin such that none of the MAP time series had to be adjusted by more than 5%.

Determining Precipitation and Actual ET from Runoff, Evaporation, and Vegetation Information

This approach uses estimates of how ET Demand varies with elevation to determine the average amount of precipitation and actual ET over a river basin. This approach is primarily for use in areas where the isohyetal estimates of annual precipitation are not considered realistic. This is frequently the case in regions with very sparse precipitation networks such as Alaska (see section "Determination of the Average Mean Areal Precipitation in Data Sparse Regions" in Section 6-

3). This could also be regions where lot of scatter actual ET elevation plot d from water computations. approach using runoff an estimate of to determine amount of annual



approach tried in there is a in the versus determine balance This relies on data and actual ET the average

Figure 6-5-8. Final ET Demand values used for the Merrimack River basin.

precipitation. In Alaska this method can give more reliable estimates of average annual precipitation than estimates based on precipitation gage data because the precipitation network is sparse and the amount of actual annual ET is relatively small as compared to annual runoff. If this approach was used in an area where evaporation is much greater than runoff, such as the central Arizona mountains, it would probably not produce precipitation estimates that were as good as those determined by an isohyetal analysis using only precipitation gage data even though the water balance estimates of actual ET using the isohyetal map information might show considerable scatter. In such an area it might be possible to use a blend between the two approaches to estimate how ET Demand should vary with elevation and to refine the precipitation pattern over the region.

The steps to follow when deriving precipitation and ET Demand versus elevation estimates from evaporation and runoff data are as follows (again a spreadsheet is ideal for doing these computations):

1. Determine a relationship between annual PE and elevation.

2. Select watersheds within the river basin with good runoff data and adjust for any diversions or other gains or losses.

3. For the initial headwater area to be calibrated determine the annual PE at the mean elevation of the drainage. If multiple elevation zones are being used, determine the annual PE value at the mean elevation of each zone.

4. Prorate the annual PE amounts into average monthly values.

5. Subjectively determine values for the seasonal PE adjustment curves based on the vegetation types and activity patterns within the watershed or each elevation zone. These curves may vary considerably with elevation if the vegetation cover and climate changes substantially with elevation.

6. Multiply the average monthly PE times the seasonal PE adjustments to get monthly ET Demand estimates at each elevation. From these monthly values compute the annual ET Demand.

7. Make an assumption as to the ratio of actual ET to ET Demand for the watershed or each zone.

8. Estimate the actual ET by multiplying the ratio from step 7 times the annual ET Demand

values from step 6. If there are multiple elevation zones, weight each actual ET value by the portion of the watershed that it represents to get the annual actual ET for the entire watershed.

9. Add the annual actual ET to the average annual runoff to get an estimate of the average annual precipitation. If there are elevation zones, this precipitation can be prorated to each zone by using the precipitation pattern shown in the isohyetal analysis. MAP time series can then be generated that contain these average annual precipitation amounts by using the mountainous area precipitation procedure described in Section 6-3.

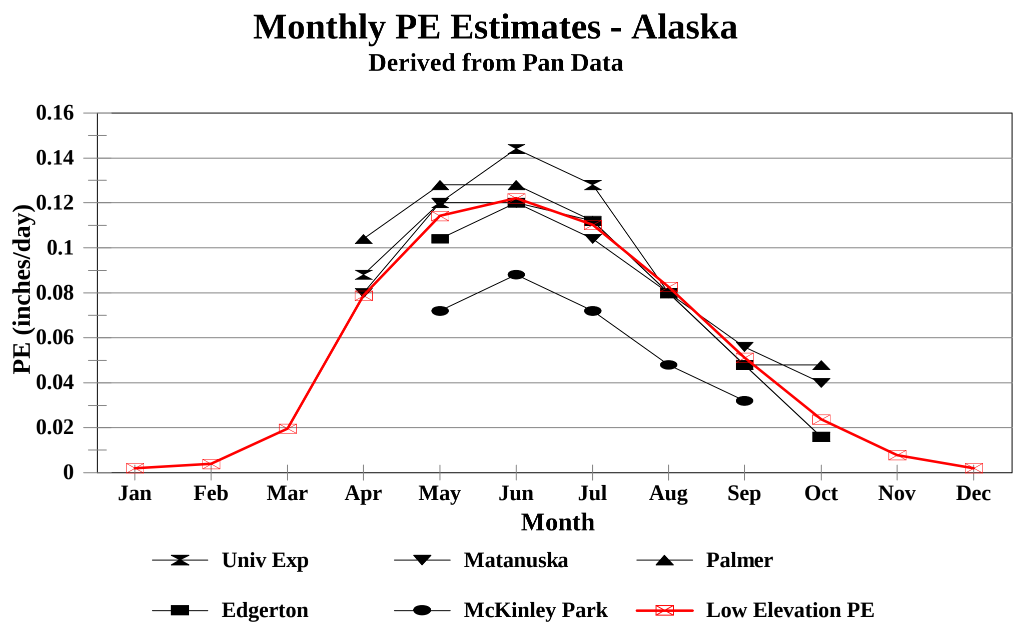
10. Calibrate the watershed using the MAP time series and the ET Demand values from step 6. The MAP time series will typically have to be regenerated a couple of times during the calibration process as the model values of the ratio of actual ET to ET Demand are more precisely determined. Also the distribution of precipitation with elevation may need to be altered if there is evidence that the initial pattern is unrealistic. The pattern of how precipitation is distributed with elevation can often be verified by comparing the amount of snow generated in various zones with available snow observations or by comparing modeled glacial changes with reported trends.

11. Calibrate other watersheds in the river basin using steps 3 through 10. Utilize the values used and determined during previous calibrations when working on new drainages. A single ET Demand versus elevation relationship for the entire river basin should emerge, as well as estimates of average annual precipitation for various watersheds and elevation zones. The ratio of these precipitation estimates to those obtained from the isohyetal analysis should be able to be used to adjust the isohyetal maps for portions of the basin where calibration is not possible.

To illustrate this approach we will use the Chisana River near Northway, Alaska. This 3280 mi^2 watershed is located on the north side of the Wrangell Mountains and varies in elevation from about 1700 to over 10000 feet with an average elevation of about 3500 feet. About 6% of the watershed is covered by glaciers. There is one precipitation station with a long record at the outlet and 2 others with short records at lower elevations in the watershed and about a dozen other such stations, all below 3200 feet and many with short records, scattered over a large area surrounding the watershed. A comparison of the PRISM estimate of precipitation for the watershed of 21 inches as compared to measured runoff of 9.7 inches results in an actual ET of 11.3 inches. This actual ET value was considered to be somewhat high given the length of the snow cover period over much of the watershed, thus it was decided to derive an estimate of average annual precipitation from runoff data and evaporation estimates. This was done in the following manner:

1. Monthly PE values were derived for low elevations in south central Alaska from pan data and an estimate of PE during the winter months. This seasonal PE curve and the pan sites used to create the curve are shown in Figure 6-5-9. The annual PE represented by this curve is 19 inches.

2. Using the shape from this low elevation seasonal PE curve and the relationship between



PE and elevation shown for south central Alaska in Figure 6-5-4, monthly PE curves were constructed for the mean elevation of the lower and upper zones in the Chisana watershed (glacier zone is considered to have no evaporation). These curves are shown in Figure 6-5-10. The annual PE for the lower zone with a mean elevation of 2400 feet is 14.3 inches and the annual PE for the upper zone with a mean elevation of 6000 feet is 6.7 inches.

3. Seasonal PE adjustment curves were subjectively estimated for each elevation zone as shown in Figure 6-5-11. The lower zone is primarily muskeg, willows, and black spruce. The upper zone is above the tree line with a mixture of tundra and barren areas.

4. Seasonal ET Demand curves were then calculated by multiplying the average daily PE for each month times the PE adjustment for that month. The resulting ET Demand curves are shown in Figure 6-5-12. The total annual ET Demand based on these curves is 8.5 inches for the lower zone and 2.0 inches for the upper zone.

Figure 6-5-9. Low elevation seasonal PE curve for south central Alaska.

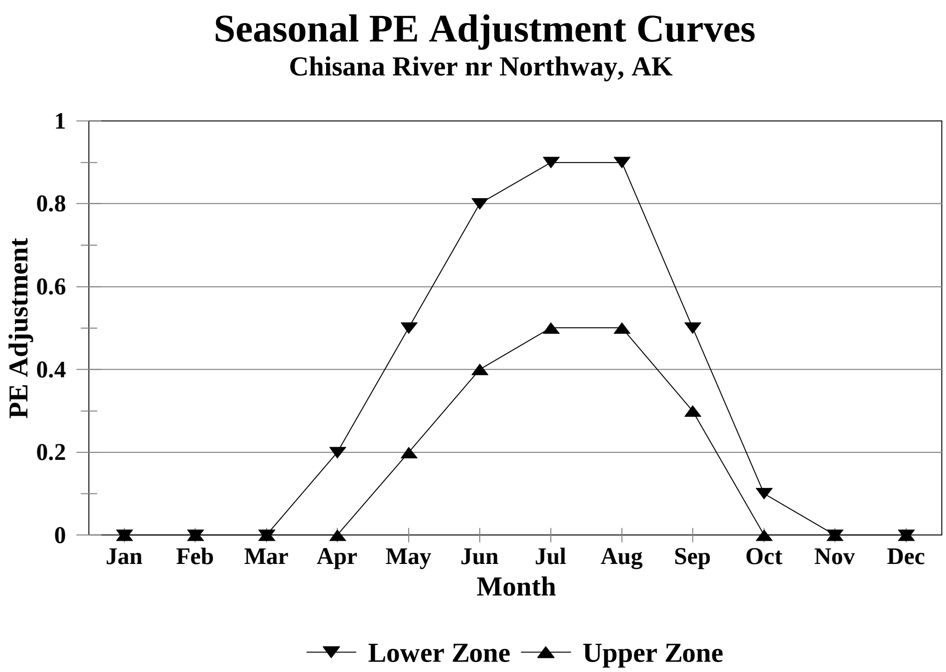


Figure 6-5-10. Seasonal PE curves for Chisana watershed elevation zones.

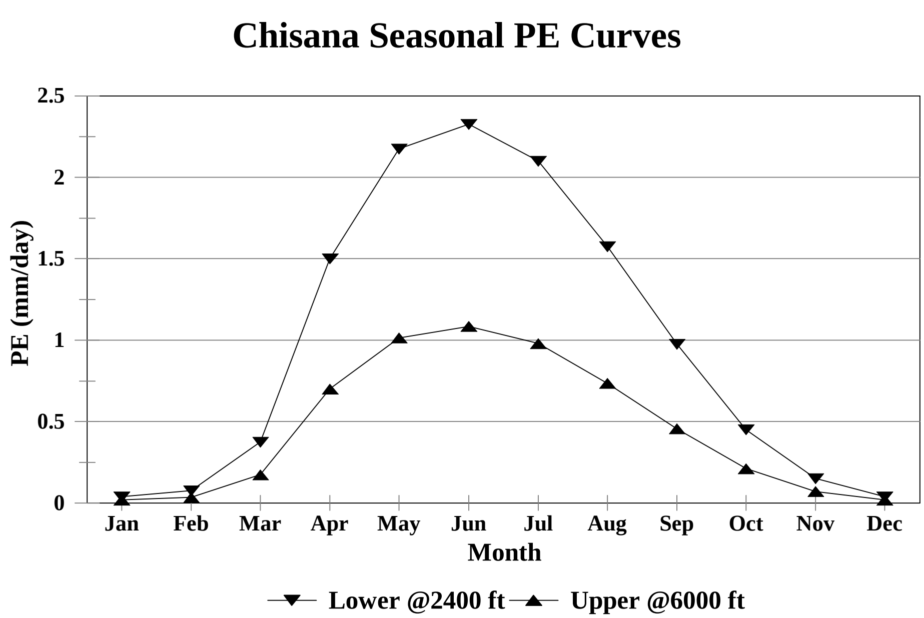
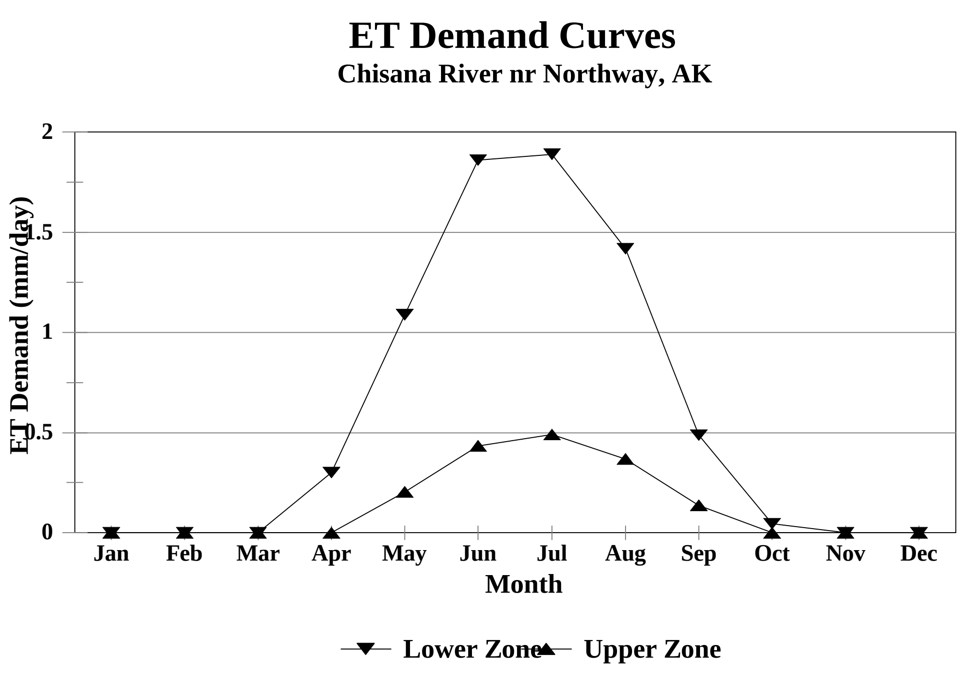


Figure 6-5-11. Seasonal PE adjustment curves for the Chisana River.

Figure 6-5-12. ET Demand curves for the Chisana River.



5. The next series of steps were to estimate the ratio of actual ET to ET Demand for each zone, use those values to calculate annual actual ET for the watershed, add annual actual ET to the average annual runoff to estimate the annual average precipitation,

generate MAP time
series based on this precipitation amount, and calibrate the watershed using this time series and ET Demand curves from step 4. Based on the calibration, the estimates of the ratio of actual ET to ET Demand were revised and new precipitation time series generated. The initial guess as to the ratio of actual ET to ET Demand was 0.75 for each zone. Based on the initial calibration, the ratio was adjusted to 0.8 for the lower zone and 0.6 for the upper zone. These values of the ratio gave annual actual ET values of 6.8 and 1.2 inches for the lower and upper zones, respectively, and a watershed average actual ET of 5.2 inches (lower zone comprises 72% of the area, the upper zone 22%, and the glaciers 6%). The average annual runoff was 9.7 inches which when added to the annual actual ET gave a watershed average precipitation of 14.8 inches (PRISM estimate was 21 inches). Elevation zone values of annual precipitation were determined by multiplying the watershed average by the ratio of zone precipitation to watershed precipitation from the PRISM analysis. These ratios were 0.73, 1.53, and 2.29 for the lower, upper, and glacial zones, respectively, which resulted in average annual precipitation values for the zones of 10.8, 22.7, and 34.0 inches. These values produced a reasonable simulation of streamflow and seasonal snow cover for the watershed and changes over time to the glaciers seemed realistic.

This approach was also used in the Upper Kenai River basin in Alaska to get annual precipitation estimates that would produce a reasonable water balance and actual ET values. For the Trail River near Lawing this approach resulted in an actual annual ET of 4.2 inches and an annual precipitation of 69.5 inches. The PRISM annual precipitation for the watershed was 96.7 inches.

Mountainous Area Evaporation Summary

No matter which of the two approaches in this manual are used to get evaporation estimates in a mountainous region or whether some other approach is followed, it is essential to end up with evaporation estimates that are physically realistic in both magnitude and spatial variability over the river basin. With the real potential for errors in precipitation amounts derived from any isohyetal analysis at the watershed scale, one cannot assume that the precipitation amounts are correct and then adjust evaporation to whatever values are needed to produce a near zero water balance. This approach is guaranteed to produce unrealistic estimates of evaporation. Therefore an approach must be followed that uses evaporation values that are realistic and vary logically with elevation. Any adjustments that may be needed to produce a near zero water balance should be made to the precipitation estimates.

Section 6-6

Mean Daily Flow Data Checks and Adjustments

Consistency Checks

Like precipitation, temperature, and evaporation data that are used to estimate input time series for model calibration, the streamflow data that are used to verify the simulation results should also be checked for consistency. Such a check can serve two purposes. First, a consistency check can reveal inconsistencies caused by factors that are not known to the user. Second, the check can determine whether known changes within the basin have a significant effect on the amount of runoff measured at the gage. Inconsistencies in streamflow data can occur for a variety of reasons including such things as changes in land use (e.g. rural to suburban, agricultural to forest, drainage of wetlands), the construction of new control structures or modifications in the operation of these structures, changes in the amount of water diverted into or out of the watershed, the effect of large forest fires, alterations in agricultural practices (e.g. changes in crops being grown, addition of drain tiles, modifications to irrigation practices), constantly shifting rating curves that aren't updated as often as they should, and changes to measurement methods or practices. Consistency checks could reveal information on both the magnitude and timing of these effects and determine whether the data may need to be adjusted or whether only portions of the period of record should be used for determining model parameters.

Consistency checks of mean daily flow data would be done using double mass analysis as it is for precipitation data. Prior to generating the double mass plots, the daily flow data needs to be converted to depth of runoff or at least the values from all the gaging sites need to be scaled to a common area. As with precipitation, the deviation of the accumulated runoff from the group average for each station would be plotted against the accumulated average runoff for the group. Unlike precipitation, only selected stations should be included in computing the group average. The group average should be computed using only stations that have consistent data, i.e. stations with known significant changes in land use, diversions, control structures, agricultural practices, etc. should not be part of the group average. Stations should be grouped geographically on individual plots as there can be shifts in the runoff relationships between watersheds due to changes in climatic patterns. Such changes are real and no adjustments are needed. Such real shifts would be indicated by having several stations in the same general area showing similar patterns of change in their double mass plots.

In most cases inconsistent runoff data would not be corrected by applying a simple multiplying factor as is done with precipitation. Generally the double mass plots would indicate that an inconsistency might exist and give an idea of its magnitude and timing. Then the reason for the inconsistency needs to be determined by looking into the history of changes that have occurred within the watershed. Once the reason is known, then a decision can be made as to how to adjust the data or whether only a portion of the data record can be used for calibration.

Even though the direct capability for making consistency checks on mean daily flow data doesn't currently exist within the NWSRFS software, there is a way that such checks might be made with some limitations using the existing programs. This would involve the following steps:

1. Convert the mean daily flow data to depth of runoff and create time series. This can be done by using a LOOKUP operation for each streamflow site. The LOOKUP operation allows the user to specify the relationship between any two variables without having to maintain the same dimension or units.   Two points are sufficient in this case to define the relationship (e.g. the 0.0,0.0 point and a point that indicates the flow volume that represents 1.0 inch of runoff). The resulting runoff time series would be declared as OUTPUT time series.

2. Use these runoff time series as input to the PXPP program which will generate the information needed to produce a double mass plot (plot displayed either by PXPP or IDMA). The PXPP program will treat these time series as if they were precipitation data. In general this shouldn't matter as far as the double mass analysis is concerned except that the procedure in PXPP for estimating periods of missing data may not be totally appropriate for runoff data, thus one needs to avoid missing data periods when drawing conclusions regarding the consistency of the streamflow data. The missing data estimation procedure in PXPP may work in regions where most of the runoff comes from rainfall, but will undoubtedly have more problems in regions where the timing of snowmelt varies considerably from one gaging site to another. Runoff consistency checks in these regions may be possible using PXPP only during periods when all stations included in the analysis have observed data. Another problem in using PXPP to check the consistency of runoff data, is that PXPP doesn't currently have the capability to eliminate certain stations from the computation of the group average (this feature exists in the MAP program, but the MAP strategy for estimating missing data involving both hourly and daily stations will not work with runoff data derived from mean daily streamflow records). Thus, discharge stations with known consistency problems should not be included as input to PXPP.

Streamflow Data Adjustments

There are two general cases that need to be dealt with regarding possible adjustments to streamflow data. The first case is where there are changes in runoff generation that occur slowly over time, such as those resulting from changes in land use or agricultural practices or from natural events like a large forest fire (fire occurs suddenly, but recovery is slow). The second case is where there are modifications to natural flow conditions caused by man-made changes or natural transfers of water across watershed divides.

When the amount of runoff generated changes slowly over time, it is very difficult to make adjustments to the data. In these cases, the normal solution is to use only the period of record that most closely reflects the current state of the watershed when determining model parameter values via calibration. Generally this is the most recent period, though in some cases the most recent period could be an aberration. For example, if a large forest fire occurred a few years ago and now the watershed has just recovered from the effects of the fire, it would be more appropriate to use the period prior to the fire for calibration.

When there are modifications to flow conditions due to man-made control structures or natural transfers across watershed divides, there are two general alternatives. The first option is to model all of the flow modifications so that the simulation results can be compared directly to the observed streamflow data. This would include modeling of such things as reservoir operations, effects of large lakes, diversions across watershed divides whether controlled by man or by nature, irrigation usage and return flow, and municipal or industrial use within the watershed boundaries. The capabilities for modeling a number of these exist within NWSRFS. If modeling these flow modifications is attempted during calibration, the data required should be available not only historically, but also in real time so that the calibration results can be directly applied operationally. If the real time operation of a control structure differs from the rules used during calibration, the changes would need to be included in the operational setup. There are definite advantages to modeling the flow modifications whenever possible. One advantage is that during operational use there is much less reliance on agencies that operate reservoirs or diversions to provide information on releases or diversion amounts. This results in much more timely forecasts at downstream locations. Another advantage is that probabilistic predictions can be extended further downstream, though the uncertainty of each modeled feature needs to be reflected in the total uncertainty of the prediction at each location.

The second option, when there are man-made or natural flow modifications, is to adjust the historical streamflow data to reflect natural flow conditions. Then the calibration results are compared to this “observed” natural flow. Operationally either the forecast can be natural flow values, or the simulated natural flow must be adjusted in some way based on real time information that is not available historically. On many western rivers where the regulation of flows is very complex based on current irrigation, municipal, industrial, fishery, and power generation demands, the reservoir and diversion operators want a prediction of the amount of natural flow generated from rainfall or snowmelt. Based on these predictions, they determine how the control structures are to be operated. This control information is then used by the RFC to create actual flow forecasts. Also in many western areas extended predictions of natural flow are used to make advance plans on items such as which acreage can likely be planted with crops and the amount of seed, fertilizer, and other agricultural products that probably will be needed. In other regions there are reservoirs and other control structures whose operations would be difficult to model historically. Operationally the RFC computes natural flow from the headwaters and locals and relies on the operating agencies to provide release information.

Some adjustments to historical streamflow data and possible methods of making these adjustments to generate natural flow time series for use when calibrating the models are listed below.

1. Diversions - these are diversions of water across watershed divides for various uses. The

ideal solution is to obtain a time series of daily diversion volumes that can be directly added or subtracted from the mean daily discharge at the downstream point. In some cases it may be appropriate to prorate how much of the diversion is applied to each day due to travel time from the diversion location to the river gage. Daily diversion time series are available in some cases along with the other streamflow data provided by the USGS. In other cases it may be necessary to request this information from whoever operates the diversion. In cases where daily diversion data are not available, there may be tabulations of monthly volumes that are published or easier to obtain from the diversion operator than daily data. These monthly volumes can be prorated into daily time series so that the mean daily flow data at downstream points can be adjusted. While the adjustments are not correct on a daily basis, at least the correct volume adjustment is made to the river data.

2. Reservoirs and lakes - this requires either the calculation of the natural inflow to the pool or the adjustment of downstream flows for storage changes and direct gains or losses such as those from rain or evaporation. The water balance equation for a lake or reservoir can be expressed as:

$$I - O + P \cdot A - E \cdot A + D = \Delta S \qquad (6\text{-}6\text{-}1)$$

where: I = Inflow,
O = Outflow,
P = Precipitation on water surface,
E = Evaporation from the water surface,
A = Water surface area,
D = Diversions into or out of the pool other than at the main outlet, and
ΔS = Change in Storage (each term is in volume units).

In some cases the amount of precipitation and evaporation may be small compared to the inflow and outflow volumes and can be neglected. Many reservoirs and most lakes don’t have any canals or pipes that divert water into or out of the pool or these volumes may be small compared to the main inflow and outflow and thus can be ignored. In other cases diversion data or estimates should be used, as well as estimates of precipitation and evaporation. An MAP time series can be generated to estimate the precipitation falling on the water surface. If the surface freezes during the winter, a rain plus melt time series may be more appropriate. Evaporation losses could be estimated from daily FWS evaporation, ideally adjusted for changes in heat storage, or from calculations of climatological mean lake evaporation.

Natural inflow is computed from Equation 6-6-1 by measurements or estimates of the other quantities. Generally, at least outflow data must be available along with either pool elevation or storage data to compute the ΔS term. To adjust streamflow data at downstream locations for the effect of reservoirs or lakes would require the computation of the combined ΔS, P, E, and D terms in the equation. This quantity would be added to the measured discharge at downstream points. In many cases the daily values of this quantity should be prorated to reflect routing effects between the reservoir or lake and the downstream locations.

3. Springs - a few watersheds in some parts of the country contain large springs which contribute a significant amount, at least at lower flow levels. Some of the water discharged by such springs undoubtedly originates within the watershed boundaries, but a large fraction may come from outside the immediate drainage. Where such large springs exist there is frequently some information on the magnitude and seasonal variation of the discharge. Sometimes it is periodic flow measurements just downstream from the spring published in the USGS Water Resources Data reports. It is also likely that the outflow from these springs varies from year to year based on changes in precipitation patterns. If sufficient information is available, either a daily time series can be created to represent the outflow from the spring or the CHANLOSS operation can be used to at least account for the general magnitude of the outflow and how it varies seasonally.

4. Flood overflows - in some locations there are overflows across drainage divides during high flow periods. This can occur when two rivers come very close to each other, when flood control dams are built near watershed boundaries, and in regions with very flat terrain. Such occurrences are usually mentioned in the remarks section of the USGS Water Resources Data reports. These reports may indicate when such overflows occurred and may provide information that would be helpful in calculating the magnitude of the flow that crosses the divide.

5. Irrigation Losses - the net loss from irrigation, i.e. evaporation loss minus return flow, is generally difficult to determine. There may be many places within a watershed where water is removed from the river for irrigation and records of withdrawals are difficult to obtain and time consuming to process if they can be obtained. There are at least three general ways for dealing with irrigation losses. The best method is to try to model the losses and the return flows with procedures like the CONS-USE operation. Another technique is to account for the general magnitude of the irrigation effects by subtracting or adding flows on a seasonal basis even though the timing and magnitude of the losses and return flows are not the same every year. This can be done with a feature like the CHANLOSS operation or even mimicked with the Sacramento Model RIVA parameter. The other method is to just recognize that irrigation exists within a basin and not alter model parameters to match observed flows during periods with irrigation effects.

Chapter 7

Step 5 - Calibration of Hydrologic Models

Introduction

Now that all the needed information is available, the variability of physical and climatological factors have been assessed, the calibration locations and periods of record to use were selected, and the data have been checked, analyzed, and put in the proper form, it is finally time to calibrate the hydrologic models. In order to simulate conditions over an entire river basin many models and procedures must be used. Most of these contain variables that must be determined. Some can be determined directly by analyzing physical or experimental data, such as reservoir storage - elevation relationships and spillway rating curves or the drainage area of a particular watershed or local area. Other variables, which constitute the majority, are model parameters that vary from one area to another based on changes in physical factors and climatology. Methods exist for estimating the parameters for many models in an *a priori* fashion based on various information. Such parameter estimates may be satisfactory for some applications, but seldom provide the accuracy needed for river forecasting. To use the models to produce reliable forecasts both in the short term and for extended periods into the future, requires that a thorough calibration be conducted to determine the appropriate values of the parameters.

This manual will primarily focus on strategies and procedures for calibrating the NWSRFS SNOW-17 and Sacramento soil moisture models, however, in order to compute the flow in the rivers, a number of other models must be used. Even for a headwater drainage with no complications, a model of the channel system is required to convert the runoff into the channel network to discharge at the streamgage location. For downstream local areas, some kind of routing model is needed to translate the flows from upstream to the downstream locations. For points with more complexity within their drainage area, models of reservoir operations, irrigation demands, glacial effects, etc. could be required. These other models will be mentioned in this chapter though not in the same detail as the snow and Sacramento models.

There are many references in the literature to calibration procedures and techniques. The vast majority of these deal with the calibration of models to an individual drainage area, usually a headwater area with few complications. While this manual includes strategies and procedures for calibrating an individual drainage, the primary emphasis is the calibration of an entire river basin which eventually leads to the calibration of the entire area of responsibility of an RFC. To calibrate the models needed for an entire RFC area for river forecasting applications, requires a calibration process that is efficient, that results in spatially consistent parameter values, and that accurately simulates streamflow and other variables under a full range of climatic conditions. If calibration of an entire RFC area is conducted as a series of largely independent efforts with various individuals working on one watershed at a time with only minor coordination, the results will not only fall short of the objectives, but will take much longer to complete than necessary. The strategies and procedures given in this chapter are aimed at fully meeting calibration objectives in the minimum amount of time.

Objectives

There are three basic objectives when calibrating conceptual hydrologic models to an entire river basin for river forecasting applications.

1. Produce a good reproduction of the observed hydrograph at each individual point on the river system. The aim is to achieve a fit that contains the minimum amount of bias possible, i.e. all errors are random. This includes all types of bias including overall bias, bias related to the magnitude of flow, seasonal bias patterns, and bias related to specific snow and soil moisture conditions such as during an abnormally large snow accumulation year or after a long dry spell. Also intermediate variables such as snow water equivalent and soil moisture deficits should compare realistically to any observations of these variables. The amount of random error should be largely a function of the random error associated with the input variables, especially precipitation. Errors in the amount of precipitation, as categorized by the typical spatial variability of this input variable, are the primary reason that lumped models do not produce satisfactory results in some areas of the country as was discussed back in Chapter 1 and illustrated in Figure 1.1.

2. The parameters of the models should function as they are intended. Both the SNOW-17 and Sacramento models are conceptual models which represent, although in a simplistic fashion, the main physical processes that occur in nature. These models were designed to have a physical basis and the parameters control portions of the models that represent specific components of the overall process. The parameters of the Sacramento model were designed to represent items such as the timing and maximum contribution of various runoff components, the maximum soil moisture deficits that can occur, and the rate of the movement of water within the soil profile with changing moisture conditions. The snow model parameters represent such items as the seasonal variation in melt rates when the area is completely snow covered, the areal depletion pattern as the snow melts, and the amount of liquid water that can be held within the snow cover. The effects of each parameter are designed to be reflected in specific sections of the simulated hydrograph under specific soil moisture or snow cover conditions. In order to be consistent with the physical basis of the models and to produce results that will not only best reproduce the full range of historical observations, but also be most likely to extrapolate correctly beyond what was observed in the available historical record, each parameter of the models should be used as it was intended.

3. There should be a realistic variation in parameter values from one area (headwater, local, or subdivision within a drainage) to another within the river basin and with areas just across the divide in adjacent river basins. Changes in parameter values from one area to the next should be explainable based on changes in physiographic factors, climatic conditions, or hydrograph response. Not only is this objective reasonable from a physical point of view, but

if adhered to, makes it much easier to monitor and understand operational variations and run time adjustments to state variables.

One question that is often asked, especially by those first learning how to calibrate conceptual hydrologic models, is "when am I done." Basically the answer is that you are done when the objectives have been met, i.e. when all possible bias has been removed, when the portions of the hydrograph controlled by each parameter are checked to make sure that the parameter is acting as intended, and when any changes in parameter values from one area to another are consistent with the assessment that was made of the spatial variability of hydrologic factors across the region.

When trying to judge whether the objectives have been met, it is important to remember that there is often considerable noise in the input data being used for calibration, especially the precipitation input. The amount of noise varies with the region of the country and the gage network. There may not only be considerable noise in the data for a given watershed, but the amount of noise can vary from one watershed to another depending on the number of gages available, as well as their location and accuracy of the measurements. Noise in the input data can make it not only difficult to determine the appropriate parameter values for a given watershed, but the variation in the amount of noise from one watershed to another can affect the spatial consistency of the results. This is why the strategy recommended in this chapter starts with calibrating the watershed that has the least noise in the data record. This is also one of the reasons why a sufficiently long period with considerable climatic variability is needed for calibration. Such a period should minimize "curve fitting", though there still may be considerable uncertainty in the value of parameters that control portions of the models that are seldom activated. Verifying the results on independent data periods should help to reduce this uncertainty and further minimize any "curve fitting". After the initial watershed in the basin is calibrated, one must be careful that realistic spatial consistency patterns are not destroyed by "curve fitting" during the calibration of the other drainages in the basin. In order to achieve the proper balance between the calibration objectives, given the amount and variation of noise in the data, the reproduction of the observed hydrograph, at least as measured by goodness of fit statistics, may have to be sacrificed somewhat in order to achieve spatial consistency of the parameters.

It is stated in objective one that all possible bias should be removed. When working with a lumped model, there are certain types of bias that are inherent in how the model is applied. In addition, there are certain model limitations that will cause trends in the results. These factors result in bias that typically cannot be removed including:

- An under simulation of the highest flows. A lumped application of a model uses the average amount of precipitation over an area, whereas in nature the amount of precipitation is seldom uniform. Since the rainfall-runoff process is non-linear, those portions of an area that have rainfall or snowmelt amounts that are greater than the mean areal value will produce relatively more runoff than parts of the area where the amounts are below the mean. This results in the actual runoff being greater than what would be produced by applying the mean value to the entire area. Adjustments to some model parameters, especially the percolation curve in the Sacramento model, can partly adjust for this tendency, but especially in regions where there is typically a large variation in intensity levels during storms over individual drainage areas, a lumped application of a model will under compute runoff during high flow events.

• A over simulation of low flows. When most models are applied in a lumped fashion it is typically assumed that baseflow is being generated over the entire area based on the contents of the groundwater storages, at least that is the case with the Sacramento model. Under the lowest flow conditions, this is likely not the case in nature. Thus, there is a tendency for a lumped application of the Sacramento model to over simulate the lowest flow levels.

• In mountainous areas where snowmelt dominates runoff production, the simulated spring snowmelt typically occurs too early during years with a much below normal snow cover. This occurs because the snow primarily only covers the highest portion of the upper elevation zone, whereas the lumped application assumes the snow is distributed over the entire zone. This situation is described further in Section 6-1 and illustrated in Figure 6-1-3.

• Some biased results when snowmelt is not occurring over the entire area. The model assumes that either melt is taking place over the entire snow covered area or it is not. Especially in mountainous areas, early in the melt season snowmelt may only be occurring at the lowest elevations and on south facing slopes. This can result in some bias in simulating runoff during the first week or so of the snowmelt period.

• The largest snowmelt runoff events are typically under simulated, particularly in regions where high winds and dew-points are associated with major snowmelt situations. This is partly due to the lumped application of the model, but primarily due to using an index to compute snowmelt. In the SNOW-17 model air temperature is used as the sole index to snowmelt. While temperature is a good indicator of melt under most conditions, during some extreme snowmelt situations the typical relationship between temperature and melt doesn't hold. Especially in the northeast, major snowmelt events are associated with high dew-points and wind speeds. This causes large amounts of latent and sensible energy exchange and alters the normal relationship between air temperature and melt. There are other situations when the relationship between temperature and melt varies from the normal, but these are not associated with a particular level of melt and thus tend to randomly affect flow interval bias computations.

• Rainfall events that occur late in the snowmelt season on watersheds with a prolonged snow depletion period, generally mountainous areas, typically are over simulated. In these situations the soil has dried out in portions of the area that have been bare of snow for sometime, whereas as long as the areal average melt computed by the model, which is coming from only a small part of the area, exceeds the evaporation rate, the soil will remain wet. This can be minimized by using additional elevation zones, but the use of too many zones can cause operational difficulties (see Section 6-1).

• Baseflow recharge can't be modeled consistently when there is a lower zone tension water deficit in the Sacramento model. This is caused by the model assuming that a constant fraction of the area (PFREE parameter) contributes to recharge during this situation when in reality the fraction should undoubtedly vary depending on the size of the deficit, i.e. the ratio of LZTWC/LZTWM. If the ratio is 0.0, little recharge should occur. As the lower zone becomes more saturated, the amount of recharge should increase.

Calibration Methods

There are two basic methods used for the calibration of hydrologic models. The first is a guided trial and error procedure where the users knowledge of the model and how each parameter affects the results are used to control changes to parameter values. Decisions as to which parameters to change are made primarily by comparing simulated versus observed values, especially hydrograph plots. This procedure is most effective when interactive, graphical software is available to view the results and make parameter changes. The calibration is finished when the user subjectively determines that the objectives have been met.

The second method is automated calibration [*Gupta et al.*, 2000]. In this method various computer algorithms are used to achieve the best simulated reproduction of observed values, typically mean daily discharge. The algorithms contain strategies for varying the values of user specified parameters in an attempt to obtain an optimal fit. Typically the user can apply limits on the range over which parameter values can varying in the hope of obtaining more physically realistic results. The quality of the reproduction is often determined by a single statistical objective function, such as minimizing the daily root mean square error. Sometimes a series of steps are used where different groups of parameters and different objective functions are used at each step (e.g. the objective function used for parameters affecting low flows may differ from the function used for parameters that primarily control storm runoff) [*Hogue et al.*, 2000]. In some approaches multiple objective functions are used to try to find a group of parameter sets that will produce good results based on several criteria [*Gupta et al.*, 1998]. Then the user can choose subjectively from this group of parameter sets. Automatic optimization has been primarily used for the calibration of individual watersheds, mainly headwater drainages. There are limited strategies available for using automated optimization over entire river basins.

Table 7-1 summarizes some of the features of the interactive trial and error method versus automated optimization of parameters (this table was prepared for a calibration training video developed by the NWS in conjunction with the Hydrologic Research Center [*Hydrologic Research Center*, 1999]). The biggest difference between the two methods is that the interactive method allows for the user to maintain the physical basis of the models, whereas the automated method relies on various algorithms to achieve a statistical best fit determination of the parameter values. NWSRFS contains software for both methods of calibration. The Interactive Calibration Program (ICP) allows for the user to make parameter changes and view the results graphically.

The automatic optimization program (OPT) contains 3 algorithms and several objective functions for use in determining best fit parameter sets. The OPT program was quite useful prior to the time when ICP was first available. Back then trial and error calibration was being done in a time consuming batch mode.

INTERACTIVE vs. AUTOMATED CALIBRATION

INTERACTIVE	AUTOMATED
• Emphasis on Component Process Representation	• Emphasis on Overall Model Fit to Data
• Requires Good Knowledge of Physical Model Basis	• Treats Model as Nonlinear Regression
• Person Intensive	• Low Personnel Requirements
• Use of a Multitude of Performance Criteria	• A Small Number of Statistical Criteria
• Less Affected by Data Quality Problems	• Sensitive to Data Quality
• Requires Well Designed Graphical Interfaces	• Requires Robust Optimization Methods
• Likely to Produce Parameter Estimates Which Would Allow Reliable Simulations of Future Events	• Likely to Produce Parameter Estimates with Uncertain Value for the Simulation of Future Events

Table 7-1. Comparison of Interactive and Automated Calibration Methods.

It is this author's belief, based on personal experience, that automated optimization methods cannot be used to meet the 2nd and 3rd objectives listed earlier in this chapter for the calibration of conceptual hydrologic models. Because of this assessment, the author has not used automated methods enough in recent years to feel qualified to include a discussion of strategies for using such procedures for calibrating conceptual models in this manual. Other references, such as those mentioned earlier in this subsection, are available for those who want to try automated methods. The biggest obstacle for the successful use of the interactive trial and error method is the time required to develop the knowledge of the model structure and how to isolate the effects of each parameter. While automated methods can in many cases achieve a good reproduction of streamflow for an individual watershed quicker than the interactive trial and error method, by following the procedures and strategies in this chapter, interactive calibration should produce not only a good reproduction of observed conditions, but preserve the physical nature of the models and do so in a very efficient manner for a large area like an entire river basin. After the calibration of the initial headwater area within a river basin, the strategies given in this chapter should produce parameter sets for subsequent drainages that meet all the listed objectives at least as fast as automated methods can meet only the first objective.

Interactive Calibration Program (ICP)

The software used to perform interactive trial and error calibration within NWSRFS is the Interactive Calibration Program (ICP). ICP provides an interactive, graphical interface for the Manual Calibration Program (MCP). MCP contains all of the models and other procedures that are used to generate a simulation and output the results. The input for MCP specifies all of the time series that are to be used, the sequence of operations (i.e. models and other procedures including displays), and parameters and initial state variables for each operation. ICP allows the user to select a watershed, run MCP, display the results, make parameter changes, save specified simulated time series, and resubmit a new MCP run with modified parameter values. This process is continued until the calibration is judged to be finished.

ICP currently contains two graphical displays. These are linked to the WY-PLOT and PLOT-TS operations of MCP. The WY-PLOT display allows the user to graphically plot mean daily flow time series, both simulated and observed. The WY-PLOT display also includes panels that show many of the state variables and internal computations for the SNOW-17 and Sacramento models. These panels are described in detail at the beginning of section 7-7 for the snow model and 7-8 for the Sacramento model. Pull down, tear off menus allow the user to rapidly switch between the snow and Sacramento panels, as well as from one subarea to another for watersheds with multiple zones. The same method can be used to quickly go back and forth between multiple WY-PLOT displays if they are specified in the MCP control file. The user can scroll through the period of record, change the length of the period displayed, alter the range of the plots, and switch from arithmetic to semi-log scales. A single simulated time series can be saved for display after a subsequent run. This allows the user to compare the results from one run to another.

The PLOT-TS display allows the user to stack from one to six plots on top of each other, all showing the same period. The time series included on each plot must have the same units, but can have different time intervals. The flexibility of the PLOT-TS display allows the user to construct plots to help in visualizing a variety of situations. Just like the WY-PLOT display, the user can scroll through the run period, change the length of the period shown at any one time, alter the range of the plots, and switch from arithmetic to semi-log scales. One time series on each plot can be saved and replotted after a subsequent run.

Other output generated by the operations in MCP can be viewed via ICP in text format. This includes the statistical computations generated by the STAT-QME operation. Graphical displays likely will be added for some of these operations in the future.

ICP contains interactive windows for changing values of selected parameters for the snow, Sacramento, and unit hydrograph operations. Plots are provided for changing multiple valued parameters like the ET-Demand curve for the Sacramento model, the areal depletion curve for the snow model, and the shape of the unit hydrograph. Other changes to the MCP control file are made by editing the file directly.

River Basin Calibration Strategy

In order to meet the calibration objectives in an efficient manner it is necessary to have a clear strategy for calibrating each of the headwater and local areas within a river basin. The recommended strategy is as follows:

1. First calibrate the headwater area with the best data and least complications. The aim of calibration is to determine the model parameter values that will provide the best possible forecasts of future conditions. Also the strategy recommended for a river basin ties the parameter values for all the other drainages within the basin to the parameters determined for the initial headwater area. Therefore, it is critical to start with an area where one has the best possible chance of determining appropriate parameters for the snow and Sacramento models. Complications such as reservoirs, diversions, irrigation, power plants, etc. and noise in the input data make it much more difficult to determine proper parameter values. The more noise caused by errors in the input data and complications that affect the observed output signal, the more difficult it is to see through the noise and determine the best values for the model parameters. Thus, the first area to calibrate should be the one with the best data and least complications. Section 7-1 describes in detail the selection criteria and the strategies and procedures that are recommended for use in calibrating the initial headwater area.

2. Calibrate other areas with minimal complications. These are other headwater areas, including reservoir inflows where the inflow hydrograph doesn't contain significant noise, as well as local areas for which a good definition of the local contribution can be determined. It includes areas where the flows have been adjusted to natural flow conditions and those where the flows were not adjusted but the man-made controls don't have a dominating effect. Once the local natural flow contribution is separated out by subtracting routed flows or correcting for man-made features, parameters for these areas can be determined in a similar fashion as the initial headwater area. The difference is that during the calibration of these areas *only the parameter values that clearly needed to be changed should be altered*. It is important not to make parameter changes for these areas merely to improve goodness of fit statistics or to make changes based on single events. Parameter changes should be based on clear evidence over many periods or events. If this philosophy is followed, the result should be a realistic variation in parameter values across the river basin. The assessment of spatial variability done in step 2 of the calibration process (see chapter 4) should provide an insight into the magnitude and types of parameter changes that should be expected. Section 7-2 describes details for determining local area hydrographs and strategies to follow when calibrating these drainage areas.

3. Determine parameters for the remaining headwater and local areas. These are areas where

a good definition of the local natural flow cannot be obtained due to the effect of man-made controls or excessive noise in the hydrograph after subtracting routed upstream flows from the discharge at the downstream point. In these areas a true calibration of the snow and soil moisture models is not possible. This step also includes areas for which the data are not available to make adjustments for or model the effect of control structures, thus a historical simulation is not possible. Parameters in both of these cases are generally obtained from nearby areas that were calibrated. Only a few simple adjustments are then made (if even possible) to remove any bias. Section 7-3 describes procedures to follow for determining the appropriate parameters for these remaining drainage areas.

By following this strategy one should be able to meet the calibration objectives in an efficient manner. The calibration of the initial headwater area must be done carefully as the parameters for all the other areas are tied to the values determined for this area. The calibration of this area should take longer than any of the other areas. The calibration of the other areas with minimal complications should go quite quickly as long as one knows how to identify the portion of the hydrograph affect by each model parameter and thus can fairly easily determine which parameters clearly need to be altered. The time required for the completion of the remaining headwater and local areas is primarily a function of how long it takes to determine routing parameters and/or remove or model man-made complications.

Statistics to Monitor

Decisions regarding which parameters need to be changed and the overall reproduction of the observed conditions are primarily determined by examining graphical plots of simulated and observed time series that are produced by the WY-PLOT and PLOT-TS displays of ICP. In addition to viewing these plots, there are various statistics that are helpful to monitor when doing interactive trial and error calibration. The currently available statistics are computed from mean daily flow time series by the STAT-QME operation and are not in graphical form (eventually it would be beneficial to be able to generate statistics for any data type, display many of the results graphically, and compute a wider variety of statistics than are included in STAT-QME). STAT-QME will optionally generate statistics on a water year basis in addition to the multi-year statistics for the entire run period. It is recommended that the user focus on the total run period statistics in order to see trends that may exist in the overall simulation. Yearly statistics are seldom of value. Of the currently available multi-year statistics there are several that are very helpful to periodically check during a calibration (Figures 7-1 and 7-2 show how these statistics appear in the output -- in the ICP program the STAT-QME output is included in the ‘Edit Wide Listing’ display). These are:

- Seasonal and overall bias – These are shown in terms of both percentage and depth of runoff. Both columns are useful. The overall bias shows whether the current data and parameters are generating a near zero water balance or whether the models are producing too much or too little overall runoff. For the calibration period the overall bias should at least be less than 5%. The monthly figures indicate how these quantities vary seasonally. The aim is to have a random variation of reasonably small deviations from zero. A definite pattern in the seasonal bias indicates that something needs to be adjusted. Several months in a row of a double digit percent bias in one direction likely indicates a problem.

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MULTIYEAR STATISTICAL SUMMARY

FRENCH BROAD-ROSMAN AREA (SQ KM) = 176.00 WATER YEARS 1954 TO 1965

MONTHLY	SIMULATED MEAN (CMSD)	OBSERVED MEAN (CMSD)	PERCENT BIAS	MONTHLY BIAS (SIM-OBS) (MM)	MAXIMUM ERROR (SIM-OBS) (CMSD)	PERCENT AVERAGE ABSOLUTE ERROR	PERCENT DAILY RMS ERROR	MAX MONTHLY VOLUME ERROR (MM)	PERCENT AVG ABS MONTHLY VOL ERROR	PERCENT MONTHLY VOL RMS ERROR
OCTOBER	5.644	5.493	2.75	2.299	42.470	13.25	47.10	15.322	6.40	8.17
NOVEMBER	4.425	4.579	-3.36	-2.267	-11.530	14.79	25.55	-15.238	11.49	13.38
DECEMBER	6.120	6.064	0.92	0.847	-17.333	12.80	26.10	14.508	6.77	8.36
JANUARY	6.568	6.380	2.94	2.856	-15.996	13.19	23.62	21.007	7.88	9.50
FEBRUARY	8.370	8.202	2.04	2.301	-8.448	11.83	17.65	12.042	4.56	5.31
MARCH	8.773	8.618	1.79	2.351	5.101	11.68	16.26	17.723	6.33	7.07
APRIL	10.218	10.594	-3.55	-5.535	-21.689	10.66	18.01	-36.210	5.48	8.13
MAY	7.310	7.404	-1.27	-1.429	-7.120	11.85	17.46	-13.731	6.12	7.29
JUNE	5.725	5.687	0.68	0.566	5.939	14.34	20.32	26.752	11.70	15.71
JULY	4.560	4.557	0.08	0.054	-5.751	16.22	23.76	-25.436	13.62	18.12
AUGUST	4.762	4.740	0.47	0.336	6.125	12.60	19.76	18.309	7.95	10.39
SEPTEMBER	4.366	4.292	1.74	1.098	11.797	16.24	27.37	26.773	12.99	17.26
YEAR AVG	6.369	6.350	0.31	3.477	42.470	12.88	23.79	-36.210	7.80	10.18

DAILY RMS ERROR (CMSD)	DAILY AVERAGE ABS ERROR (CMSD)	AVERAGE ABS MONTHLY VOL ERROR (MM)	MONTHLY VOLUME RMS ERROR (MM)	CORRELATION COEFFICIENT DAILY FLOWS	LINE OF BEST FIT OBS = A + B*SIM A	B
1.510	0.818	7.403	9.663	0.9696	0.4717	0.9229

FLOW INTERVAL	NUMBER OF CASES	SIMULATED MEAN (CMSD)	OBSERVED MEAN (CMSD)	PERCENT BIAS	BIAS (SIM-OBS) (MM)	MAXIMUM ERROR (CMSD)	PERCENT AVG ABS ERROR	PERCENT RMS ERROR
0.00 - 2.00	305	1.712	1.634	4.75	0.0381	0.931	13.64	18.71
2.00 - 4.00	1213	2.966	2.979	-0.41	-0.0060	2.120	13.82	17.46
4.00 - 6.00	916	4.881	4.917	-0.73	-0.0177	4.169	14.00	18.10
6.00 - 9.00	968	7.250	7.303	-0.73	-0.0261	5.268	12.68	16.23
9.00 - 14.00	464	11.169	10.813	3.29	0.1745	7.041	11.90	16.76
14.00 - 30.00	212	18.751	18.440	1.69	0.1526	7.290	11.38	14.29
30.00 AND ABOVE	32	44.073	46.414	-5.04	-1.1492	42.470	15.20	23.90

Table 7-1. Illustration of Overall (Year Avg. Percent), Monthly (Percent and Runoff Depth), and Flow Interval Bias (Percent) Output from the STAT-QME Operation.

• Flow interval bias – This table indicates whether mean daily discharges are over or under computed for 7 intervals. The preferred option is for the user to specify the intervals (possibly using physically meaningful values such as bankfull and flood flow), though the STAT-QME operation will generate interval ranges if user specified values are not entered. Again percentage and depth of runoff columns are included, but only the percentage column is worth examining. The aim is to have a random variation of reasonably small deviations from zero, though as mentioned under the objectives section of this chapter there is a tendency with lumped models to under simulate the highest flows and over estimate the lowest flows.

• Accumulated flows and errors – This optional table tabulates the accumulated simulated and observed flows and their difference on a quarterly basis (produced when the 'QUAR' input field is included). Ideally the errors for each period should be random and the accumulated error should meander back and forth around zero. Trends in the quarterly accumulated errors indicate that the relationship between simulated and observed discharge is changing over time. This may indicate an inconsistency in the input or discharge data or a physical change within the watershed that is not being considered. This table doesn't need to be monitored as frequently as the overall, seasonal, and flow interval bias values.

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ACCUMULATED FLOW IN MM

PERIOD	YEAR	OBSERVED	SIMULATED	ACC ERROR	ERROR THIS PERIOD
OCTOBER TO DECEMBER	1953	168.06	160.61	-7.45	-7.45
JANUARY TO MARCH	1954	542.81	525.73	-17.09	-9.63
APRIL TO JUNE	1954	799.86	780.28	-19.58	-2.50
JULY TO SEPTEMBER	1954	881.93	865.58	-16.35	3.23
OCTOBER TO DECEMBER	1954	987.47	966.18	-21.28	-4.93
JANUARY TO MARCH	1955	1211.08	1214.44	3.36	24.64
APRIL TO JUNE	1955	1593.08	1584.05	-9.04	-12.40
JULY TO SEPTEMBER	1955	1838.30	1789.53	-48.77	-39.73
OCTOBER TO DECEMBER	1955	1961.83	1894.51	-67.32	-18.55
JANUARY TO MARCH	1956	2220.75	2139.16	-81.58	-14.27
APRIL TO JUNE	1956	2490.30	2378.58	-111.72	-30.14
JULY TO SEPTEMBER	1956	2622.37	2484.45	-137.92	-26.20
OCTOBER TO DECEMBER	1956	2792.93	2644.84	-148.09	-10.17
JANUARY TO MARCH	1957	3146.74	2982.87	-163.88	-15.79
APRIL TO JUNE	1957	3607.68	3428.88	-178.80	-14.92
JULY TO SEPTEMBER	1957	3806.87	3642.86	-164.01	14.79
OCTOBER TO DECEMBER	1957	4262.06	4084.87	-177.19	-13.18
JANUARY TO MARCH	1958	4653.86	4462.38	-191.48	-14.30
APRIL TO JUNE	1958	5062.24	4857.98	-204.25	-12.77
JULY TO SEPTEMBER	1958	5272.48	5084.24	-188.24	16.01
OCTOBER TO DECEMBER	1958	5397.99	5212.71	-185.28	2.95
JANUARY TO MARCH	1959	5671.75	5510.14	-161.60	23.68
APRIL TO JUNE	1959	6081.86	5935.07	-146.79	14.82
JULY TO SEPTEMBER	1959	6303.80	6162.87	-140.93	5.86
OCTOBER TO DECEMBER	1959	6657.06	6541.30	-115.75	25.18
JANUARY TO MARCH	1960	7095.50	6988.56	-106.94	8.82
APRIL TO JUNE	1960	7432.55	7322.72	-109.83	-2.89
JULY TO SEPTEMBER	1960	7638.30	7518.04	-120.25	-10.43
OCTOBER TO DECEMBER	1960	7825.32	7691.68	-133.65	-13.39
JANUARY TO MARCH	1961	8138.75	8026.83	-111.92	21.73
APRIL TO JUNE	1961	8484.82	8369.68	-115.14	-3.22
JULY TO SEPTEMBER	1961	8878.04	8742.62	-135.43	-20.28
OCTOBER TO DECEMBER	1961	9243.02	9120.68	-122.34	13.09
JANUARY TO MARCH	1962	9689.95	9611.56	-78.39	43.95
APRIL TO JUNE	1962	10068.47	10002.94	-65.52	12.87
JULY TO SEPTEMBER	1962	10193.77	10156.20	-37.58	27.95
OCTOBER TO DECEMBER	1962	10349.19	10341.75	-7.44	30.14
JANUARY TO MARCH	1963	10611.38	10629.90	18.53	25.97
APRIL TO JUNE	1963	10833.53	10862.24	28.71	10.18
JULY TO SEPTEMBER	1963	10980.88	10996.57	15.68	-13.02
OCTOBER TO DECEMBER	1963	11120.88	11123.67	2.79	-12.89
JANUARY TO MARCH	1964	11546.26	11537.09	-9.17	-11.96
APRIL TO JUNE	1964	11951.35	11912.78	-38.57	-29.40
JULY TO SEPTEMBER	1964	12240.48	12260.09	19.61	58.18
OCTOBER TO DECEMBER	1964	12811.19	12850.57	39.38	19.77
JANUARY TO MARCH	1965	12811.19	12850.57	39.38	0.00
APRIL TO JUNE	1965	12811.19	12850.57	39.38	0.00
JULY TO SEPTEMBER	1965	12811.19	12850.57	39.38	0.00

Table 7.2. Sample Accumulated Flow and Error Table from the STAT-QME Operation.

While these statistics don't indicate which parameters or data need adjustments, they do give some insight into trends that exist and possibly the parameters and model components that should be examined. Many of the other statistics that are produced by the STAT-QME operation only give an indication of the overall goodness of fit and may be useful when evaluating the results, but they aren't very helpful in providing insights into making changes to parameters.

Flows to Route Downstream

After calibrating each point within the river basin, time series need to be produced and saved for use in calibrating and evaluating the simulation at the next location downstream. In order to best calibrate these downstream locations and to properly evaluate the ability to reproduce historical conditions at downstream gages, the following two time series should be generated at each point:

- Adjusted instantaneous discharge – these time series are used when calibrating the downstream local areas. Ideally a quality controlled observed instantaneous discharge time series whose volume matched that of the USGS mean daily flows would be routed downstream, but such a time series is rarely available. As a substitute an adjusted instantaneous discharge time series can be generated with the ADJUST-Q operation. This operation uses the simulated instantaneous and observed mean daily flows to create adjusted instantaneous discharge values. Periods of observed instantaneous discharge can also be included. The adjusted instantaneous discharge time series uses the shape information from the simulated time series, but adjusts the daily volume to match the observed mean daily flow. These adjusted instantaneous flow time series are then routed to the next downstream point and subtracted from the observed flow at that location to get the local area contribution which is then used to calibrate the local area. By adjusting to the observed volume, errors in upstream simulations are not propagated downstream. The calibration of the local areas are then based on observed discharges just like the headwater drainages. If observed daily flows are not available for some periods at an upstream gage, the adjusted time series will contain just the simulated values. Such periods should be avoided when calibrating the local area.

- Simulated instantaneous discharges – these time series are used to evaluate the ability to forecast at downstream locations. When forecasting, whether it be a short term or extended forecast, there are no observed data in the future (forecast values may be modified somewhat based on the last available observations of streamflow). To determine how well one can reproduce conditions at downstream points in the forecast mode, simulated discharge for the entire drainage area above the gage needs to be compared to observed flow. If only adjusted discharges are routed downstream, errors and bias from upstream locations will be removed from downstream simulations. Relatively minor errors and bias at upstream points could add up to larger errors and bias downstream.

These two time series are generated and saved after completing the calibration at each location. For headwaters, both time series can be created in the same run. For downstream points, two runs are needed. To generate the adjusted time series, adjusted flows should be routed down from upstream points in addition to using the ADJUST-Q operation at the downstream location. This insures the best possible simulated instantaneous discharge at the downstream point and will use as much observed volume data as possible if there are periods of missing data at that location. To generate the simulated time series, simulated flows must be routed down from upstream points so that all the flow at the downstream location is made up of simulated values.

At some locations it is impossible to perform a historical simulation due to the lack of the necessary data to adjust or model the effect of control structures. At these locations the sequence of routing simulated flows downstream is broken. Observed flow data at these locations can be used to create instantaneous streamflow values to route downstream (generally instantaneous flows are calculated from observed mean daily discharge data using the CHANGE-T operation and, when available, observed instantaneous flows can be used) for use in calibrating the next downstream location, however, a full historical simulation of the entire drainage area below such points is not possible.

Recalibration

Over time there will undoubtedly be a need to recalibrate all or part of a river basin. Reasons for needing to recalibrate were given in chapter 2. Whether a recalibration is necessary can be the user's choice in some cases and mandatory in others. Cases when the user must decide if a recalibration is needed include:

- calibration expertise and knowledge has increased and as a result past calibrations, as well as operational performance, are reviewed to determine at what locations a recalibration is likely to improve results (if the increase in expertise and knowledge will likely result in improved data estimates, then the affected historical data record should also be regenerated).

- operational results are unsatisfactory under certain circumstances -- after determining the situations that cause problems, the user must decide if these were the result of cases that were missing, overlooked, or modeled improperly during the calibration – if so, a recalibration is a possible solution (in many of these cases the historical data record must first be extended to include the situations that didn't occur within the previous calibration period), and

- physical changes (such as new agricultural practices, large forest fire, or modifications to land use) have occurred within portions of the basin and based on decreased operational performance it is decided that the effects are significant – if so, a recalibration is needed for the affect portions of the basin (in this case the historical data must first be extended and then only the period after the change was well established would be used to modify the model parameters).

- climatic changes have occurred and it appears that the operational output exhibits trends such as over estimation of runoff during certain seasons which might be attributed to increased evaporation rates - if so, a recalibration should be explored using an extension of the historical record. Adjustments, such as those to climatological average ET-Demand values might not require recalibrating every watershed, but only selected drainages to determine the size of the adjustments to apply over the entire area.

In the first of these cases it is probably best to totally redo the calibration, i.e. calibrate the headwater area with the best data first and then move on to the other watersheds following the recommended guidelines. Trying to start with the parameters from the previous unsatisfactory calibration will only interfere with and negatively influence the process. In the other two cases it is recommended that one start with the existing parameter values and change only those that clearly need to be modified.

Situations when a recalibration is mandatory include:

• existing operational models are being replaced with new models (such as replacing an event API type rainfall runoff model with a conceptual soil moisture accounting model) in an attempt to improve forecast results (the existing historical data may be able to be used to calibrate the new model, however, in many cases the new model may require new data types or the data may need to be in a different form (e.g. continuous as opposed to event data)),

• historical data have been reanalyzed using different procedures (such as switching from the non-mountainous area technique to a mountainous area procedure) resulting in input time series that are biased as compared to those used for the previous calibration (in this case new model input data must be generated for the entire historical data period),

• new methods which should improve model input (such as determining precipitation estimates from a combination of gage, radar, and other data), but likely produce values that are biased compared to that used in the current calibration, have generated a sufficiently long historical record to be used to adjust the model parameters (in this case the recalibration can use only the period for which consistent data can be determined using the new method), and

• new forecast points are to be established at locations within the basin that were not part of the current calibration thus resulting in a subdivision of existing drainage areas and changes to the routing reaches (frequently the historical data must be extended in order to have as much historical streamflow data as possible at the new locations).

In the first of these cases a complete calibration of the new models is required since the new models are being applied to the basin for the first time. In addition it may be necessary to modify parameters or at least check the performance of other models that were part of the previous calibration. For example, if the rainfall runoff model is being replaced, the parameters for the snow and channel response (e.g. unit hydrograph) models may need to be modified. Even though the snow model should be independent from the rainfall runoff model, its parameter values may have been affected by how the parameters and data for the rainfall runoff model were determined in the previous calibration. The same thing holds true for the channel response model and, in addition, the function of the channel model may vary depending on the structure of the rainfall runoff model (e.g. the Sacramento model requires a different unit hydrograph than an API type model – see section 7.6). As long as the other models were properly calibrated previously, only adjustments that are clearly needed should be made to the parameters for these models.

In the other cases when a recalibration is mandatory, a complete new calibration is generally not required. It should be possible to utilize the parameters from the previous calibration as a starting point and then modify only the values of those parameters that need to be changed. For the snow and soil moisture models changes should be substantial only when there is a significant bias between the new and previous input data. Guidelines for the specific case of using radar based precipitation estimates for operational forecasting are included in chapter 8.

Section 7-1

Calibration of Initial Headwater Area

Selection Criteria

The following criteria, not in any particular order, should be used for selecting the initial headwater area to calibrate within a river basin:

- The period of observed streamflow data should be as long as possible, ideally covering most or all of the period of record used for the historical data analysis. This long period is needed for two reasons. First, besides needing a period to calibrate the models at the location, it is also important to have some independent periods to validate the results. Second, many times it is helpful to make comparisons between calibrations at other locations within the basin and the initial headwater area and since the streamflow data for the other locations may have varying periods of record, the initial headwater point needs a long record to insure that there are overlaps with the other sites.

- The physical characteristics of the drainage area should have been basically stable over time, i.e. no substantial land use, vegetation cover, or agricultural changes and the streamflow data should be consistent. In addition, the initial headwater should be physiographically representative of the total river basin, or at least the portions of the basin that produce significant runoff.

- The networks used to estimate the model input variables, especially precipitation, should have good coverage. Noise in the input data, especially precipitation, makes it more difficult to determine the proper parameter values, thus the mean areal inputs need to have a minimal amount of random error.

- If there is a wide variation in the amount of annual runoff over the river basin, especially if there are drainages with small amounts of runoff, the initial headwater area should be a drainage with average to above average runoff relative to the other parts of the river basin.

- There should be minimal complications. There should be no significant reservoirs or large lakes that dampen out the hydrograph response. Diversions, if any, should be small and should have observed data that can be used to adjust the streamflow to natural conditions. The amount of irrigated acreage should have little, if any, effect on flow. There shouldn't be any power plants or other controls that cause substantial noise at low flows. Glacier contribution to runoff should be avoided if possible.

Using these criteria, all of the headwater gages within the river basin should be evaluated and the one that comes the closest to meeting the criteria should be used as the initial area for calibration.

Periods of Record

As mentioned in Chapter 7, besides calibrating the models for the initial headwater area, a validation should be done on a separate period of the record at that location. If a careful validation is done on the initial headwater, it is probably not necessary to run separate validations at the other locations within the river basin. Guidelines for selecting the period to use for calibration are as follows:

- The calibration period should contain as much variety in hydrologic conditions as possible. There should be events with very high flows and there should be extended dry periods with very low flows. Ideally there should be significant runoff events at all times of the year and under different initial soil moisture conditions. There should be years with both much above and considerably below normal volumes of runoff. If snow is a factor, there should be years with both very large and abnormally small amounts of snow cover and ideally snowmelt periods at various times during the snow season. However, it is probably best to not include the flood of record, the minimum flow of record, or other extremes within the calibration period. It would be better to save these events and periods for validation so that you can see if the calibrated models can extrapolate beyond the conditions experienced during calibration.

- The calibration period typically needs to be about 10 years long, at least in the areas where lumped, conceptual models generally provide satisfactory results. Experience has shown that a period of about 10 years is needed in order to determine stable values of the model parameters. When the models are calibrated using shorter periods, the parameters are more likely to vary depending on the period used. In regions where lumped models give marginal results, the calibration period may need to be longer in order to get a sufficient number of events and variety of conditions to determine the parameter values. In regions where the results are typically unsatisfactory, even the full period of record is likely not going to be adequate for determining the parameters with any degree of certainty.

- If possible, it is a good idea to have the calibration period for the initial headwater overlap with periods when most of the other streamgages within the basin also have observed daily flow records. In this case the same period can be used at most locations for calibration and observed discharges will be available to adjust the instantaneous flows that are routed downstream.

The periods to use for validation should be as long as possible and, as mentioned above, ideally will contain some extreme events and situations to test the extrapolation capabilities of the calibrated models. Essentially the entire period with observed mean daily flow data, except for the calibration period, will be used for validation.

Initial Model Parameter Values

Initial parameter values for the snow and Sacramento models can be obtained in one of two ways for the initial headwater area.

- If an adjacent river basin has been already calibrated, the initial snow and Sacramento model parameters should be obtained from the headwater area within the previously calibrated basin that is the most hydrologically similar to the initial headwater in the current river basin. This nearby headwater should have good data, minimal complications, and its calibration results have met the objectives so that you are quite confident in the parameter values. In this case the strategy for calibrating this initial headwater will be the same as for other headwaters and locals with minimal complications within the river basin, i.e. only change those parameters that clearly need to be altered. By following this procedure parameter values should not only end up being consistent from one area to another within a river basin, but should show realistic variations across the entire RFC area.

- If no adjacent river basin has been previously calibrated or if there is a considerable difference in hydrologic conditions between this initial headwater area and any drainage that has been previously calibrated in the region, then the initial snow and Sacramento model parameters can be derived from available information. Guidelines and methods have been developed to derive initial parameter values by analyzing hydrographs and from physical or climatic information. Section 7-4 contains guidelines for determining initial parameter values for the SNOW-17 model. Section 7-5 describes techniques for deriving initial parameter values for the Sacramento model. Even if the initial parameters are obtained from a previously calibrated drainage, it is a good idea to read and understand the material in these sections. The information included should help in understanding the function of each parameter, assist in knowing how to isolate the effects of the parameters, and give some insight into a reasonable range of values.

Initial parameter values for the channel response model that is used to convert the runoff entering the channel system to a discharge hydrograph at the gaging location should always be determined directly for each drainage area. The channel network for each drainage is unique and the response function for one area should not be used for another. Section 7-6 discusses how the unit hydrograph technique is used in conjunction with the Sacramento model and methods for deriving an initial estimate of the unit hydrograph ordinates.

Calibration Strategy

Once initial parameters have been determined for each of the models, the next step is to adjust the parameter values so that the simulation results meet the calibration objectives. The calibration of a conceptual model by making interactive adjustments to model parameters is completely dependent on having the proper knowledge of the function and how to isolate the effects of each parameter. The function of each parameter is determined by understanding the structure of the model. Knowing the model structure will also help in understanding what conditions must exist in order to select the portions of the simulation results to examine to determine if changes should be made to the value of a given parameter. It is critical for a person to gain a reasonable understanding of how to isolate the effects of each model parameter if they are going become competent at calibrating conceptual models. Without a reasonable proficiency in knowing the effects of each parameter on model response, interactive calibration becomes a very inefficient process with little probability of the user ever determining the proper parameter values. Without this knowledge the user would be better off using an automatic calibration method. Section 7-7 contains a discussion of how the major snow model parameters affect model response. Section 7-8 contains a similar discussion for the Sacramento model. An understanding of these 2 sections and the structure of each model is an absolute prerequisite to interactive calibration.

When using the interactive trial and error method of calibration, it is best to follow a proven strategy for determining which parameters need to be modified rather than just randomly looking at various portions of the record and making parameter changes. Even though a step by step strategy is outlined, it cannot be followed in a cookbook fashion. The steps give a general pattern to follow, but the user must remain somewhat flexible. Some general items to consider concerning calibration in general and in particular when using the recommended strategy are:

- Be reasonably bold when making parameter changes. Finding the proper value will take less time if the changes to parameter values are fairly large. If you overshoot, it is much easier to estimate your next trial value than if you only make a sight incremental change.

- Model parameter values are selected to produce the best results over a number of events or occurrences of a given situation and should not be assigned based on a single event. The random errors that occur for individual events during calibration can hopefully be minimized operationally by improved data estimates or run-time modifications to model computations.

- Remove large errors in parameter values whenever they are detected. The first step in the strategy involves removing large errors that exist at that point in the process, but during later steps significant errors in other parameters may become apparent. When these errors are causing enough noise in the simulation results that they make it difficult to determine the proper value of the parameters currently being worked on, the parameters causing this noise must be modified, at least to the degree that their effect is not interfering with the current step.

- One should periodically return to previous steps to recheck the results. Parameter changes in subsequent steps may necessitate adjustments, usually small, to parameters values determined during an earlier step.

- Remember to periodically check the statistics mentioned in chapter 7. These statistics help to identify trends in the simulation and assist in determining the periods, and possibly the parameters, to examine.

- Change the duration and scale of the ICP displays depending on which flow components and parameters are being examined. Long durations, typically one or two years, and a semi-log scale are used when working on low flow components and parameters, while shorter periods, generally in terms of months, and an arithmetic scale are used when examining storm events or snowmelt runoff periods.

The recommended strategy for calibrating an individual watershed is as follows:

1. Remove large errors. If certain initial parameters or some of the input data are considerably in error, there will be a large discrepancy between the simulated and observed hydrograph. These problems need to be corrected before proceeding in a more step by step fashion through the parameters. The amount of noise caused by these errors make it very difficult to isolate the effect of individual parameters and to determine which parameters need to be modified and by how much. The aim at this point is not to totally correct these errors, but to get the simulation results at least in the right ballpark.

Large timing errors should typically be corrected first, since they can also be a source of volume discrepancies. The most common large timing problems that exist at this point in the process are:

- Large error in the percolation rate for the Sacramento model such that there is way too much storm runoff and not nearly enough baseflow or vice versa. This problem can usually be corrected by changing the LZFSM and LZFPM parameters by the same ratio such that the PBASE term in the percolation equation is increased or decreased until the split between storm runoff and baseflow is more reasonable.

- Large error in the amount of surface runoff generated by the Sacramento model such that major storm events are way over or under simulated. This problem is generally corrected by changing the UZFWM parameter upwards or downwards.

- Improper channel response function is being used for the Sacramento model (see discussion in Section 7-6). This occurs when the unit hydrograph contains the timing effects of interflow, as well as surface runoff. This problem is corrected by removing interflow from the unit hydrograph being used.

There could also be large timing errors associated with snowmelt runoff, however, if the initial parameter guidelines are followed and the temperature data are reasonably unbiased, this should not be a problem. There could be timing problems with the snowmelt during the largest snow years due to the approach recommended for determining the SI snow model parameter, but this is to be expected at this point.

In general, for most watersheds the overall volume error should be no more than about 10%. For watersheds with small amounts of annual runoff, especially those with less than an average of 5 inches per year, the initial volume error may be greater. If the initial volume error is larger than expected, it is important to look carefully at the components of the water balance to determine if there is a problem that needs to be corrected before proceeding with the calibration. The most likely problems are biased precipitation or evaporation data or streamflow data that haven't been corrected for diversions or other gains or losses. In some cases the tension water capacities of the Sacramento model could be off so far that the ratios of contents to capacity remain too large or too small and thus result in an error in the amount of computed actual evaporation. This is most likely in a arid or semi-arid region. In some cases the problem is merely that the unit hydrograph ordinates do not represent the specified drainage area (this should result in a warning from the UNIT-HG operation if the correct drainage area was entered). Any significant volume errors need to be corrected before proceeding with the calibration.

In some regions, especially the northeastern United States, there may be frequent errors in determining the form of precipitation, i.e. rain versus snow. This not only affects the model response at the time of the precipitation event, but also will affect the volume of snow available for melt at a later date. The amount of noise in the simulated results caused by this problem will make it very difficult to determine appropriate parameter values. When this occurs, the data for individual events, typically temperature, need to be modified so that the form of precipitation is generally correct before proceeding with the calibration. Suggestions for how to correct the form of precipitation are included in Section 7-4 under the "Form of Precipitation" section.

2. Obtain a reasonable simulation of baseflow. In order to obtain the best results from the Sacramento model, it is important to properly calibrate all components of the model. At many forecast points one may be primarily interested in high flows, however, the structure of the model makes it impossible to maximize the ability to predict high flows when low flows are not reasonably modeled. Contrary to the thoughts of some people, the model doesn't need multiple sets of parameters (e.g. one for simulating floods and another for extended predictions involving all flow levels). The simulation of the various flow components are all interconnected, thus the percolation of water into the lower zones and the computation of baseflow must be correct in order to get a good reproduction of storm runoff. A proper calibration should yield parameter values that will not only reasonably simulate low flows, but will also provide the best simulation of high flows.

Since many of the low flow parameters are involved in the percolation equation, it is necessary to concentrate on this part of the model first to obtain a good foundation before focusing on upper zone soil moisture and storm runoff. The aim of this step initially is not to finalize the parameters that control baseflow, but to get the simulated hydrograph to generally match the observed under low flow conditions. Then as the calibration proceeds, you will periodically return to this step and make refinements to the parameter values.

When working on getting a reasonable reproduction of low flows, it is best to start with primary baseflow. Section 7-5 discusses the importance of determining in advance which portions of the observed hydrograph are to be modeled with each of the available runoff components and that the identification of primary baseflow is critical to a successful simulation. That section also describes situations when it is difficult to isolate primary baseflow. The periods when primary baseflow is the only source of runoff or at least predominates are examined to determine if the LZPK and LZFPM parameters need to be modified. Next supplemental baseflow periods are examined to check the values of LZSK and LZFSM. Changes to all these parameters will alter the PBASE term in the percolation equation and thus not only affect the amount of water going to the lower zone and baseflow, but also modifying the amount available for storm runoff. Thus, if the overall volume is in the right ballpark, the total volume of storm runoff should become more reasonable as the simulation of baseflow improves. Another parameter to examine at this point is PFREE. In some cases it may be necessary to make some crude adjustments to the shape of the percolation curve, i.e. parameters ZPERC and REXP, at this stage of the process, but the refinement of the shape of the percolation curve occurs in a later step.

When working on getting a reasonable reproduction of low flows, one should recognize whether there are periods when baseflow is drawn down due to evaporation from riparian vegetation or from irrigation withdrawals. Both of these causes of low flow draw down have a similar effect on the hydrograph. Knowledge of the basin is required to decide which is most likely the cause. Such periods should not be used when making adjustments to the main parameters that control low flow. After other low flow periods are being simulated in a reasonable fashion, one can then try various values of the RIVA parameter or introduce the Consumptive Use operation (CONS_USE) to see how well the draw down periods can be modeled. RIVA should then be set back to zero or the CONS_USE operation removed and these periods ignored until the final step.

3. <u>Adjust major snow model parameters, if snow is included</u>. Once the baseflow simulation is reasonably good, the major snow model parameters should be checked to determine if adjusments are needed to the volume and timing of snowmelt. The major snow model parameters are MFMAX, MFMIN, SCF, UADJ, SI, and the areal depletion curve. The minor snow model parameters generally should not need to be adjusted during calibration, but in a few cases modifications to these parameters may be necessary. It is most important to check the snow model parameters at this point in areas where snowmelt runoff is significant and especially when there is an extended melt season. If snowmelt events are infrequent and generally occur over a short period, it may be necessary to wait and adjust snow model parameters at the same time as the Sacramento model parameters that primarily affect storm runoff (step 5). If form of precipitation problems were not corrected in step 1 and it is now apparent that noise resulting from the mistyping of winter events is making it difficult to determine the proper parameter values, then the data should be corrected as described in Section 7-4. If mistyping of precipitation is infrequent and random, it should not be necessary to correct the data in order to determine the snow model parameter values.

If it is necessary to use snowmelt parameters (primarily MFMAX and MBASE) that are considerably different from those suggested in Section 7-4 or if snowmelt occurs consistently early or late in spite of the changes that are made to the parameters, it is quite likely that the temperature estimates are invalid. There may be other reasons for discrepancies at the beginning of the snowmelt season as discussed near the end of Section 7-7, but significant overall timing problems or unreasonable parameter values are a good indication that the computation of the MAT values should be reexamined using the guidelines in Section 6-4. Especially in mountainous areas, the initial MAT estimates may need to be redone because of difficulties in determining the temperature versus elevation relationship due to scatter in the station data or the use of improper lapse rates.

4. Adjust tension water capacities. This step involves finding periods that isolate the effect of tension water deficits in both the upper and lower zones of the Sacramento model, i.e. the UZTWM and LZTWM parameters. The idea is to determine whether the deficits are generally too large, too small, or about right, thus indicating how the parameters should be modified. During this step is also a good time to check the value of the PCTIM parameter. Fast response runoff during periods when upper zone tension water deficits exist can only be modeled by constant impervious area runoff.

5. Adjust parameters that primarily affect storm runoff. This involves altering the value of UZFWM to get the proper division between surface runoff and interflow, changing UZK to get the correct timing of interflow, determining if ADIMP is needed and if so, finding the best value, and refining the shape of the percolation curve over a large range of LZDEFR values primarily by adjusting the ZPERC and REXP parameters. When making adjustments to the percolation rates in the Sacramento model, it is best to look at the entire curve and determine what changes are necessary and then select parameter values that will produce the curve that is needed. A procedure for evaluating the entire percolation curve is described in Section 7-8.

6. Make final parameter adjustments. This typically includes looking at the following:

- If riparian vegetation evaporation effects exist, determine the final value of the RIVA parameter or if there are irrigation withdrawals, add the CONS_USE operation and make the necessary adjustments to its parameters.

- Refine the timing of major peaks, mainly those that produce surface runoff, by modifying the shape of the channel response function (unit hydrograph).

- Adjust ET-Demand curve values to improve the seasonal bias pattern (if it can be deduced that ET errors are the cause of any trend in the seasonal bias). When making modifications to mean monthly ET-Demand values, the monthly PE adjustment curve should be examined to make sure that the values are realistic and that abrupt changes do not occur from one month to another.

• Raising or lowering the entire percolation curve to improve the flow interval bias pattern by changing LZFSM and LZFPM by the same ratio.

Indeterminate Parameters

It needs to be recognized that depending on the conditions that exist within a given watershed and the types of events that occur within the calibration period of record, there may be some parameter values that cannot be reliably determined. This occurs when the parameter is never or rarely activated during the calibration period. It is important to understand when this occurs since it may affect the operational ability of the model to extrapolate to conditions outside the range of what was included in the calibration period. Parameters for which reliable values sometimes cannot be determined are:

Snow Model:

• SI – If bare ground occurs as soon as snowmelt begins during every year, i.e. there is no significant period when the area remains at 100 percent snow cover, it is impossible to determine the value of SI other than to know that it is greater than the maximum average areal water equivalent that occurred during the calibration period.

• UADJ – If few or no significant rain-on-snow events with warm temperatures occur, it is not possible to obtain a reliable value of the UADJ parameter.

Sacramento Model:

• UZFWM – If surface runoff never occurs, it is impossible to determine the proper value of UZFWM other than to say that it has to be great enough that the model will never generate surface runoff. When there are only a few events with surface runoff, the value of UZFWM generally contains much uncertainty in watersheds where the distribution of rainfall is highly variable during these large storms.

• LZTWM, UZTWM, and PFREE – In very wet regions where significant soil moisture deficits never occur, at least during the calibration period, it is not possible to determine the value of the tension water capacities or PFREE. In some areas there are sufficient dry spells to estimate the UZTWM parameter, but none of sufficient length to determine LZTWM or get a good estimate of PFREE. Also in semi-arid regions, there may never be sufficient moisture to fill the lower zone tension water, thus it is not possible to know the proper value for this parameter. In very dry regions there is not enough runoff to be confident in any of model parameter values.

• ZPERC and REXP – If the vast majority of events occur over a limited range of lower zone moisture conditions, it is very difficult to obtain unique values for ZPERC and REXP. Various combinations of these parameters can result in similar percolation rates over a small range of soil moisture. This is especially common in wet regions.

Special Situations

There are some special situations that can exist when calibrating watersheds that need some additional discussion. This includes watersheds with multiple zones, glaciers, and frozen ground.

- Multiple Zones – It is important to maintain a realistic relationship between parameter values from one zone to another within a watershed whether the drainage is subdivided based on elevation zones, travel time zones, or some other breakdown. There are 2 basic recommended approaches:

    - Start with the same values for all parameters for each zone. Then keep the parameter values the same as the calibration progresses except when there are events that clearly allow one to determine unique parameter values for a given zone. These could be rain events where the precipitation only occurs over one of the zones or snowmelt runoff periods where all or most of the melt is coming from one zone.

    - Start with parameter sets that have different initial values for some parameters and then maintain the ratio or difference in these parameters between the various zones as parameter values are modified. The initial differences can be based on relationships, either objective or subjective, between parameters based on soils, vegetation, or climatic conditions or based on differences in parameter values from previously calibrated watersheds that most likely represent one zone or another. The initial relationship between the parameters for each zone are only modified during the calibration if there are a number of events that clearly allow for a unique determination of certain parameter values for a given zone. ICP contains a feature (included with the Selected Parameters option under the Edit menu) that allows the user to maintain the ratio or difference (fixed for each parameter) between zones when changing parameter values for the snow and Sacramento models. When this feature is on, the parameters in all zones are altered to maintain the ratio or difference whenever the value for any one zone is changed.

- Glaciers – A separate zone is typically used to model glacier effects. One glacier zone should be sufficient unless possibly the glacier covers most of the drainage and covers a wide range of elevations. Two general modeling approaches have been used to simulate the streamflow response from the glaciated area:

    - Use the snow model to simulate the accumulation and melt that occurs on the glacier surface and the GLACIER operation to model the time delays that take place as the water moves through the glacier. The GLACIER operation allows for a variable withdrawal rate of any liquid water passing through the glacier that is a function of the amount of inflow at the glacier surface in the recent past. This results in little outflow and a storage buildup when rain or meltwater first enters the glacier. As warmer weather persists and passages within the glacier open up, there is a much faster response to surface inflow and the water in storage is released. This results in both a delay and dampening effect.

- Use the snow model to simulate the accumulation and melt at the surface, plus some of the delay that occurs when water passes through the glacier and use the Sacramento model to handle the variation in attenuation rates of this water. In this case a user specified seasonal melt factor variation is used in the snow model to artificially produce some of the delay between when rain or melt occurs and when the water reaches the streamgage. Only certain portions of the Sacramento model are used, primarily those that control the attenuation of water through the system by dividing it into the various components, surface, interflow, and supplemental and primary baseflow. The following Sacramento model parameters can be set to zero for a glacier; PCTIM, ADIMP, RIVA, PFREE, and the ET-Demand values. The tension water capacities can be set to a non-zero value and the storage initially set to the capacity, which will not change during the run since the evaporation rate is zero.

In both cases the initial water equivalent of the snow cover should be set to a very large value (typically 30,000 mm has been used) and the initial liquid water storage should be equal to the PLWHC parameter multiplied by the initial water equivalent (i.e. liquid water storage should be full at the start of the run). During the calibration it is important to monitor the change in the water equivalent to insure that any increase or decrease in glacier ice is reasonable compared to any available mass balance studies for glaciers in the region.

The main advantage of using the GLACIER operation is that it is a more conceptually correct approach. The snow model is being used as it was intended and the GLACIER operation is attempting to model the effects of the glacier on storing and attenuating the surface melt and rain water. The main advantage of using the Sacramento model is that it allows for more runoff components. The GLACIER operation allows for a variable withdrawal rate which can produce values that are similar to interflow and supplemental and primary baseflow rates in the Sacramento model. The GLACIER operation cannot pass water through the glacier as quickly as surface runoff occurs in the Sacramento model. High intensity rains on some glaciers in the late summer when passages through the ice are fully open show a surface runoff type response. The GLACIER operation cannot mimic this type of response.

• Frozen Ground – Extensions to the Sacramento model are used in an attempt to model the effects of frozen ground. The algorithms consist of an indicator of the amount of frost in the soil (either a frost index as in the preliminary frozen ground model or frost depth in a new procedure being developed) and then a modification of portions of the Sacramento model, typically percolation and interflow withdrawal rates, based on the amount of frost. Frozen ground mainly has a significant effect on streamflow in somewhat open regions where there are cold periods with little snow cover during portions of the winter and percolation rates are quite different for frozen and non frozen soil. Regions where dense forests and/or significant snow cover exist provide enough insulation to prevent substantial frost from developing except at far northern latitudes where permafrost occurs. Regions where percolation rates are very low even when the soil is not frozen or where permafrost exists (percolation rates remain similar throughout the year), typically don't require the use of the frozen ground algorithms.

When deciding whether to include the frozen ground algorithms, it is a good idea to start the calibration without considering frozen ground and concentrate on events during the summer and fall, plus spring events during years with a substantial snow cover over most of the winter accumulation period. The frozen ground algorithms can be included and the amount of frost displayed, but the effect of the frost on the Sacramento model should be turned off (done in the preliminary frozen ground model by setting the SATR parameter to zero). Thus, one can see when the algorithms could change the response of the Sacramento model and a decision can be made as to whether the inclusion of frozen ground is needed and should likely improve the results.

Use of Other Data during Calibration

The primary observations used to compare against model simulated results during calibration are mean daily flow data, however, there are other observations that should also be used when they are available. This includes other types of flow data and snow observations.

• There are two types of streamflow data that should be used whenever possible besides mean daily discharges. These are instantaneous discharges and peak flows.

- Instantaneous discharge data are very helpful for faster responding watersheds and when there is a significant diurnal variation in flows during snowmelt periods. The instantaneous discharges are not needed on a continuous basis, just during selected storm events and snowmelt periods. When the storm hydrograph from a watershed doesn't peak for 2 to 4 days or more, generally mean daily flows are adequate for determining the parameters that control storm events (primarily UZFWM and possibly ADIMP) and the shape of the unit hydrograph, however, for areas that peak sooner, instantaneous discharges are often needed to refine these parameters. The same is true of watersheds with snowmelt periods that last for more than a few days. Mean daily flow data will not indicate the magnitude of diurnal fluctuations that may exist. This can only be determined by examining instantaneous discharge data.

To illustrate the situation involving diurnal variations in streamflow during snowmelt we will use data from the Central Sierra (CSSL) and Upper Columbia (UCSL) Snow Laboratories. These data were collected in the late 1940's and early 1950's as part of the Snow Investigations conducted by the Corps of Engineers and the Weather Bureau [*Snow Hydrology*, 1956]. The watersheds used are both small (CSSL watershed is 3.96 mi^2 and the UCSL watershed is 8.09 mi^2), thus any damping of the response due to the channel system is minor. The original calibrations for both of these watersheds were done using only mean daily flow data.

Figure 7-1-1 shows the simulation of mean daily flows for the 1950 snowmelt period for CSSL. This figure includes the original calibration, based only on daily flows, which had no surface or variable impervious runoff during snowmelt periods, and the final calibration, which used observed 6 hour instantaneous discharges to determine model parameters and as a result generated both of these runoff components. As can be seen the mean daily flow simulations in both cases are quite good. Figure 7-1-2 shows the instantaneous flow simulations from the original calibration that show a much more damped response than what actually occurred. Figure 7-1-3 shows a much more realistic reproduction of the instantaneous flows after the UZFWM value was reduced to produce surface runoff during high intensity snowmelt periods and the ADIMP parameter was used to generate fast response runoff when snowmelt rates were lower. The simulated instantaneous discharges are delayed somewhat from the observed because a 6 hour time interval is being used, whereas a hourly interval would be more appropriate for such a small, quick responding watershed, however, the amplitude is quite reasonable. Without instantaneous flow data one would not know which parameter set was most appropriate.

Figure 7-1-4 shows the simulation of mean daily flows for the original calibration from the UCSL. Figure 7-1-5 shows the simulation of instantaneous discharges at a 6 hour

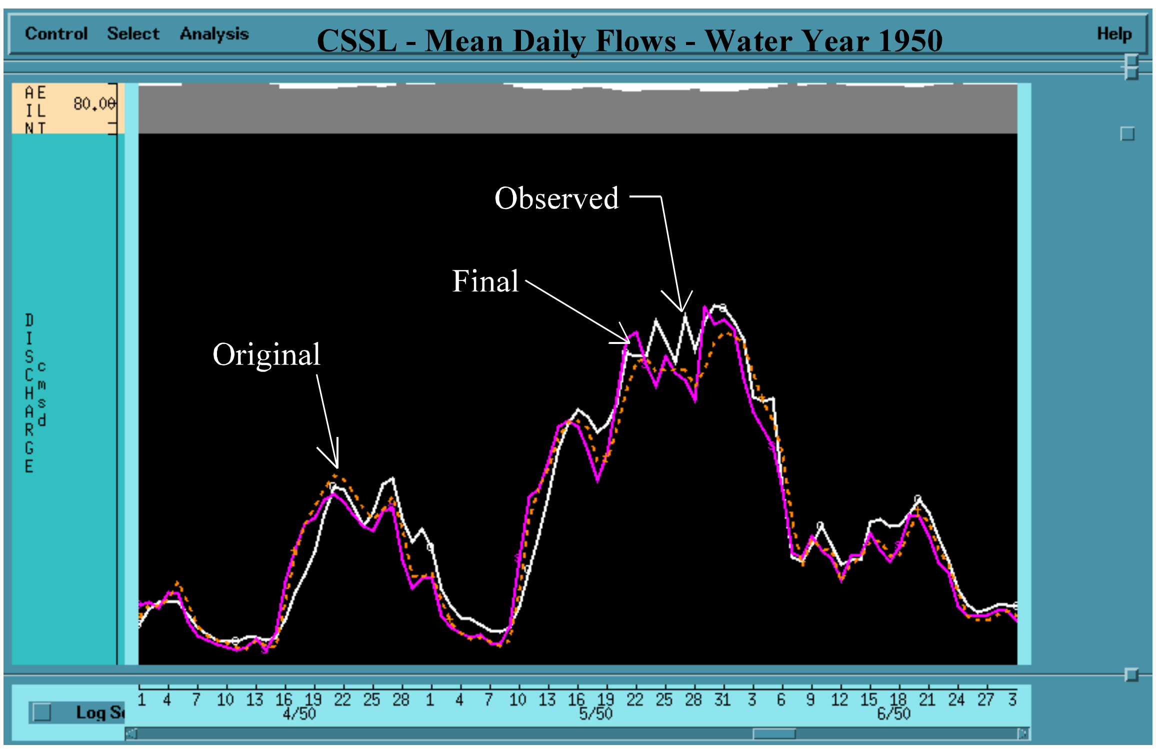

Figure 7-1-1. Simulation of mean daily flows for CSSL.

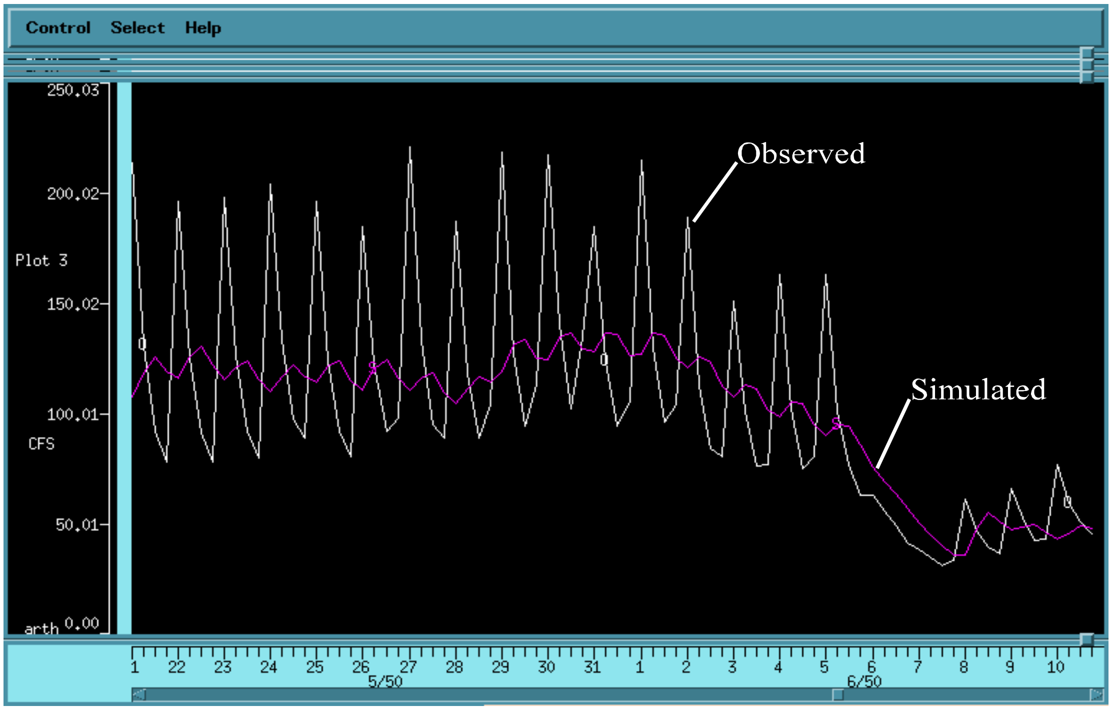

Figure 7-1-2. Simulation of instantaneous flows from the original calibration for CSSL.

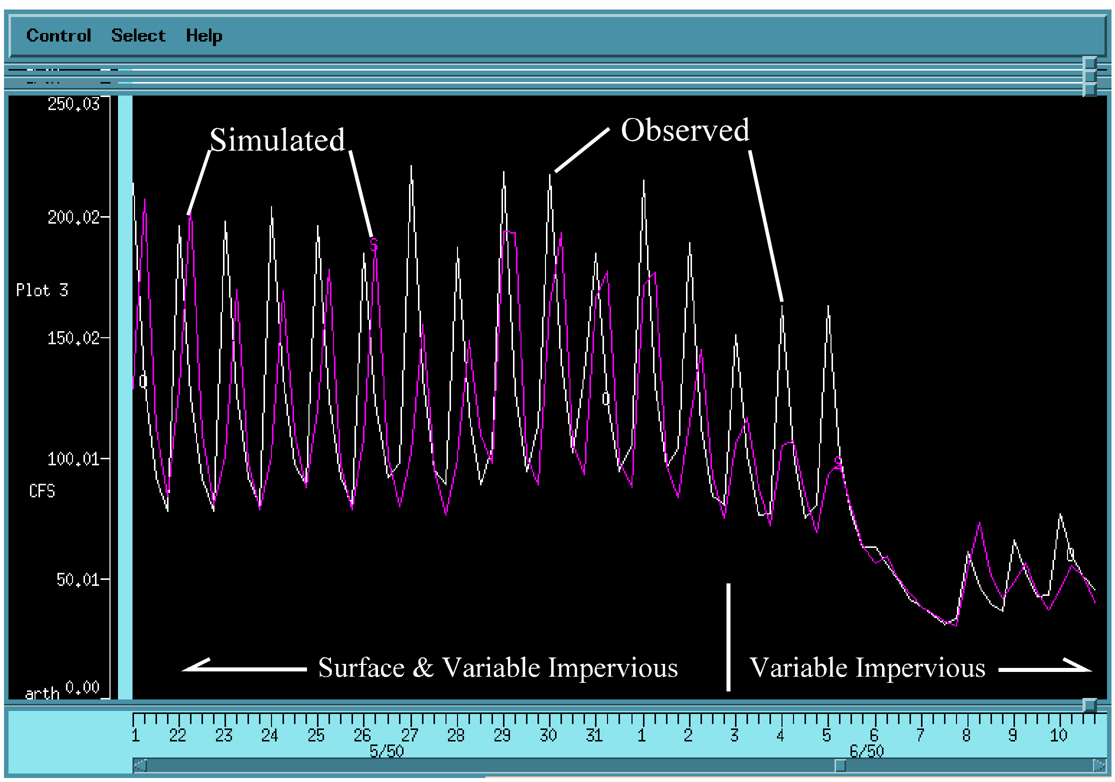

Figure 7-1-3. Simulation of instantaneous flows from the final calibration for CSSL.

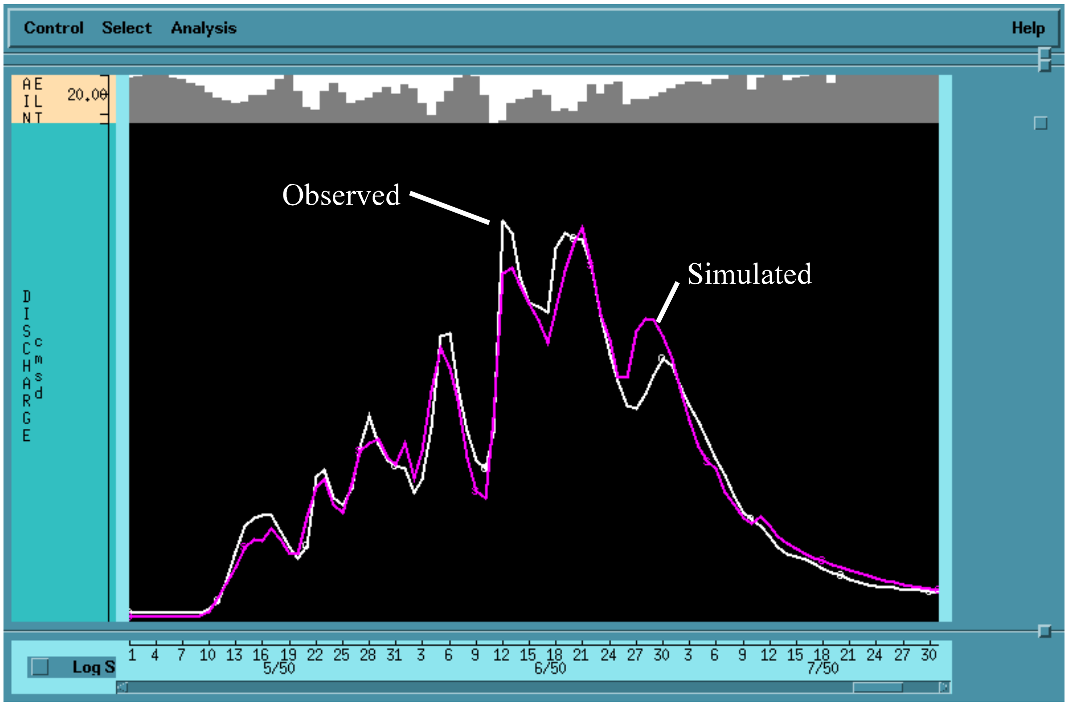

Figure 7-1-4. Mean daily flow simulation for the original UCSL calibration.

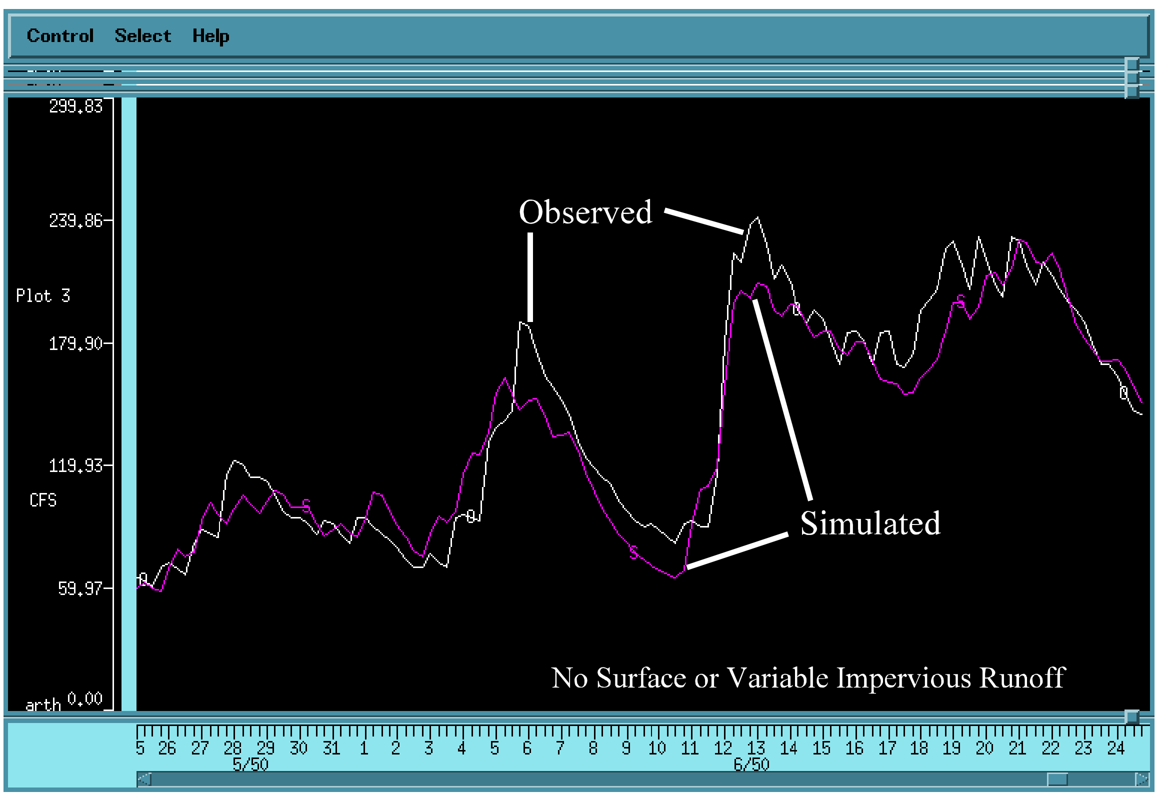

Figure 7-1-5. Instantaneous discharge simulation from the original UCSL calibration.

interval for this same parameter set. In this case the instantaneous flow simulation is quite realistic based on only using mean daily flows for calibration, however, one wouldn't know for certain unless some observed instantaneous discharge data were available for examination.

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/home/eaa/calb_report/figures/peakflow.temp line 4, col 61, 3421 bytes

PEAKFLOW DISCHARGE AND TIMING ERROR SUMMARY

OBSERVED PEAK Q(CFS)	H(FT)	DATE	FLAG Q	H	SIMULATED PEAK Q(CFS)	DATE	TIMING ERROR(DAYS)	DISCHARGE ERROR(CFS)	DISCHARGE RATIO (SIM/OBS)
3620.0	8.1	3/19/1968	6		3150.0	3/20/1968	-1	-470.0	0.87
3420.0	8.1	1/26/1979	6		2610.0	1/27/1979	-1	-810.0	0.76
2580.0	7.2	4/ 7/1987	6		2910.0	4/ 7/1987	0	330.0	1.13
2300.0	6.7	6/ 7/1982	6		2300.0	6/ 8/1982	-1	0.0	1.00
1960.0	6.4	4/ 2/1993	6		1890.0	3/31/1993	2	-70.0	0.96
1780.0	6.3	6/ 3/1984	6		1690.0	6/ 1/1984	2	-90.0	0.95
1780.0	6.1	2/12/1970	6		1530.0	2/12/1970	0	-250.0	0.86
1690.0	6.0	3/27/1969	6		1620.0	3/27/1969	0	-70.0	0.96
1590.0	5.9	3/23/1972	6		1530.0	3/24/1972	-1	-60.0	0.96
1420.0	5.6	3/29/1978	6		1470.0	3/29/1978	0	50.0	1.04
1360.0	5.5	3/16/1986	6		1340.0	3/16/1986	0	-20.0	0.99
1260.0	5.5	3/13/1983	6		1470.0	3/13/1983	0	210.0	1.17
1250.0	5.4	3/15/1977	6		1540.0	3/15/1977	0	290.0	1.23
1160.0	5.2	2/ 4/1973	6		1370.0	2/ 4/1973	0	210.0	1.18
1030.0	5.0	1/28/1976	6		1590.0	1/29/1976	-1	560.0	1.54
1030.0	5.0	2/26/1975	6		1160.0	2/26/1975	0	130.0	1.13
1020.0	4.8	3/23/1980	6		1240.0	3/23/1980	0	220.0	1.22
899.0	4.5	3/17/1971	6		614.0	3/18/1971	-1	-285.0	0.68
857.0	4.5	2/27/1981	6		1430.0	2/27/1981	0	573.0	1.67
830.0	4.7	3/23/1974	6		1140.0	3/23/1974	0	310.0	1.37
779.0	4.3	4/23/1991	6		703.0	4/23/1991	0	-76.0	0.90
775.0	4.3	4/ 5/1990	6		717.0	4/ 5/1990	0	-58.0	0.93
739.0	4.3	5/13/1989	6		688.0	5/13/1989	0	-51.0	0.93
692.0	4.1	3/28/1988	6		960.0	3/28/1988	0	268.0	1.39
614.0	4.0	11/24/1991	6		870.0	11/24/1991	0	256.0	1.42
403.0	3.4	2/13/1985	6		484.0	2/14/1985	-1	81.0	1.20
MEAN: 1417.0	5.4				1462.0		-0.1	45.3	1.09

(OBSERVED DISCHARGE EVENTS ONLY)

"*" INDICATES SIMULATED PEAK ON SEARCH WINDOW BOUNDARY, WHICH PROBABLY IS NOT THE TRUE PEAK.

DISCHARGE RMS ERROR = 296.500 (CFS)
TIMING RMS ERROR = 0.760 (DAYS)
AVERAGE PERCENT ERROR (AVEOBSQ-AVESIMQ)/AVEOBSQ = 3.2 %
CORRELATION COEFFICIENT (DISCHARGE) : R = 0.936
BEST FIT LINE: OBSQ = A + B * SIMQ : A = -227.600(CFS) B = 1.120

Figure 7-1-6. Sample display from the PEAKFLOW operation.

- Peak flow data are helpful to determine how well the magnitude of the instantaneous peaks are reproduced, especially when instantaneous discharge data are not available at all or only for a small portion of the calibration period. These data are most valuable for fast responding streams, but can also be helpful when diurnal flow variations occur during snowmelt. The current PEAKFLOW operation tabulates a comparison of observed and simulated peaks by calculating the difference between the values and their ratio as shown in Figure 7-1-6. There is also a timing comparison, but only in terms of which day the peak occurred since the archived records don't contain the time of the observed peak during the day. It is somewhat difficult to use this tabular summary directly, since if mean daily flows are over or under simulated, the peaks on those days should also be similarly affected (i.e. if the highest daily flows are somewhat under simulated, it should be expected that the peaks should show a similar tendency, however, there is no tabulation of the daily flow bias just for the days with observed peak flow data). It would be better to compare the ratios of the observed peak to the observed mean flow for each peak flow day to the same ratios for simulated discharges. This would more clearly indicate whether the instantaneous flow simulations had a similar diurnal pattern as the observed discharge data.

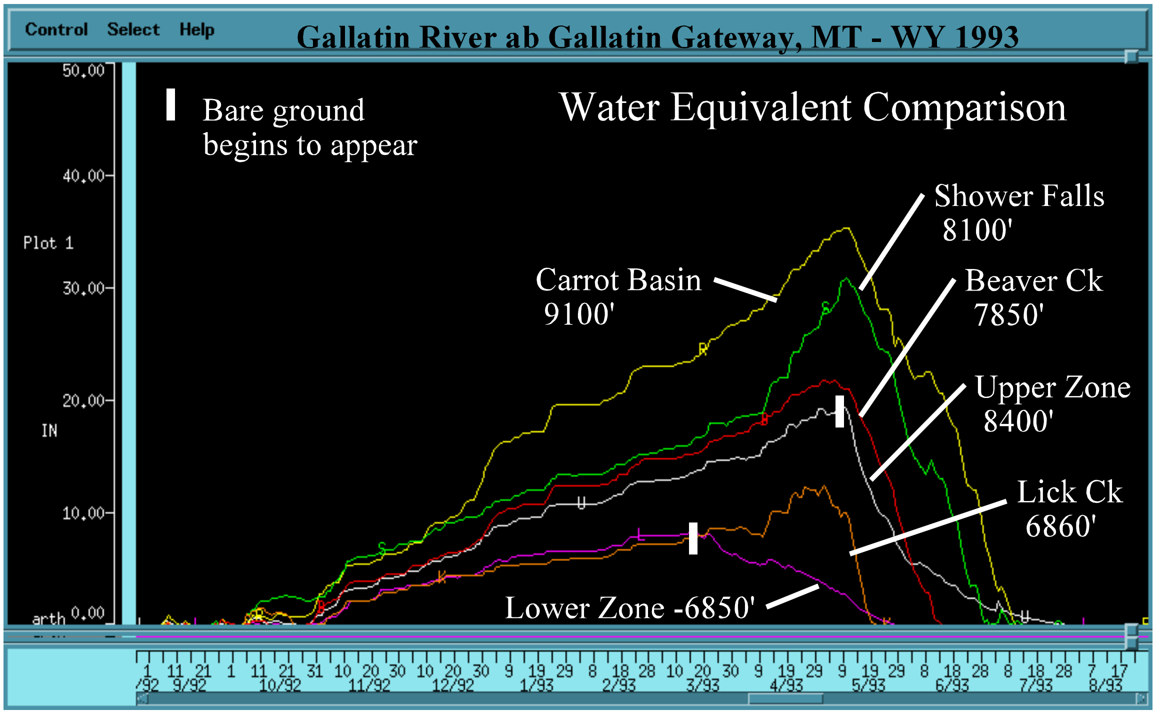
• Snow observations can be used to verify the snow model computations by assisting to discern the actual form of the precipitation and to confirm whether the simulation of the snow cover is reasonable. Snow data that can be used for these purposes are snowfall, water equivalent and depth, and possibly areal extent of cover.

- Snowfall data – Data on new snowfall can be helpful in the determining if the form of precipitation selected by the snow model is correct or whether it needs to be modified. Section 7-4 includes of discussion of problems associated with the model determining the correct form of precipitation under certain conditions. This section also shows how snowfall data can be used along with streamflow response and possibly water equivalent or depth data to check whether the form of precipitation needs to be changed.

- Water equivalent and depth data – Comparisons can be made between the mean areal water equivalent computed by the model and point or flight line observations of water equivalent to determine if the model computations are reasonable. There is always the problem that point or even flight line measurements only represent a small portion of a drainage area and thus there will seldom be a one to one correspondence between computed and measured values. Even so, observations of water equivalent can provide information as to how realistic are the model calculations. It is especially helpful to have several observations of water equivalent scattered through the area and at a range of elevations in the mountains. Generally the more observations, the more likely that one can realistically assess the model performance. In the mountains the model computations should typically show a pattern that is similar to snow course or SNOTEL observations during the accumulation period. During the melt period the observation sites should go bare before the mean areal water equivalent goes to zero. The model water equivalent will exhibit a more gradual decrease once bare ground begins to show up in portions of the watershed, while point measurements will go abruptly to zero. In flatter terrain where the time from complete cover to no snow conditions occurs over only a few days, this effect is less apparent. Figure 7-1-7 shows a water equivalent comparison for the Gallatin River above Gallatin Gateway, Montana. Model water equivalents for the upper and lower zones are plotted along with data from 4 SNOTEL sites.

If no water equivalent data are available, comparisons can be made between modeled water equivalent and observed depth of snow on the ground. When doing this one must remember that the density of the snow cover changes throughout the snow covered period, thus the relationship between water equivalent and depth is ever changing. In spite of this, depth data can be helpful to assess whether the model results are reasonable.

Figure 7-1-7. Water equivalent comparison for Gallatin River ab. Gallatin Gateway, MT.



- Areal extent of snow cover – Areal extent observations derived from satellite data are available for many western mountain areas for more recent years. The satellite estimates are available for entire watersheds and specific elevation bands. These observations can be compared against the areal extent of snow cover computed by the model, however, one must be aware that there should not be a one to one correspondence between the model areal extent and direct observations. The reason for this is that the areal depletion curve in the model implicitly includes other factors than just the areal snow cover as discussed in Section 7-4. The model should be using an areal extent that is less than that observed during the period when bare ground exists, with the largest discrepancies occurring in areas with the most rugged terrain. Thus, if one takes this difference between model and actual areal extent into account, the observations should be helpful in assessing whether the model results are reasonable.

Validation of Results

As indicated previously it is a good idea to validate the calibration results for the initial headwater watershed on other portions of the period of record. If done properly, this will test the extrapolation capabilities of the calibration results and determine if "curve fitting" occurred during the calibration (i.e. parameters were tweaked just to improve goodness of fit statistics). As mentioned earlier, the validation period should ideally include events that are outside the range of what occurred during the calibration period, i.e. the flood and low flow of record would be in the validation period. Ideally statistics for the calibration and validation periods should be similar, though typically the calibration period statistics are slightly better as some degree of "curve fitting" is hard to avoid. A variety of statistics can be used to compare the results during the calibration period and one or more validation periods. These can include:

- Root mean squared errors, both daily flows and monthly volumes,

- Differences and standard deviations of monthly mean flows to test seasonal variations,

- Autocorrelation functions of observed flows and simulation residuals,

- Frequency distributions of observed and simulated flows, and

- Histograms of high flow peaks and their simulation errors.

Some possible causes of validation problems, i.e. differences in results between the calibration and validation periods, besides "curve fitting" include:

1. Calibration period is not adequate either because the validation period contains events that excite certain model components for the first time or events that seldom occurred during calibration occur during the validation period under somewhat different conditions (e.g. surface runoff may have occurred once during calibration with a certain spatial rainfall pattern, but occurs with a different rainfall pattern during the validation period). Also certain problems present, but unnoticed in calibration, may be amplified in validation.

2. Factors external to the models are changing over time, i.e. the observed flow data are not consistent due to changes in factors such as reservoir releases, agricultural practices, and vegetation and land use changes.

If these problems occur the suggested actions are as follows:

Case 1. Use the entire period of record to refine the calibration so that all possible model components are used and so that the maximum number of occurrences of specific situations are included in determining the most likely value of each parameter. This should only involve modifications to those parameters whose values were based on few, if any, events during calibration. Parameters whose values are based on only a few events or control components that were never used will contain a high degree of uncertainty. Parameters that sometimes fall into this category were mentioned in the section on Indeterminate Parameters in this section. For all parameters, but especially these, a subjective estimate of the degree of uncertainty (e.g. ± percentage of the parameter value to represent the standard deviation of the uncertainty) should be made for operational use.

Case 2. The observed flow data should be made consistent over both periods of record or another watershed should be selected for the initial calibration. This case should not occur if the selection criteria for the initial headwater area were followed.

If a thorough validation is done for the initial headwater area within the river basin, validation is probably not necessary for the other drainages in the basin. Using the strategy recommended in this chapter, the parameter sets for all the other drainages in the river basin will be closely tied to the parameters determined for the initial headwater area.

Section 7-2

Calibration of Other Headwaters and Locals with Minimal Complications

Introduction

This section describes procedures and strategies to follow when calibrating other drainages within a river basin for which a good definition of the local flow contribution can be determined. The calibration for these areas will be closely tied to the results from the initial headwater area after taking into account information determined earlier about the spatial variations of physical, climatic, and hydrologic conditions over the basin. In order to determine if a drainage area falls into this category, it is necessary to examine the hydrograph produced from the area. In order to obtain this hydrograph it may only be necessary to look at the observed streamflow data or it may be that some computations must first be performed to remove the effect of control structures or upstream flows. Once the local drainage area hydrograph is established, an evaluation can be made as to whether model parameters can be reliably determined or whether there is so much noise in the hydrograph that a full calibration is not possible. This decision is subjective, but guidelines for making the choice include:

- Compare the hydrograph to the streamflow record for the initial headwater area or other headwaters that have no complications caused by such things as reservoirs, large lakes, diversions, or irrigation. Determine whether the general pattern is similar or, at least any differences are reasonable. For instance see if the hydrographs go up and down at the same time though the time to peak and amount of attenuation may vary, and if the magnitude and timing of snowmelt runoff makes sense.

- Examine baseflow periods to assess whether the general magnitude of the flow and the recession rate can be reasonably determined most of the time at these flow levels. A semi-log scale should be used when making this determination. Considerable scatter might occur at times when looking at low flow periods, but if such periods are few or the effects minor enough so that the baseflow pattern can be reasonably ascertained, a calibration of low flow parameters is possible.

Derivation of the Hydrograph for the Drainage Area

As mentioned previously for many headwater areas the observed mean daily flow data defines the hydrograph for the drainage area. In other cases computations may be necessary in order to determine the hydrograph that can possibly be used for calibration. This includes situations where the flow data need to be adjusted to natural flow conditions by adding or subtracting diversions, the inflow to an upstream reservoir is computed from outflow and storage data, and downstream local area contribution is derived by subtracting routed upstream flows from the observed flow at the gaging station. In a few cases the computations may involve a combination of these situations, e.g. a downstream local area may contain some diversions.

Adjustment to Natural Flow

In order to determine natural flow conditions to use for calibrating the snow, soil moisture, and channel models, the streamflow data need to be adjusted for man-made effects. Primarily this includes adjustments for diversions into or out of the drainage area. It could also include adjustments for the effects of reservoirs within the area, a large spring, or flood overflows across drainage divides. Section 6-6 discusses adjustments to mean daily flow records. Once the adjustments are completed, an evaluation can be made as to whether the resulting hydrograph can be used for calibration or whether too much noise exists.

Computation of Reservoir Inflows

The inflow hydrograph for a reservoir can be computed, if sufficient data are available, and possibly used to calibrate the models to the drainage area. Inflow hydrographs to any reservoir can be calculated though it is highly unlikely that the derived flows can be used for calibration other than the case of a headwater reservoir, i.e. a dam with no upstream calibration points. The water balance equation for a reservoir, as was shown in Section 6-6 (Eq. 6-6-1), is:

$$I - O + P \cdot A - E \cdot A + D = \Delta S \qquad (7\text{-}2\text{-}1)$$

where: I = Inflow,
O = Outflow,
P = Precipitation on water surface,
E = Evaporation from the water surface,
A= Water surface area,
D = Diversions into or out of the pool other than at the main outlet, and
ΔS = Change in Storage (each term is in volume units).

In order to compute the inflow, the outflow and the other terms must be known. At a minimum the outflow and change in storage terms are required. The change in storage can be computed from reservoir storage data using the DELTA-TS operation. If pool elevation measurements, rather than storage, are available, then they must first be converted to storage using the elevation-storage curve for the reservoir with the LOOKUP operation. Precipitation and evaporation could possibly be ignored if the water surface area of the reservoir is very small as compared to the drainage area above the reservoir, i.e. if the volume of water transferred at the water surface is small compared to the inflow. If precipitation and evaporation are included, the computations are relatively straight forward when the water surface area can be assumed to be a constant (LOOKUP operation used to convert depth of precipitation or evaporation to a volume based on the surface area). If the water surface area changes substantially over the range of pool elevations that occur, then this needs to be accounted for in the computations. In that case the volume of water transferred is a function of both the amount of precipitation and evaporation and the amount of storage or the pool elevation. Unfortunately the 3 variable relationship operation in NWSRFS, LOOKUP3, is currently only programed to solve for depth as a function of discharge and depth or 2 discharge variables and is not in a general form for any 3 variables (this application would require solving for volume as a function of depth and volume or 2 depth variables).

In many cases when calculating the flow from the drainage area above a reservoir, errors in the various terms used to compute the inflow will result in considerable variability in the resulting time series. This is especially true at low flow levels and when the reservoir surface area is quite large. Also noise can result from problems caused by wind effects on the measurement of storage or pool elevation. High winds will tend to pile water up on the downwind edge of the lake resulting in inaccurate values of the change in storage term when the wind speed and direction differ greatly from one day to the next. For these reasons, in many cases it is not possible to derive a reservoir inflow time series that is of good enough quality to be used for model calibration.

Computation of Local Flows for Downstream Locations

The typical sequence for a downstream location is to route the upstream flows to the downstream gage and then subtract the routed flow from the total downstream flow to get the local area contribution. The resulting local area hydrograph can be examined to determine if a separate calibration can be done for this drainage or whether there is so much noise that it will minimize the chance of obtaining model parameter values with any degree of confidence. The flow to be routed downstream should be the adjusted instantaneous discharge, as discussed in Chapter 7, so that simulation volume errors from upstream locations are not carried downstream. In some cases, primarily based on where the local drainage network enters the main channel, it may be more realistic to add all or a part of the local area contribution to the upstream flow before routing. This situation is illustrated in Figure 7-2-1. In this case it would be most realistic to add the flow from Areas 1 and 2 to the flow at point A before routing since these areas enter the main channel at the very upstream

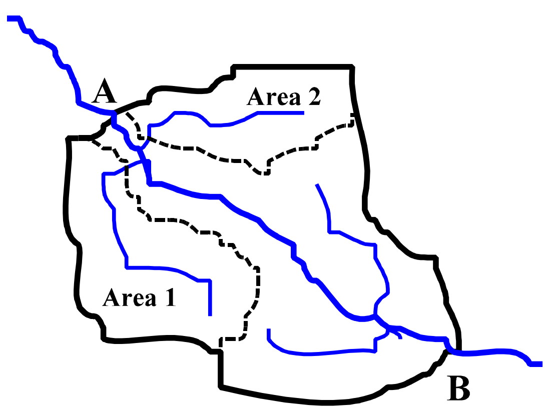


Figure 7-2-1. Routing

example.
end of the local drainage. In this situation a separate local area hydrograph is not obtained and a full calibration of the local area is not possible.

NWSRFS contains a number of routing models that can be used to move upstream flows to a downstream location. Generally the parameters of these routing models can best be determined from instantaneous discharge data for a number of storm events with different magnitudes of flow. In some cases routing model parameters can be adequately determined using mean daily flow data. This occurs mainly when the response time of the watersheds is relatively slow and there is a considerable amount of lag and attenuation in the river reach. The verification of the routing model parameters can be accomplished by using a long continuous record with a wide variety of flow conditions. An evaluation of the resulting local area hydrograph is one of the best methods of determining whether any further refinement of the routing model parameters is necessary. The steps in this process are as follows:

1. Generate adjusted instantaneous discharge hydrographs at each upstream location. If simulated instantaneous flows are not available at an upstream point, i.e. the area above that location has not been modeled, then adjusted instantaneous flows can be derived from just observed mean daily discharge data, rather than using the ADJUST-Q operation with both observed daily and simulated instantaneous flows. An option within the CHANGE-T operation allows for the generation of an instantaneous discharge time series from mean daily flow data. The shape of the resulting hydrograph should be quite realistic for areas with a slow response time, i.e. peaks in terms of days, but cannot be guaranteed for fast responding streams.

2. Route these adjusted instantaneous upstream flows, either separately or in some combination, to the downstream point.

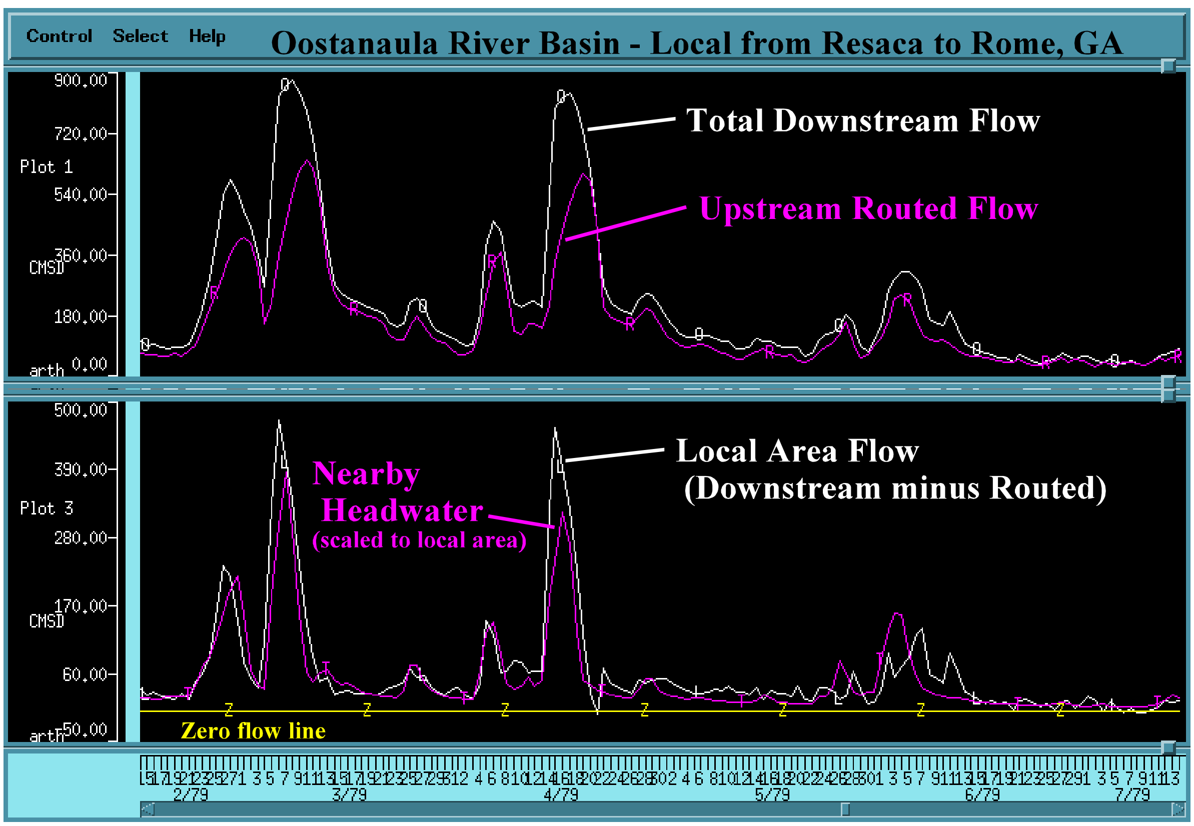
3. Use the MEAN-Q operation to produce a mean daily routed time series.

4. Subtract the routed mean daily flow from the observed mean daily flow at the downstream location to generate a mean daily hydrograph for the local area. This also can be done for instantaneous discharges for periods when observed instantaneous flow data are available at the downstream point.

5. Produce two daily flow plots to evaluate the results. One plot should contain the total routed and downstream observed discharges. It can also contain the local area flow, upstream inflows (before routing), and individual routed flows. The second plot would contain the local area hydrograph and discharges from one or more nearby headwater areas with minimal complications. The hydrographs for the nearby headwaters should be scaled to the local drainage area before plotting. These plots can be produced using two WY-PLOT operations or a single PLOT-TS operation. Using PLOT-TS has two

advantages. First, both plots can be viewed at the same time and second, negative values can be seen (generated when routed flow is greater than the downstream total flow - a zero flow line can be shown by having a time series included for which all values have been set to zero using the CLEAR-TS operation). The results are evaluated by seeing if the local area flow plot looks like it should by comparing it to the hydrographs for nearby headwater areas. Peaks should occur at the same time and the recessions should be smooth without any sudden dips caused by the routed flow being close to or exceeding the total downstream discharge.

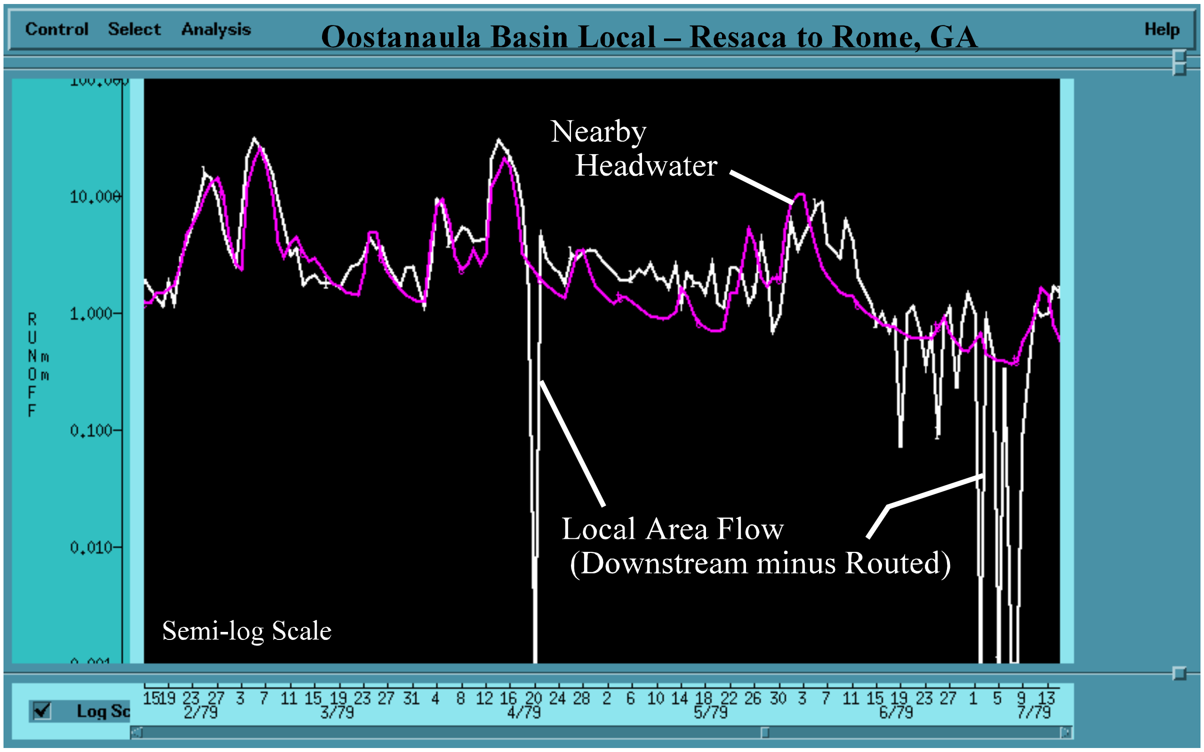
6. Modify the routing model parameters if needed to try to improve the resulting local area hydrograph and rerun the computations. Once the best possible results are obtained, decide whether the local area hydrograph is of sufficient quality to use for a full calibration. If a full calibration can be done, the local area daily flows can be saved to a file for use while calibrating (routing operations would not be included while working on the local area) or the local area flows can be recomputed on each run, rather than being read from a file, by including the routing computations. During calibration the simulated and “observed” (total minus routed) local flows would be used to determine and evaluate changes to model parameters. At the end, both the local and total area flows should be



examined before finalizing the parameter values.

Figure 7-2-2. Sample PLOT-TS display for deriving a local area hydrograph.

Figures 7-2-2 and 7-2-3 show examples of the types of plots used to evaluate the routing model parameters. Figure 7-2-2 is a PLOT-TS display that has two daily flow plots. The top plot shows the routed and total downstream flows. The bottom plot includes the local flow (total downstream minus routed), the hydrograph from a nearby headwater that is scaled to the local drainage area, and a time series of all zeros. In general the derived local area flow looks fairly reasonable though there are times when the local flow dips to zero or below due



to the routed flow being equal or exceeding the downstream discharge. There also appears to be more variability in the derived local flow than in the hydrograph for the nearby headwater at lower flows.

Figure 7-2-3. Sample WY-PLOT semi-log display for deriving a local area hydrograph.

Figure 7-2-3 shows a semi-log display of the lower panel of the previous figure using the WY-PLOT operation display. This plot accentuates the dips and the flow variations in the local area flow. While this derived local area hydrograph is probably of sufficient quality to make some limited parameter adjustments, it is not good enough for a full calibration.

Strategy to Follow

The recommended strategy to follow when calibrating these other headwater and local areas with minimal complications and for which a good definition of the hydrograph can be determined is:

1. First calibrate the other headwater areas with minimal complications. These headwaters should not contain any large discharge adjustments or be reservoir inflow points. These should be the next best drainages for determining parameter values. Start with a watershed that is close to the initial headwater and then move across the river basin. The steps to follow for each of these watersheds are:

a. Determine the calibration period – It is best to use the same period to calibrate the remaining watersheds as was used to calibrate the initial headwater area. In some cases this is not possible because the other headwater areas may not have observed streamflow data for this period or there may have been changes within the drainage area over time that dictate that another period be used for calibration.

b. Assign initial parameter values – Initial values for the snow and Sacramento models should be those determined for the most hydrologically similar area that has been previously calibrated. Different values could be used for some of the minor snow model parameters if there are significant differences in the typical amount of snow from one area to the next. Differences in soils and vegetation could be used to alter some of the Sacramento model parameters if there is sufficient confidence in the relationship between a given parameter and the physiographic information. Also, the ET-Demand curves could vary based on elevation and vegetation cover as described in Section 6-5. A unique channel response function should be derived for each new watershed as drainage areas and the channel network will vary from one watershed to the next.

c. Determine parameter adjustments -- Follow the strategy described in Section 7-1 for the initial headwater area with the exception of *only changing those parameters that clearly should be altered*. Possible changes to parameters that affect certain components of the models may be suggested based on the assessment of spatial variability that was described in Chapter 4, but parameter values should not be actually altered until closely examining the simulation results in a step by step manner. Modifications for large errors should involve changing as few parameters as possible. Then as you go through the various groups of parameters, i.e. starting with parameters that control low flows, then major snow model parameters, then tension water capacities, then storm runoff parameters, and at last the final adjustments, locate those portions of the hydrograph where the effects of each parameter can be isolated and then only change the parameter value when there is clear evidence that a change is justified. The magnitude of the parameter change doesn't have to be large, but there must be no doubt that the change is needed based on looking at multiple situations when the parameter's effects can be isolated. The statistics mentioned in Chapter 7 should be monitored during the calibration and may assist in determining which parameters may need to be modified. Also additional data, such as instantaneous and peak flows and snow observations should be used when available just like for the initial headwater area.

Making only those parameter changes that are clearly justified, will result in a consistent and realistic variation in parameter values across the river basin. It is important to base any changes on a consistent pattern involving a large number of cases when the effect of a given parameter can be isolated. Parameter changes shouldn't be based on one or two events or a sight improvement in some 'goodness of fit' statistic. It is more important to achieve spatial consistency in the parameter values than to change values merely to improve some statistical value. By starting with parameters from a previously calibrated watershed and then looking at each parameter in an organized manner should also result in significantly reducing the time needed for calibrating the remaining drainages within the river basin, thus making the whole calibration process much more efficient.

2. Calibrate the remaining drainages in this category for which it has been determined that the hydrograph is of sufficient quality to support a full calibration. This includes locations with large flow adjustments, headwater reservoir inflow points, and downstream local areas. The sequence of steps and the strategy for making parameter changes should be the same as was just described for the other headwater areas. Many of these drainages will contain somewhat more noise in the "observed" discharge hydrograph. The more noise that exists, the harder it generally is to justify parameter changes, thus these drainages will typically have fewer parameter modifications than the main headwater areas. The time needed to calibrate these locations is largely dependent on the time needed to make flow adjustments or derive the hydrograph for the drainage area. The time needed for making snow and soil moisture model parameter adjustments shouldn't take very long if done in an organized manner.

Section 7-3

Model Parameters for other Headwaters and Local Areas

Introduction

This section discusses procedures for determining parameters for drainage areas for which a full calibration is not possible. These are portions of the river basin where the hydrograph for the drainage area, either headwater or local, contains considerable noise and those areas where there is not even sufficient information to derive the flow contribution from the area, e.g. the area above a reservoir that doesn't have storage or outflow data. For such areas the general approach is to assign snow and soil moisture parameters from the most similar previously calibrated watershed and then see if it is possible to make any adjustments to those parameter values to remove bias in the resulting simulation. In some cases it may not even be possible to produce a historical simulation for these drainage areas.

Strategy

The recommended strategy to follow for these drainage areas is as follows:

1. Determine the period to be used for possible calibration. It is best to use the same period as was used for the initial headwater area and all, or at least most, of the other locations within the river basin that have previously been calibrated, but in some cases this is not possible. Needed observed data may not be available for this area for that period or there may have been changes within the drainage area over time that dictate that another period be used for calibration. For downstream local areas it is best to use a period for which not only downstream flow data are available, but also observed upstream flows so that errors in upstream calibrations are not propagated downstream.

2. Attempt to derive a hydrograph for the drainage area as discussed in Section 7-2 to determine to what extent a calibration can be performed. In some cases it will not be possible to calculate the flows for the drainage area due to a lack of sufficient information. Examples include reservoirs lacking storage (or pool elevation to compute storage) or outflow data and areas with large diversions for which data are not available. If a hydrograph for the drainage area can be derived, make a judgement as to what level of calibration is possible based on the amount of noise in the calculated flows. This may range from a full calibration (in that case refer to Section 7-2 for the strategy to follow), to the possible adjustment of selected parameters, to only the chance of a crude adjustment to remove any bias in the simulation results at the downstream location. If a full calibration is not possible based on your judgment proceed to the next step.

3. Assign initial parameter values to the models used to simulate the local area contribution to the flow. Initial values for the snow and Sacramento models should be those determined

for the most similar area for which a full calibration was possible. Similarity is generally a subjective decision based on the assessment of spatial variability of physiographic features that was described in Chapter 4. When the hydrograph for the drainage area can be calculated with sufficient reliability, at least at certain flow levels, parameter sets from several calibrated areas can be tried in order to see which best represents this area. Different values could be used for some of the minor snow model parameters if there are significant differences in the typical amount of snow from one area to the next. Soils or vegetation information could possibly be used to alter some of the Sacramento model parameters if there is enough confidence in the relationships between the parameters and these data. Also, the ET-Demand curves could vary based on elevation and vegetation cover as described in Section 6-5. A unique channel response function (unit hydrograph) should be derived for each new watershed as described in Section 7-6 as drainage areas and the channel network will vary from one area to the next.

4. There are two basic cases at this point. The first is that a historical simulation is possible and calculated values can be compared with computed, adjusted, or observed data. The second is that a historical simulation is not possible due to a lack of information.

a. Historical Simulation Possible – In this case two basic situations exist. The first is that the natural flow from the drainage area, either headwater or local, can be determined. The second is that the effect of the control structures will be included as part of the historical simulation as opposed to just modeling natural flow.

When natural flow can be calculated it could be for a headwater reservoir where inflows are derived from storage, outflow, and possibly precipitation and evaporation data; for a headwater location where observed discharges have been adjusted to natural flow conditions to correct for diversions, changes in storage, and other factors; or for a downstream location where both local (total minus routed) and total flow, possibly first adjusted for the effect of control structures, are available. In this situation simulated streamflow is compared to these computed “observed” natural flow values. Simulating the flow should only involve the use of snow, soil moisture, and channel response models for the drainage area and routing models if this is a downstream location.

When the effect of the control structures are being modeled, total simulated discharge is compared directly to the total measured observed flow data which contains the effect of the structures. This involves modeling everything of significance that occurs within the drainage area. In addition to snow, soil moisture, channel response, and routing models; reservoir operations, irrigation usage, and diversions will be modeled.

In both of these situations the aim is produce an unbiased estimate of flow taking into account errors and noise in the data. Water balance components should be examined to make sure they are consistent with adjacent drainages. Precipitation and evaporation values should be reasonable if the guidelines in Sections 6-3 and 6-5 were followed when the MAP time series and evaporation estimates were generated. Computed runoff values will contain considerable uncertainty when there are large diversions, reservoir effects, or irrigated areas or when the local area is small relative to the upstream area. Changes are generally not made to individual snow and soil moisture model parameters unless the hydrograph for the drainage area being modeled can be derived and is of sufficient quality to clearly indicate that such change is justified. When this occurs the magnitude of the change should be significant since the hydrograph is not of sufficient reliability to make minor adjustments. Even if the hydrograph is not well enough defined to isolate the effects and make changes to individual parameters, some general adjustments can often be made to correct for any bias that exists between the computed and "observed" values. This should only be done if there is reasonable confidence that the long term runoff is realistic. In that case, the following types of parameter changes can be considered:

- For volume bias, either overall or seasonal, adjustments can be made to the overall amount of precipitation, the snowfall correction factor, and/or the amount or seasonal variation in ET-Demand.

- For bias related to the magnitude of the flow (e.g. under simulation of low flows and over simulation of high flows), the Sacramento model percolation curve can be shifted upwards or downwards. This is done by changing LZFWM and LZFPM by the same ratio.

If any of these changes are made, it is important to make sure that the resulting values are physically reasonable compared to those for nearby drainage areas.

In this situation most of the effort is involved in calculating the "observed" flow to use and/or in determining parameters for the routing, reservoir, irrigation, or diversion models. The data are not of sufficient quality to allow for many changes to the snow, soil moisture, and local channel response models.

b. Historical Simulation Not Possible – A historical simulation is not possible when there is insufficient information to compute inflows to a reservoir, adjust discharges to natural flow conditions, or model everything of significance that occurred within the drainage area. In many of these cases the information and data necessary to simulate streamflow are available for operational forecasting use, but not historically. In a few cases the data may exist, but the method of operating the control structures are not included in any available modeling operation. One option in these cases is to add a new operation to NWSRFS that will handle the situation. When historical simulation is not possible at a given location within the river basin, the snow, soil moisture, and channel model parameters that were assigned to the drainage area cannot be adjusted. Also, simulated and adjusted instantaneous flows cannot be computed in the normal manner for routing to subsequent downstream locations. In these cases, instantaneous discharges must be generated from mean daily observed flows at the downstream location using the special feature in the CHANGE-T operation for use in calibrating the next point down the river system.

Section 7-4

Initial Parameter Values for the SNOW-17 Model

Introduction

This section provides guidelines for assigning initial parameter values for the SNOW-17 snow accumulation and ablation model. These guidelines can also be used as an indication of whether parameter values being used for a given watershed or subarea are physically realistic. The snow model parameters are related to the physical and climatic features of the area being modeled. The main physical features that are important are vegetation cover and terrain features such as slope and aspect. The main climatic features are the typical amount of snow cover and the prevailing winter temperatures.

This section doesn't attempt to define the structure or the algorithms of the model. Readers are referred to section II.2-SNOW-17 of the NWSRFS Users Manual for a complete model description.

Form of Precipitation

The form of precipitation, i.e. rain or snow, can be specified in one of three ways for the SNOW-17 model. The methods of determining the form of the precipitation are:

1. By a threshold temperature which is the parameter PXTEMP. If the air temperature for the current time interval is less than or equal to PXTEMP, then the precipitation is assumed to be snow. If the temperature is greater than PXTEMP, then the precipitation is treated as rain.

2. By a rain-snow elevation time series. This time series specifies the elevation above which snowfall is occurring and below which the precipitation is in the form of rain. In this case an area-elevation curve is input to the snow model so that the fraction of the area with snow and the fraction with rain can be computed based on the rain-snow elevation value for each time interval. The rain-snow elevation time series can be generated by the RSNWELEV operation in NWSRFS. This operation uses either an air temperature time series for a specified elevation or a freezing level time series along with a user specified lapse rate and the PXTEMP parameter to calculate the elevation at which the PXTEMP temperature value occurs. The equation used by the RSNWELEV operation is:

$$E_{rs} = E_v + ((T_v - PXTEMP) \cdot (100/L_p)) \qquad (7\text{-}4\text{-}1)$$

where: E_{rs} = Rain-snow elevation (m),
E_v = Elevation associated with T (m),
T_v = Temperature at elevation E (°C),
L_p = Lapse rate during precipitation (°C/100m).

When air temperature is the input variable, T_v is the temperature for the time interval and E_v is the elevation associated with the time series. When freezing level is the input variable, E_v is the freezing level elevation and T_v is 0°C. The lapse rate used is typically the saturated adiabatic lapse rate (0.55°C/100 m or about 3°F/1000 ft) since the only relevant time periods are those when precipitation is occurring. If the value of the rain-snow elevation is missing for a given time interval, then method #1 is used to specify whether all the precipitation is rain or snow.

Generally when calibrating an MAT time series is used as the input to the RSNWELEV operation since historical freezing level data are seldom available. For watersheds with multiple elevation zones there is a question as to which MAT time series should be used to determine the rain-snow elevation for each zone. Physically there is only one rain-snow elevation for the watershed for a given time interval. This would suggest using the MAT time series for only one of the zones to compute a single rain-snow elevation to be used by all the zones. However, for example, if the rain-snow line was near the mid-point of the upper elevation zone and the MAT for the lower zone was being used to calculate the rain-snow line, the lapse rate would be applied over a considerable elevation range which would likely result in a less accurate estimate of the rain-snow line than if the upper area MAT was being used. This would suggest using the MAT time series for each elevation zone to compute the rain-snow elevation for that zone to minimize the elevation range over which the lapse rate was being applied. In this case when the actual rain-snow elevation is within a given elevation zone, the MAT for that zone would be used to estimate the elevation and although different rain-snow elevations would be calculated for the other zones, they would generally be outside the elevation range of those zones and not affect the form of the precipitation. Which MAT time series are used to estimate the rain-snow elevation for watersheds with multiple elevation zones is also dependent on the elevations of the stations used to compute the MAT values for each zone. If a zone has no temperature stations within its elevation range, the MAT has been calculated by applying seasonally varying lapse rates over a large elevation difference, and not the saturated adiabatic lapse rate. In this case, the MAT could be more likely to be in error during periods when precipitation occurs.

Based on the discussion in the previous paragraph, the following recommendations are offered for computing rain-snow elevations for watersheds with multiple elevation zones for use during calibration.

- If there are actual temperature stations within an elevation zone that were used to compute MAT, then the MAT time series for that zone should be used to calculate the rain-snow elevation for the zone.

- If there are no temperature stations within an elevation zone that were used to compute the MAT for the zone, then the MAT time series for the zone that has the smallest elevation difference to the zone in question and has actual temperature stations within its elevation range should be used to compute the rain-snow elevation.

Operationally a single rain-snow elevation should be used for all elevation zones so that only one value has to be changed to alter the division between rain and snow.

3. A time series can be used to specify the fraction of the precipitation that is in the form of snow during a given time interval. This time series is referred to as a percent snowfall time series. The values assigned to this time series are generated outside of the operations table. Historically the information needed to specify the form of precipitation might only be available for a research location. Operationally a procedure involving meteorological data, observations of the form of precipitation, and forecaster interaction could be devised to produce a percent snowfall time series. If the percent snowfall value is missing for any time interval, then method #1 is used to determining if all the precipitation is rain or snow.

Most studies have indicated that a reasonable threshold temperature for separating rain from snow is around 1 - 1.5°C. The Snow Hydrology manual indicates about 45% snow, 25% mixed, and 30% rain at 34°F and 33% snow, 17% mixed, and 50% rain at 35°F. The Snow Hydrology manual also shows cases of rain occurring when the surface temperature is 29°F and snow at 40°F. In the intermountain west, at least at higher elevations, winter precipitation is almost always in the form of snow even when the temperature is near 40°F. Usually in this region the temperature drops fairly quickly after the onset of snowfall, but it may be fairly warm when the event begins. It is clear that air temperature measured at ground level is not a perfect indicator of the form of precipitation. In NWSRFS the problem is compounded by only using max/min air temperature to compute historical MAT time series. The assumptions of when the max and min occur and the use of a fixed diurnal temperature variation result in incorrect temperature values during certain periods (see section titled "Limitation of Current NWSRFS Historical MAT Program" in Section 6-4). This most commonly occurs when temperatures are changing substantially from one day to the next which typically occurs with a frontal passage which is also when precipitation is most likely. From experience it is clear that the use of historical MAT values computed from only max/min temperature results in more cases of the form of precipitation being in error than the use of a threshold temperature to separate rain from snow. The use of the threshold temperature in the snow model to determine the form of precipitation should be less of a problem operationally because the OFS MAT preprocessor uses both instantaneous and max/min temperature data during the observed data period. The instantaneous temperatures are used to determine the daily temperature variation for stations that only report max/min values.

It is recommended that a value of PXTEMP in the range of 0.5 to 2.0°C be used with the SNOW-17 model. Generally a value of 1.0°C should be adequate. In many intermountain west areas it may be necessary to use a considerably higher value, in the range of 3-5°C in order to minimize errors in the form of precipitation (in this region temperatures frequently go well above freezing during portions of days with snow showers, however, the temperature drops back to near freezing whenever the precipitation intensifies and generally in the winter and early spring all precipitation is in the form of snow). It is also recommended that once a value of PXTEMP is established for a given region, that it should be used for all areas within the region. It is not worth the effort to try to varying PXTEMP for each area to try to get a near equal number of cases when rain should have been snow and vice versa. Since most of the problems are caused by the use of only max/min temperatures, varying PXTEMP is generally not very productive. The use of only max/min temperatures also results in a bias in the form of precipitation determination in many regions, e.g. errors in the daily temperature variation result in more cases of rain being typed as snow than vice versa. Thus, there is a built-in bias that varying PXTEMP cannot correct. It is best to assign a reasonable value to PXTEMP and then correct the form of precipitation for individual events as needed. Also operationally it is much easier to deal with a single value of PXTEMP for all areas in a given region than to have to remember or look up a unique value for each area.

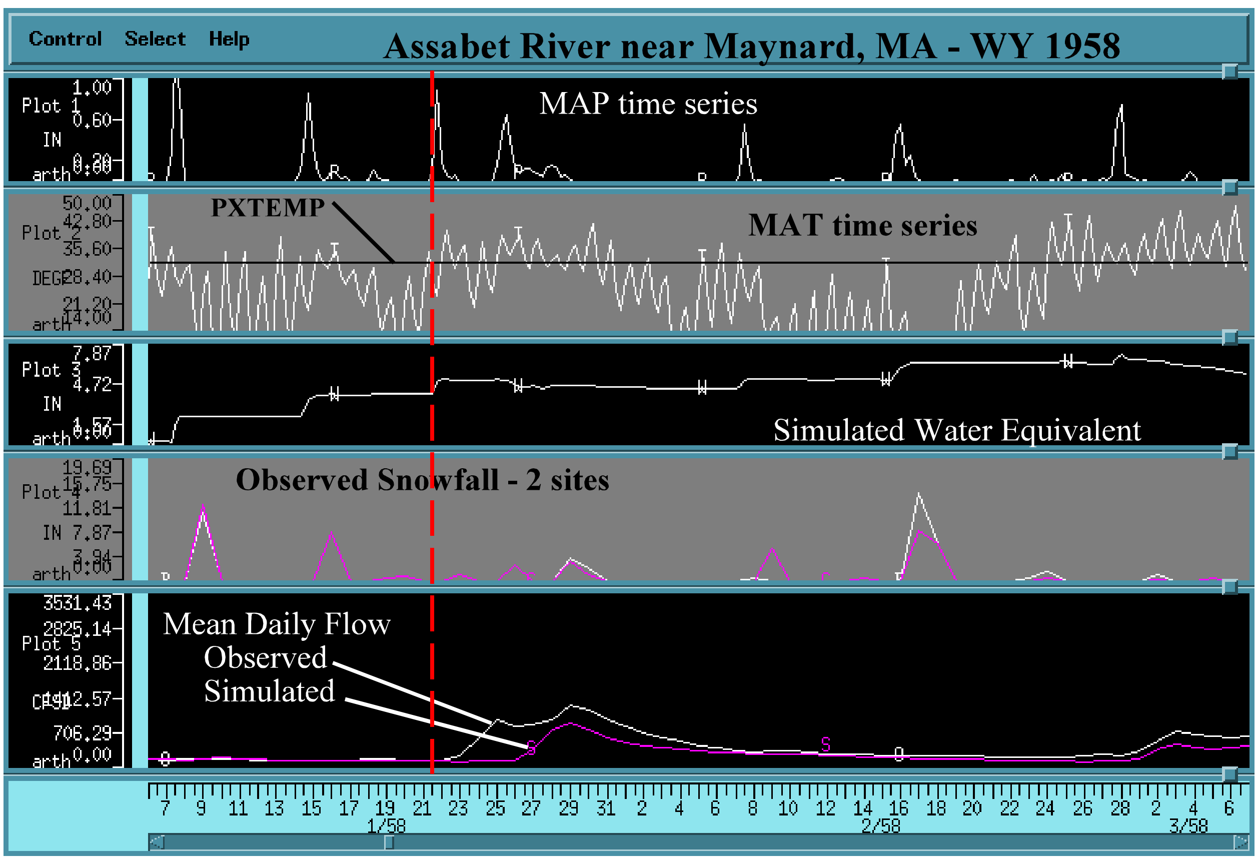
From a calibration standpoint, it is only necessary to correct the form of precipitation for individual events when the mistyping causes so much simulation noise that it is impossible to determine the other model parameters with confidence. Obviously having the correct form of precipitation for all events will produce the best results and minimize goodness of fit statistics, however, the aim of calibration is to determine the proper parameter values for operational use and not to minimize certain statistics. Thus, the form of precipitation only needs to be corrected for individual events when errors interfere with determining the proper values of other snow model parameters and parameters for the other models being used. It is not cheating to correct the form of precipitation when it interferes with determining parameter values. Operationally there should be much more information available, besides air temperature, to indicate whether it is raining or snowing at a given location. In many regions, especially those with temperatures below freezing during most precipitation events such as the north central states, the intermountain west, and Alaska, it is necessary to correct the form of precipitation for few, if any, events. Only events with a large of amount of precipitation that is in the wrong form typically need to be corrected in these regions. In other regions, where the temperature is frequently near freezing during periods of precipitation, there can be many events where the form of the precipitation is mistyped. This case is very common in the northeastern part of the United States. There can also be problems with the division of rain and snow west of the Cascade Range in the Pacific northwest due to errors in the diurnal temperature variation. In this region the rain-snow elevation option is generally used to separate rain from snow since rain occurs during most winter events at lower elevations whereas it is snowing higher up in the mountains.

Correcting the form of precipitation is also needed when the historical time series are to be used for ESP applications. For calibration, significant errors in the form of precipitation only need to be corrected for the period used to calibrate the models. For ESP applications, the entire historical period of record should be corrected. If not, bias produced by an improper assignment of the form of precipitation will influence the probabilistic distribution of the ESP products. It is probably only necessary to correct larger events that are in error, just like calibration. Errors in small events shouldn’t affect the probability distributions generated by an ESP application. It is especially important to correct the form of precipitation for watersheds where there is a tendency for the errors to be dominantly in one direction (e.g. many more cases of rain treated as snow than vice versa).

When attempting to correct the form of precipitation it should be done in a systematic manner and with as much information as possible to support any changes that are made. The form should not be changed just to get a better fit between simulated and observed flow values. Generally the form of precipitation is altered by changing the MAT value for one or more time intervals. The information that can be used to support the decision includes streamflow response, snowfall observations, and water equivalent and depth data. In data sparse regions, such as portions of Alaska, the decision may have to be solely based on streamflow response since the other data are not available. In that case changes should only be made when the streamflow response clearly indicates that the form of precipitation is most likely in error.

The use of the PLOT-TS display in ICP can be very helpful when trying to determine when the form of precipitation is in error and what MAT values need to be changed to correct the problem. All of the data needed to decide whether the form of precipitation as determined by the model is correct or whether it needs to be changed can be shown on a single display. Figure 7-4-1 shows an example of such a PLOT-TS display. In this case 5 plots are included. The top plot shows the 6 hourly MAP time series. The next plot down contains the 6 hourly MAT values. The next plot is the 6 hourly simulated water equivalent. The next plot is daily snowfall observations from 2 climatological stations near the watershed. The bottom plot shows the resulting simulated and

Figure 7-4-1 Sample display for validating form of precipitation determination in model.



observed mean daily flow. The exact value and time of any plotted value can be displayed by clicking on the display. By examining all of this information it can be decided as to whether the form of precipitation needs to be altered. For example, in the figure during the first period on the 22^{nd} of January a large amount of precipitation is typed as snow since the MAT value is well below PXTEMP. This causes the simulated water equivalent to increase. However, the climate observers reported very little snowfall during the event and the observed streamflow showed a considerable increase in the subsequent days, both indicating that the precipitation was most likely predominately rain. Thus, the MAT value was changed to be greater than PXTEMP with an editor. The MAT was most likely in error during this case due to the minimum temperature recorded on the morning of the 22^{nd} actually occurring on the previous morning. By proceeding through the period of record using such a display, problems caused by the form of precipitation being in error can be systematically corrected before continuing with the calibration.

Major Snow Model Parameters

The major parameters of the SNOW-17 model are the snow correction factor SCF, the non-rain melt factors MFMAX and MFMIN, the areal depletion curve and the related SI parameter, and sometimes the average wind function during rain-on-snow events UADJ. These are the parameters that typically have the greatest effect on model results and are the only ones generally modified during calibration.

SCF – SCF is the only parameter in the snow model that has a significant effect on the volume of water available for snowmelt runoff. It is used to adjust any precipitation that is typed as snow. The main reason for SCF is that most precipitation gages under catch snowfall as shown in Figure 7-4-2. The under catch is related to the wind speed at the orifice of the gage and the effect can be reduced by the installation of a windshield. The wind speed at the gage is influenced greatly by the exposure of the site. Most climatological stations are situated where there is protection from the wind whenever possible. A site with a good exposure doesn't need a windshield. Of course the MAP time series generally involves the weighing of a number of gages with different exposures and possibly some with and some without windshields.

The SCF parameter is related to the average wind effect on snowfall catch over all the events during the period of record. The catch deficiency varies from event to event, and even within an event, as the wind speed at the orifice changes. If there are a large number of events involved in the build up of the snow cover, the effect of variations in catch deficiency from event to event tend to cancel out, though there may be some years when there is more wind during snow storms than other years.

Besides explicitly trying to account for the average catch deficiency during snowfall events, the SCF parameter implicitly includes other factors that affect the accumulation of a snow cover that are not included in the snow model. This includes sublimation losses, both from

the snow surface,
from snow
intercepte d by the
forest, and
from wind
blown snow,
and snow

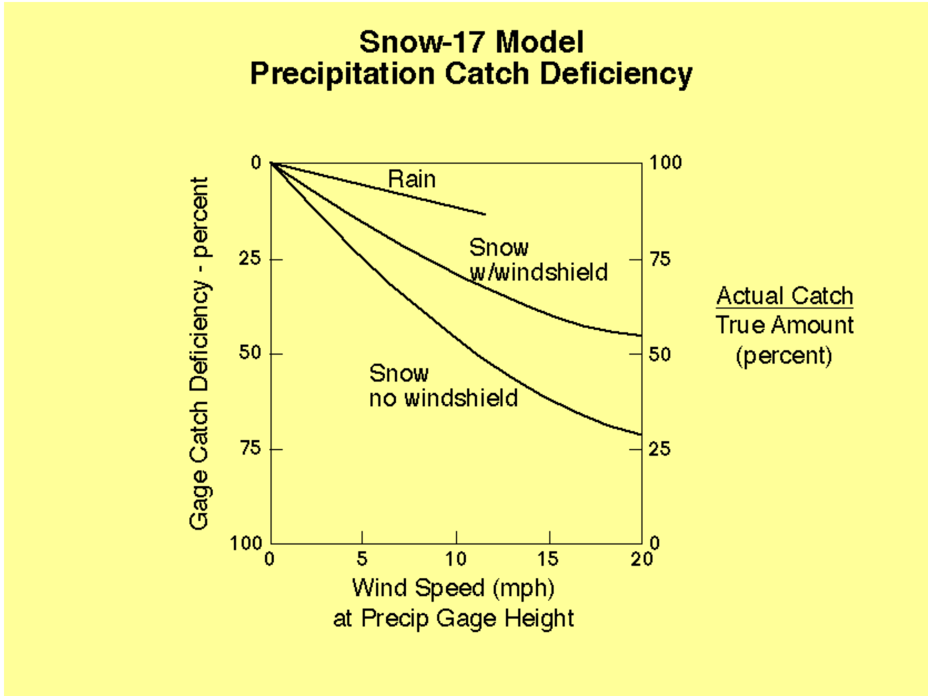


Figure 7-4-2. Typical precipitation catch deficiency due to wind.

blown across the watershed divide. Sublimation losses tend to be small in most areas, but can be moderately significant in places with low humidity and high wind speeds during the winter. Generally the amount of snow transported from one watershed to another is negligible in most regions.

After considering all these factors, a reasonable initial value for the SCF parameter is in the range of 1.1 - 1.2. Higher values would be expected in watersheds where there are few gage locations with good exposures such as in the northern plains. In such a region SCF values could start in the range of 1.3 - 1.6. In regions where all the precipitation stations have good exposures and there are significant sublimation losses, SCF could be equal to 1.0 or even slightly less without being physically unrealistic.

The value of SCF can also be affected by whether water balance computations were used to determine the magnitude of the MAP input for the model. When mean annual precipitation is estimated directly from the water balance as in the method described in Section 6-3 under "Determination of the Average Mean Areal Precipitation in Data Sparse Regions", the processes related to SCF are implicitly absorbed in the MAP values. In this case in order for the precipitation used by the model to be the same as the amount computed by the water balance, SCF should be initially set to 1.0. Since gage catch deficiencies are not considered when deriving the average annual precipitation with this method, the net result could be not enough snowfall and too much rain. When a water balance analysis is used primarily to identify portions of the basin where the isohyetal analysis needs to be modified as described in Section 6-3 under 'Determination of Average Mean Areal Precipitation for Each MAP Area", there is less chance that the value of SCF will be affected. In any case SCF should not be used in regions dominated by snowmelt runoff to correct for volume problems resulting from an inadequate precipitation analysis.

MFMAX and MFMIN – These are the maximum and minimum values of the seasonally varying non-rain melt factor. MFMAX occurs on June 21st and MFMIN on December 21st. In regions where the snow cover generally builds up throughout the winter and doesn't melt until mid or late spring, MFMAX dominates the computations of melt. In regions where snowmelt periods can occur anytime throughout the cold season, both factors are important.

The non-rain melt factor determines the melt rate when the area is completely covered by snow, thus it has a controlling effect from when melt first begins until significant bare ground exists. This melt factor is based on the average relationship between air temperature and melt at the surface of the snow cover over the entire period of record. It is to be expected that there will be situations when the actual melt rate is greater or less than the average. Adjustments can be made during these situations operationally as discussed in Section 8-1, but during calibration it is the average melt rate that is sought. The average value of the melt factors are physically related to forest cover, slope and aspect, and typical meteorological conditions. Some items to consider when choosing or evaluating values for the melt factors are:

- If an area had an extremely dense forest cover, i.e. so dense that no sunlight reached the forest floor and calm conditions always prevailed such that only longwave radiation exchange between the forest canopy and the snow below caused melt, a lower limit for the melt factor could be computed. This value would be about 0.32 mm/°C/6 hr and there would be no seasonal variation. Such a situation doesn't exist for an area of any reasonable size.

- If a region, such as the north Pacific coast, has persistent cloud cover most of the time, this will act similarly to a dense forest cover. It would be expected that the maximum melt rate would be relatively low and there wouldn't be a pronounced difference between MFMAX and MFMIN. If cloud cover generally persists for some months, but not for others, the seasonal melt factor variations built into the model (normal sinusoidal or Alaska, northern latitude, pattern) may not be appropriate. In this situation there is an option in the SNOW-17 operation for the user to specify the seasonal variation pattern. This option should be used only when it can be substantiated that the seasonal variations built into the model are not adequate.

• The melt rate should be the greatest for a large open area in a region where dew-points typically exceed 0°C and windy conditions prevail during periods of substantial melt. In such an area all forms of energy exchange could contribute to melt. In general, in an area with low humidity, solar radiation will be the dominate cause of melt as atmospheric radiation will be less than that emitted by the snow surface due to generally clearer skies and negative latent heat exchange will tend to offset positive sensible heat exchange. This would result in a lower average melt rate than for an area with generally higher humidity for the same amount and type of forest cover.

• Open zones in the mountains, such as above tree line, generally have lower melt rates than a flat open area due to variations of slope and aspect caused by the rugged terrain. This is especially true early in the melt season when the non-rain melt factor controls the computations as melt is typically not occurring over an entire mountainous zone.

•In northern and high elevation regions where the snow ages slowly and melt seldom occurs during the mid-winter period, the MFMIN parameter will tend to have lower values than in regions where substantial melt frequently occurs at various times throughout the winter.

• The largest ratio of MFMAX to MFMIN should occur in mostly open areas in regions with generally low humidity levels and infrequent mid-winter melt periods, such as high elevation zones of the intermountain west, portions of interior Alaska, and other places where MFMIN tends to have low values. The smallest ratios of MFMAX to MFMIN are expected in heavily forested areas in regions with more humid climates and periodic mid-winter melt, such as coastal areas and much of the eastern continental United States.

Based on these considerations and prior calibration results the following recommendations are offered for selecting initial values for the MFMAX and MFMIN parameters.

Description of Area	MFMAX	MFMIN
Dense conifer forest or persistent cloud cover	0.5 - 0.7	0.2 - 0.4
Mixed cover - conifer, deciduous, open	0.8 - 1.2	0.1 - 0.3
Mostly deciduous	1.0 - 1.4	0.2 - 0.6
Mostly Open		
flat terrain	1.5 - 2.2	0.2 - 0.6
mountainous terrain	0.9 - 1.3	0.1 - 0.3

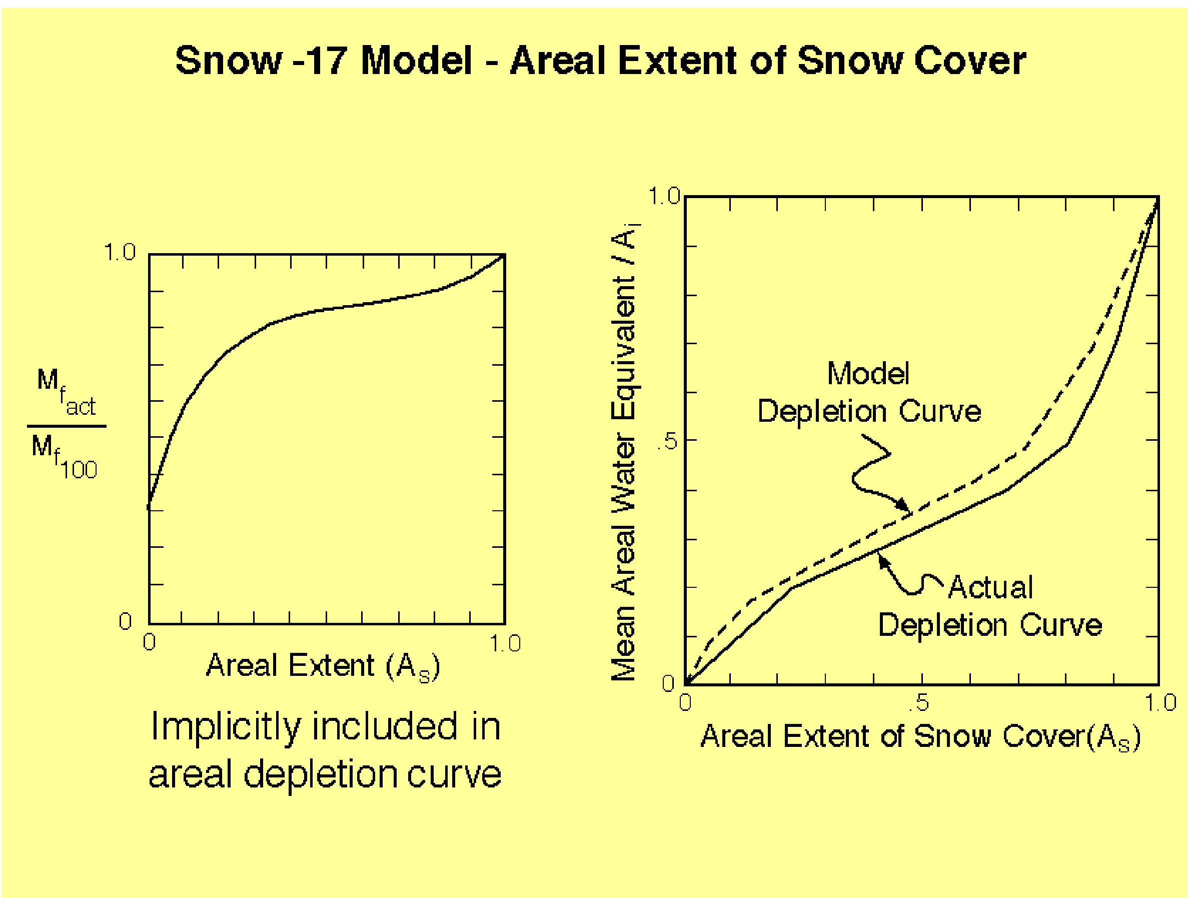
Table 7-4-1. Suggested initial values for MFMAX and MFMIN.

These guidelines can also be used to decide if the parameter values determined during calibration are reasonable. If the calibrated values fall significantly outside these ranges, it could be due to biased temperature data, i.e. the MAT values being used are warmer or cooler than what actually occurred in nature.

Areal Depletion Curve -- The areal depletion curve controls the melt rate when only portions of the area being modeled are covered by snow. The idea behind the areal depletion curve is that the pattern of snow accumulation and ablation is similar from one year to the next. For example, during the accumulation period the variation in the amount of snow on the ground, including the location of drifts and shallow places, is similar each year due to terrain and vegetation effects and prevailing storm and wind directions. Also, the melt pattern is similar with lower elevation, south facing, bare slopes melting first and higher elevation, north facing, forested or sheltered areas retaining snow the longest. The main function of the depletion curve is to account for how much of the area is covered by snow, however, like in any conceptual model, everything that is occurring in nature is not explicitly being modeled. Besides accounting for the areal extent of the snow cover, the depletion curve also absorbs variations in the melt rate over the snow covered portion of the area. The non-rain melt factor determines the melt rate when there is 100 percent cover, but as the snow cover depletes the melt rate over the area that still has snow is reduced. This occurs because the portions of the area with the highest melt rates, such as south facing slopes, typically go bare first. The areas where snow generally remains the longest are forested or sheltered north facing slopes with much lower melt rates. This variation in melt rates ends up being

Figure 7-4-3. Model versus actual snow cover depletion curve.

implicitly included in the areal depletion curve. Thus, the areal depletion curve is really calculating an "effective" areal extent of snow cover and not the actual areal extent. This is illustrated in Figure 7-4-3. This figure shows a possible variation in the ratio of the actual melt rate $\left(M_{f_{act}}\right)$ to the 100 percent cover rate $\left(M_{f_{100}}\right)$ as a function of the areal extent of the snow cover and how that relationship would cause the depletion curve needed by the model to differ from that which would be constructed based on detailed measurements of water equivalent and the fraction of the areal actually covered by snow. The areal depletion curve for the model should indicate a lower areal extent of snow cover than would be determined by satellite or other aerial observations.



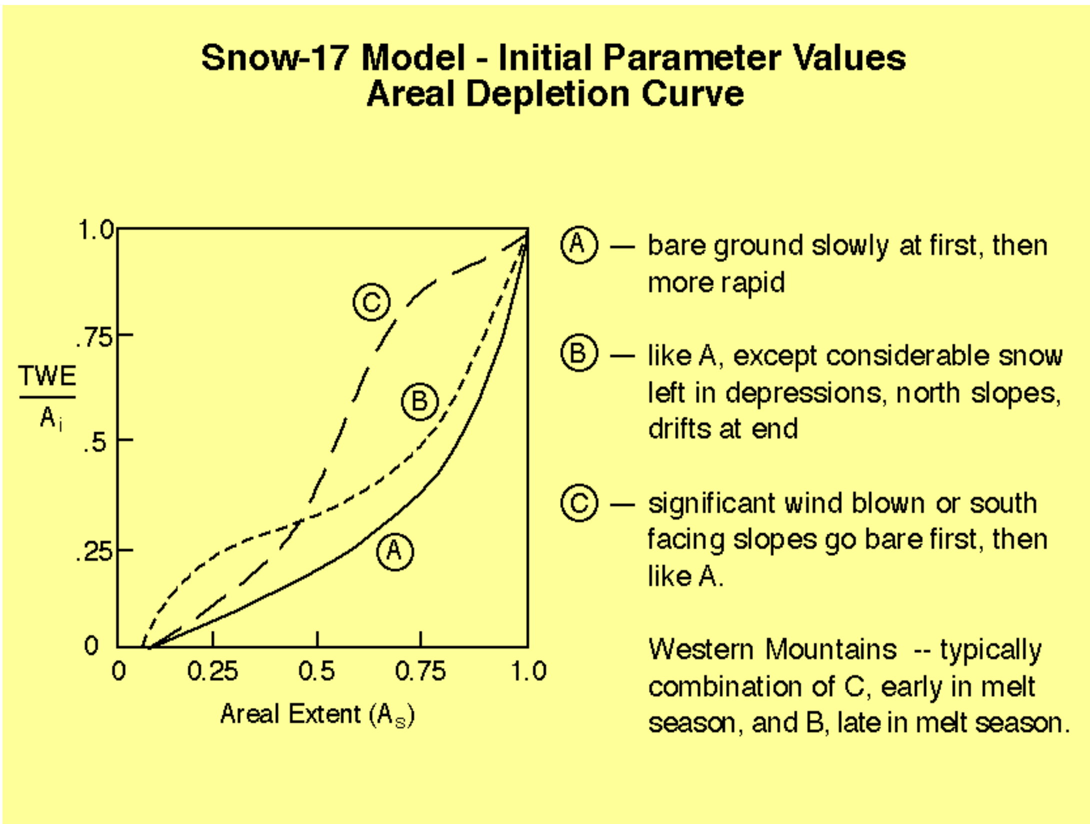


Figure 7-4-4. Typical shapes of areal depletion curves.

The factors that affect both the pattern of areal snow cover and the variation in melt rates as the snow cover depletes are primarily controlled by terrain, vegetation, and climatic conditions. Thus, the shape of the areal depletion curve for a given area can be estimated based on a knowledge of these factors. Figure 7-4-4 shows some typical shapes for areal depletion curves. The "A" curve represents an area with generally flat to hilly terrain, either uniform or randomly mixed vegetation cover, and not an excessive amount of redistribution of snow due to blowing and drifting. In this case bare ground shows up slowly at first and then more rapidly as the snow cover depletes. Curve "B" represents a flat to hilly area where the terrain and redistribution pattern results in portions of the area having more snow, typically in sheltered depressions or drifts, than other parts. These parts of the area with disproportionally more snow are typically the last portions to go bare. Curve “C” represents an area that has windblown portions with little snow cover or significant south facing slopes that go bare fairly quickly after melt begins. Thus, the areal cover depletes rapidly at first and then the remaining portion of the area has a depletion pattern similar to the “A” curve. Mountainous regions, especially in the western states and Alaska, typically have a depletion curve that is a combination of the “B” and “C” curves. In the mountains there are frequently portions of the area with south facing slopes or shallow cover due to wind effects that go bare quickly after melt begins and also sheltered depressions and conifer forested, north facing slopes that still retain snow well after most of the area is bare.

SI – The SI parameter is the mean areal water equivalent above which the area essentially has 100% snow cover. The easiest way to determine the appropriate value for SI is to set the initial value greater than any average areal water equivalent that ever occurs during the period of record. Then during calibration the years with the greatest amount of snow are examined to determine if the areal cover needs to remain at 100% for some time period after the beginning of melt. By analyzing these years as described in Section 7-7 one can arrive at the value to assign to the SI parameter. Typically the initial SI is set to 999 mm or 9999 mm depending on the amount of water equivalent expected. By using all 9's for the initial value, it is easy to later tell whether a value for the SI parameter was assigned during calibration or whether bare ground begins to show as soon as melt starts every year, i.e. the area doesn’t remain at 100% cover once melt starts and thus the value of SI is left as all 9's.

UADJ – The UADJ parameter represents the average wind function during rain-on-snow events. The wind function is involved in the latent and sensible heat, i.e. turbulent transfer, terms in the energy balance. The UADJ parameter will not affect the longwave radiation and heat from rain water terms in the rain-on-snow melt equation used in the model. Based on energy balance studies [*Anderson*, 1976] the wind function parameter can be computed as:

$$UADJ = 0.002 \cdot u_1 \qquad (7\text{-}4\text{-}1)$$

where: u_1 = 6 hr. wind travel in km at a 1 meter height above the snow surface.

Thus, if one can estimate the average wind speed over the entire area being modeled during significant rain-on-snow events at one meter above the snow surface, then an initial value for UADJ can be computed. Significant rain-on-snow events are those that occur when the air temperature is well above freezing. Clearly it is difficult to estimate the average wind speed at one meter for a forested, mountain watershed, but generally a rough guess is sufficient for an initial value. Also the UADJ parameter is not real sensitive for most regions. Typical values for UADJ range from about 0.05 (2.5 mi/hr wind speed) to 0.20 (10 mi/hr wind speed). Forested areas will tend to have lower wind speeds than mostly open areas.

Minor Snow Model Parameters

The remaining parameters in the snow model are assigned based on climatic information and are typically not changed during the calibration process. These parameters generally do not have a very significant effect on the simulation results as long as the value is in the right ballpark.

TIPM – The TIPM parameter is used to compute an antecedent temperature index that is intended to represent the temperature inside the snow cover but near the surface. The gradient defined by the antecedent index and the air temperature (used to estimate the temperature at the snow surface) determines the direction of heat flow during periods when melt is not occurring. The lower the value of TIPM the more weight is assigned to the temperatures from previous time intervals and the antecedent index then represents the temperature of the snow further below the surface. For areas with generally shallow snow cover the antecedent index should represent a temperature fairly close to the surface in order to best estimate the direction of heat flow. For regions that typically have a deep pack, the antecedent index should represent the temperature further below the snow surface. It is recommended that a value of TIPM = 0.05 be used for areas that experience a deep snow cover (greater than 3 feet maximum depth during most years). A value of TIPM = 0.20 is appropriate for areas with shallow (generally less than 1 foot depth) or intermittent snow cover. Intermediate values should be used for other areas.

NMF – The negative melt factor determines the amount of energy exchange that occurs when melt is not taking place at the snow surface. The NMF parameter is the maximum value of the negative melt factor. The seasonal variation in the negative melt factor is the same as for the non-rain melt factor. A seasonal variation is needed since density is the primary factor that affects the thermal conductivity of the snow and the snow density generally varies in a seasonal manner. The density is lowest during periods of accumulation and increases as the snow ages during melt periods. Simplified heat transfer calculations indicate that a reasonable value for NMF is around 0.15 mm/°C/6 hr. This value is generally independent of the typical amount of snow that occurs in an area. It is based on a maximum snow density of 0.3 for shallow snow cover and 0.5 for a deep pack. If an area generally has a maximum density less than these values, NMF should be decreased and if the maximum density is typically greater than these values, NMF would be increased. A maximum reasonable range for the NMF parameter is from 0.05 to 0.30.

MBASE – The MBASE parameter is the base temperature used to determine the temperature gradient for non-rain melt computations. When modeling an area with a variety of vegetation cover, slopes, and aspects, the value of MBASE is almost always 0°C. This includes most watersheds where snowmelt runoff is significant. Generally if a non 0°C value of MBASE is needed for most watersheds in order to properly simulate snowmelt, there is a good chance that there is a bias or error in the MAT computations. Thus, before using a non 0°C value for MBASE, in most cases, one should carefully check and reevaluate the MAT calculations. There is a chance that a MBASE greater than 0°C is needed in high elevation, open areas with generally clear skies and relatively low humidity during the melt season. Under such conditions negative longwave radiation and latent heat exchange can offset solar radiation and sensible heat exchange at temperatures slightly above 0°C during the day and refreezing of the water in the upper snow layers occurs at night even though the temperature is above freezing. MBASE values greater than 0°C are frequently needed when applying the snow model to a open, high elevation point location such as a snow course site. Non 0°C values are also frequently needed when modeling other point locations due to site specific factors that control the relationship between measured air temperature and melt amounts.

PLWHC – The PLWHC parameter controls the maximum amount of liquid water that can be retained within the snow cover expressed as a decimal fraction of the amount of ice in the snow cover. The PLWHC parameter should be selected based on ripe snow cover conditions, i.e. the snow is well aged, isothermal at 0°C, and has its liquid water capacity full. Fresh (i.e. newly fallen, low density snow) snow can hold more liquid water than ripe snow, however, the existence of the liquid water will cause metamorphism to begin and within hours, if sufficient water is applied, the snow will become ripe. Most studies indicate that the maximum liquid water holding capacity for ripe snow is in the order of 2 to 5 percent. Thus, the PLWHC parameter should be assigned a value in the range of 0.02 to 0.05 with generally the lowest values being used for areas with very deep snow covers. In addition to snow retaining liquid water throughout the pack, a slush layer generally builds up at the snow-soil interface. For a deep snow cover the amount of water held in this slush layer is inconsequential, but for a shallow snow cover it can be significant. To account for the slush layer, it has been found that in areas with shallow snow covers, especially in the plains and open agricultural areas of the midwest, that a higher value is needed for the PLWHC parameter in order to properly delay the onset of melt water entering the soil. In such areas values for PLWHC in the range of 0.1 to 0.3 are quite common.

DAYGM – The DAYGM parameter controls the amount of melt per day that occurs at the snow-soil interface. This is a constant amount of melt that takes place whenever there is a snow cover. The following values are recommended for the DAYGM parameter:

DAYGM = 0.0 for areas with generally frozen soils under the snow, and
DAYGM = 0.3 for areas with intermittent snow cover or with fairly temperate climates, such as the Sierra Nevada mountains in California, during the winter.

Other areas would use DAYGM values somewhere in between these limits.

Section 7-5

Initial Parameter Values for the Sacramento Model

Introduction

In most cases initial parameter values for the Sacramento Model are obtained from a nearby previously calibrated watershed. This can be a watershed within the river basin being worked on or one in an adjacent river basin that has previously been calibrated. However, when calibrating the initial headwater area in a river basin where no nearby watersheds, or at least none with physiographic features at all similar to the current area, have been previously calibrated, initial parameter estimates should be derived. Procedures are available for obtaining initial parameter estimates from an analysis of the observed daily flow hydrograph and from soils information.

Besides providing recommendations for deriving initial parameter values, this section also contains information on the physical basis for some of the parameters. This information should help in better understanding of how the model works and provide a basis for possibly altering parameters from one area to another based on physical characteristics. The portions of the section that describe how to determine parameter values from a hydrograph analysis should also help in understanding what to look for in order to isolate the effects of many of the parameters. Section 7-8 focuses on how to isolate the effect of each parameter, but the material in this section should provide some added emphasis to understanding this critical aspect of interactive calibration of a conceptual model. This section doesn't attempt to describe the structure and algorithms of the Sacramento model. For that information the reader is referred to Part II.3-SAC-SMA of the NWSRFS Users Manual.

Before describing the techniques for deriving initial parameter estimates, we first need to talk about how the various runoff components of the Sacramento model are going to be used to reproduce the hydrograph for the watershed. It is very important to take some time prior to starting the calibration to examine the various runoff time delay segments that are represented in the hydrograph and decide which runoff component is to be assigned to each segment. This effort should provide the best chance for obtaining good results in the least amount of time. If the runoff components are not assigned properly at the beginning, considerable time can be wasted modifying the parameter values once one realizes that the runoff components are not being used correctly.

Assigning Runoff Components

The Sacramento model contains 4 basic runoff components with various time delays that can be used to represent the various portions of the hydrograph. These are primary baseflow, supplemental baseflow, interflow, and surface runoff. The model is designed so that the longest time delay, usually in terms of months or years, is assigned to primary baseflow. Supplemental baseflow generally has a time delay in terms of weeks or months and interflow typically has a time delay in terms of days. Surface runoff has no time delay in the Sacramento model, i.e. it becomes inflow to the channel during the same time interval as the rain or melt that produced it. The Sacramento model can also generate constant and variable impervious area runoff components. Both of these respond immediately just like surface runoff. Variable impervious runoff can be produced from low intensity rain or melt when the watershed is quite saturated. Constant impervious runoff can occur whenever there is rain or melt no matter what the soil moisture conditions. An analysis of the hydrograph may determine if these two additional components will be needed, but primarily at this stage of the calibration we are trying to decide which portions of the hydrograph will be assigned to each of the 4 main runoff components.

The first step in this process is to identify when primary baseflow is the only or at least the dominant source of runoff. Primary baseflow typically sustains flow in the channel long after any events that produced storm runoff have occurred and after perched, or supplemental, aquifers have been drained. Primary baseflow is used to represent the flow segment with the longest time delay. It is critical to properly identify what portion of the hydrograph represents primary baseflow because the time delays for the other runoff components are all going to be based on this determination. The segment of the hydrograph with the next slowest time delay will be assigned to be modeled with supplemental baseflow and then the next slowest with interflow. Surface runoff can only be used to produce immediate storm runoff from high intensity events. Periods of surface runoff can usually be identified by comparing the immediate amount of storm runoff to the amount of rain plus melt (the period for determining the amount of immediate storm runoff is dependent on the response time of the channel system as represented by the unit hydrograph -- initial snow model parameters are used to get an idea as to the amount of melt). If the amount of immediate storm runoff is around 50% or more of the rain plus melt, then it is likely that surface runoff needs to be generated for these events. Identifying what runoff component will be used to represent each portion of the hydrograph prior to beginning the calibration should insure that all the components are used properly and that the various time delays that occur can each be modeled.

In some regions it is quite easy to identify which runoff component will be used to model each portion of the hydrograph. If the time delays for each runoff component are close to typical values, there are sufficiently long dry periods after major events to allow for a clear identification of interflow and supplemental baseflow recessions, and there are also some even longer dry periods when primary baseflow becomes the only component with no distortions of the flow during these periods, the runoff components can be fairly easily identified. However, in many regions, probably the majority, there are complications that make it more difficult to clearly identify what portion of the hydrograph represents each component of runoff, especially to properly identify primary baseflow. Primary baseflow becomes more difficult to identify in very wet regions, when frequent small rains occur during low flow periods, when the supplemental baseflow recession is very slow, and when riparian vegetation evaporation draws down the flow during dry periods.

Figure 7-5-1 illustrates the case of assigning runoff components in a very wet region. In such a region rainfall or snowmelt occurs frequently and soil moisture conditions remain quite wet. Dry periods that exist for a long enough time so that primary baseflow predominates only occur on

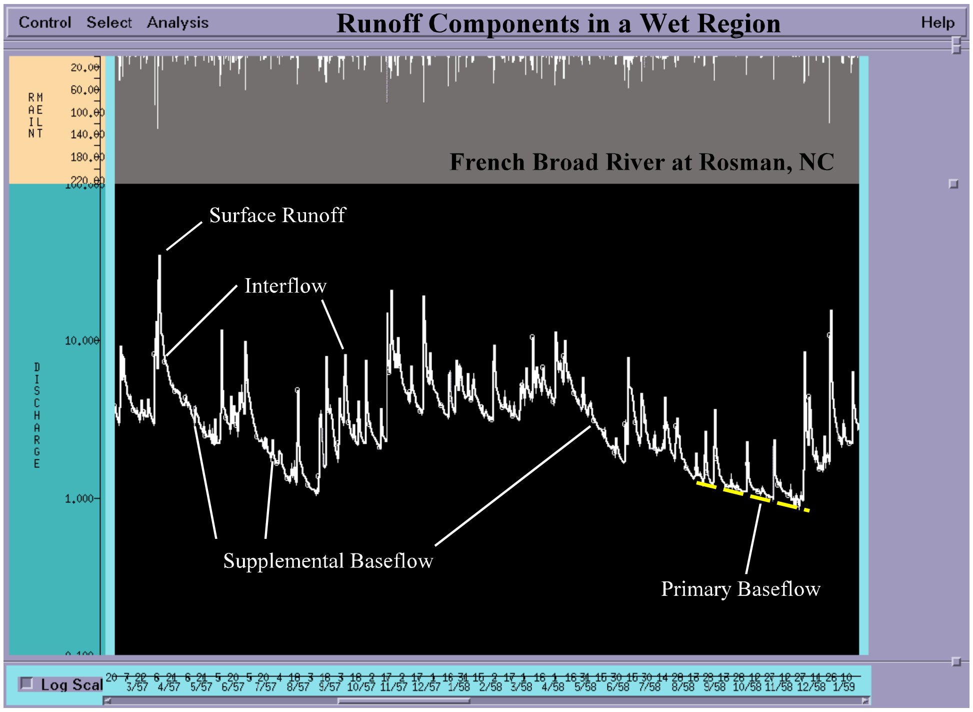


Figure 7-5-1. Assigning runoff components in a wet region.

the average about once every 5 to 10 years. Even then there are frequent small rain events that occur during these periods. Thus one must look very carefully at a long period of record to properly determine the appropriate primary baseflow recession. Once primary baseflow is identified, generally the times when the other components can be isolated fall into place. In regions with high percolation rates such as the one in this figure, surface runoff seldom occurs, if at all. If surface runoff does occur, it is associated with only the largest flood events. Interflow produces most of the rises from rain or melt periods, as well as the early part of the recession for the flood events that generate surface runoff.

Figure 7-5-2 illustrates the case when there are frequent small rain events during the low flow periods when primary baseflow dominates. In such regions, periods when primary baseflow dominates occur during the majority of the years, but the recession doesn't show up as a nice straight line on a semi-log plot due to the frequency of constant impervious runoff produced by small rain storms. One must again determine the primary recession rate by the general slope of the semi-log plot during periods when no recharge occurs, i.e. there is no other runoff than that from constant impervious areas. As with most cases, once primary baseflow is identified, the other runoff components fall into place.

Figure 7-5-3 illustrates the case where the supplemental baseflow recession is very slow. In

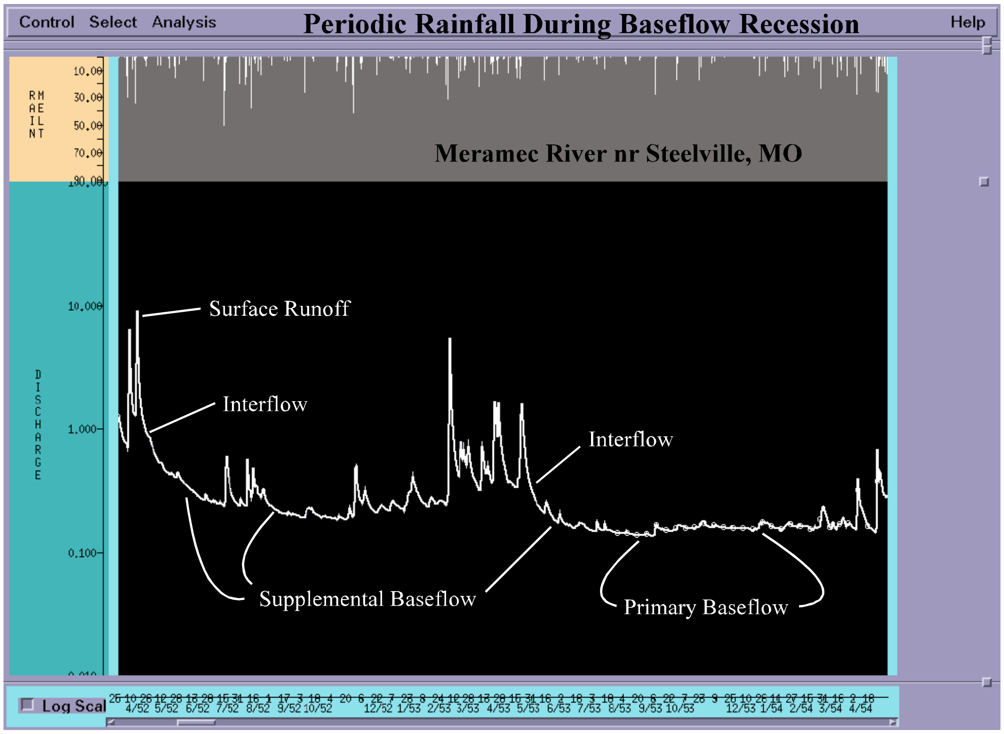


Figure 7-5-2. Runoff components in regions with frequent small events during baseflow periods.

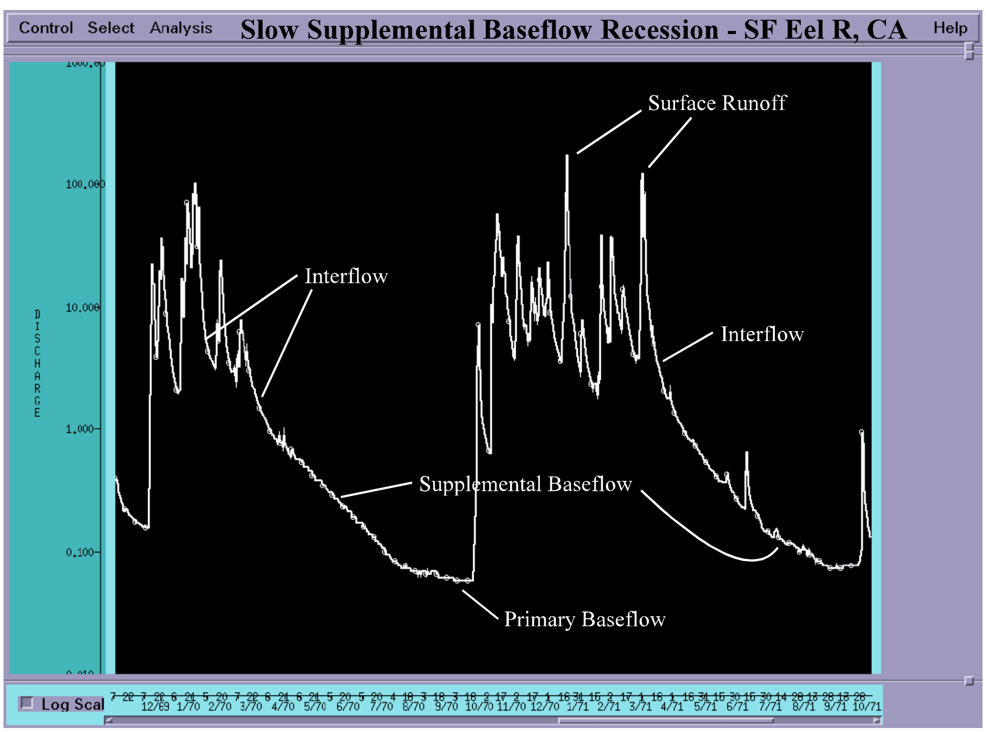


Figure 7- 5-3.

Watershed with a very slow supplemental baseflow recession.

these situations it may take many months for the supplemental aquifers to drain, thus requiring quite a long dry period before there are situations when primary baseflow predominates. Periods with only primary baseflow may only occur once every 10 years or more, especially if this is in a region with year around rainfall. This is probably the most difficult case for determining how to allocate the runoff components. There is a tendency to not look carefully at a sufficiently long record to find the few cases when primary baseflow dominates. Instead the periods labeled as supplemental baseflow are modeled as primary causing simulated baseflow to drop off too rapidly when primary baseflow actually predominates. When this is done, it is likely that supplemental baseflow and interflow will end up with similar withdrawal rates.

Figure 7-5-4 illustrates the case when there is a large amount of evaporation from riparian vegetation during summer and early fall dry periods. These are also the periods when primary baseflow predominates. The evaporation from the riparian vegetation draws down the water table near the stream causing a rapid decrease in baseflow. In such regions if dry conditions persist into the late fall and winter, the baseflow level will increase with no recharge occurring due to the reduction in riparian vegetation effects caused by a decrease in evaporation and the vegetation becoming dormant. It is these late fall and winter periods that must be used to determine the proper primary recession rate. When modeling such a watershed, the simulated baseflow should follow the dashed line shown in the figure when the RIVA parameter is set to zero, i.e. evaporation from riparian vegetation is not being included. It is important to be able to recognize when riparian vegetation affects baseflow and ignore these periods when deriving baseflow recession rates.

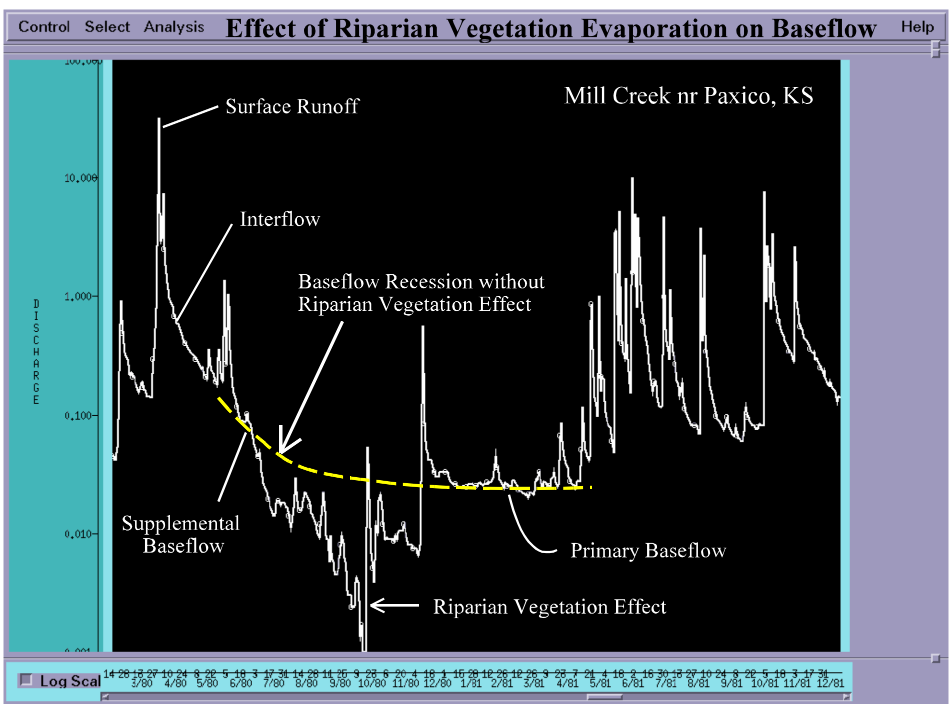


Figure 7-5-4. Assigning runoff components in a region with riparian vegetation.

It is very important to understand these complications when determining how the runoff components of the model are going to be used to simulate the various time delay segments of the hydrograph. It is also critical to take the time to do a careful analysis of the observed hydrograph over a long period in order to understand how the runoff components of the model should be used. Doing this should simplify the calibration and produce the best possible results in the least amount of time.

Deriving Initial Parameter Values

The Sacramento model was designed so that each model parameter serves a particular function and the effect of the parameter controls the hydrograph response under a specific set of circumstances. In most cases this effect can be isolated when the proper situation occurs and thus, the appropriate value of the parameter can be estimated by analyzing the observed hydrograph over a period of many years. Thus, hydrograph analysis is the most direct method of deriving initial estimates for most parameters of the model. For some parameters a numerical derivation is not possible, but an analysis of the hydrograph contains information that suggests the general range of values. In other cases the specific set of circumstances needed to derive the parameter value doesn't occur during the period of available record. In some of these cases a lower limit for the parameter can be computed based on less than ideal circumstances and in other cases the initial value must be assigned using general guidelines or another method.

Procedures have been developed to derive *a priori* estimates of the model parameters based on physiographic information. The procedures proposed up to this point in time have relied solely on soils information to estimate the values for most of the Sacramento model parameters. The most recent of these procedures [*Koren*, 2000] is included in CAP. This procedure utilizes STATSGO soil texture data in 11 soil layers to derive 11 of the 16 Sacramento model parameters. In reality many of the Sacramento model parameters are related to factors in addition to soils information, including vegetation, geology, terrain, and man-made features such as farm ponds and agricultural drain tiles. This means that methods using only soils data typically have to rely on assumptions that may not be valid for all regions or even for all watersheds in a given region.

One of the possible uses of *a priori* parameter estimates is as a source of initial values for model calibration. More importantly, if such a procedure can be shown to produce good results in a given region, it could be used to determine how parameter values should vary from one watershed to another, to obtain parameter estimates for ungaged areas, and to specify how parameter values vary within the boundaries of a watershed. Such estimates would be helpful when applying the models to a large region, when trying to apply models to small ungaged watersheds for flash flood forecasting, and for distributed applications of a conceptual model. An *a priori* method could be used to directly obtain parameter values or it could be used to determine differences in parameters from one watershed to another or within the drainage boundaries. In the second case a calibration would be used to determine the appropriate parameter values for a watershed and then the parameter variations within the drainage or with adjacent watersheds would be obtained by adjusting the calibrated values by the relationships between *a priori* estimates for these areas.

Model calibration involves determining appropriate model parameter values based on data sets that contain noise, both in the input and output data. When the amount of noise becomes excessive, it becomes very difficult to determine the values of many of the parameters. As discussed previously in this manual, a sufficiently long period of record is generally needed to filter out the effect of the noise during individual events. Since the amount of noise will vary from watershed to watershed, primarily based on the number and location of precipitation gages, differences in calibrated parameter values from one watershed to another may not be totally reflective of physical differences between the areas, but could be influenced by differences in the amount of noise in the data. This is why the procedure recommended in this manual stresses only changing those parameters that can be clearly justified when moving from the initial headwater area to other watersheds in the river basin. If an *a priori* parameter estimation procedure can be shown to produce realistic values for a given region, it could be a useful tool to achieve spatial consistency in model parameters. Given the noise in the data, it is important to have physically realistic variations in parameter values across the river basin even if it means less accurate overall fit statistics.

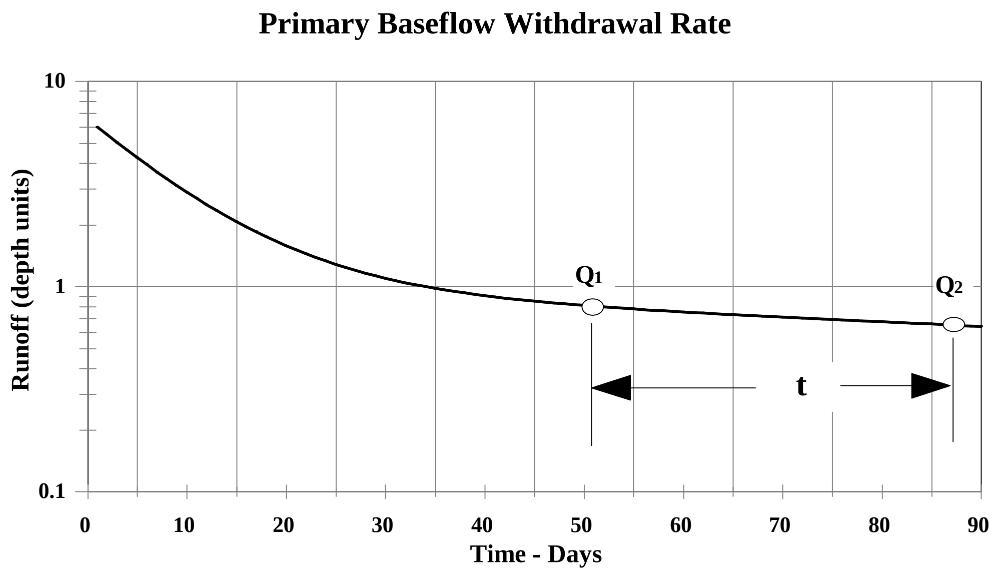
An evaluation of any *a priori* parameter estimation procedure for a conceptual model like the Sacramento model should examine how each derived parameter behaves during times when the effect of the parameter can be isolated. Comparisons of overall 'goodness of fit' statistics for simulations based on *a priori* parameter estimates to those based on calibrated values don't reveal whether the procedure results in physically realistic parameter values. It is suggested that before an *a priori* parameter estimation procedure is used in a given region that comparisons be made between simulations using the *a priori* estimates and observed hydrographs for gaged headwater areas. These comparisons should concentrate on those portions of the hydrograph where each of the parameters can be best isolated to determine if the *a priori* estimation procedure is deriving realistic parameter values. Comparisons should ideally be made for several watersheds in the region, especially cases where the spatial analysis conducted in step 2 (see Chapter 4) suggests that some of the model parameters are quite different. In order to take full advantage of an *a priori* parameter estimation procedure, the method should be able to detect these differences. Section 7-9 illustrates such an evaluation for the Koren *a priori* parameter estimation procedure for several regions scattered around the country.

On the following pages recommendations are given for deriving the initial value of each of the

Sacramento model parameters for use in model calibration. The recommendations are primarily based on deriving the values from a hydrograph analysis, but also utilize estimates from *a priori* parameter estimation procedures in certain situations. Also for a few of the parameters, this author's opinion as to what the parameter physically represents is included. As mentioned in the introduction to this section, all this information should be helpful in understanding the structure of the model and how to isolate the effects of the various parameters even if it is seldom used to derive initial values.

LZPK

The LZPK parameter reflects the slowest baseflow recession rate which occurs after there has been no groundwater recharge for a period that is typically in terms of months. The only method for obtaining a reasonable value for LZPK is from a hydrograph analysis. The identification of periods when primary baseflow dominates the hydrograph is discussed in the section "Assigning Runoff Components" in this section. It is critical to properly identify when primary baseflow is dominate before deriving the value of LZPK. Once the proper periods are found, the values needed to compute LZPK are obtained as shown in Figure 7-5-5 from the straight line portion of a semi-log plot. The straight line segment will have to be estimated when complications such as riparian evaporation, small power plants, and diversions cause fluctuations in the flow.



Figu
re 7-5-5. Hydrograph values needed for deriving LZPK.

Using time, t, in days, the primary recession rate, K_p, can be computed as:

$$K_p = \left(\frac{Q_2}{Q_1}\right)^{1/t} \quad (7\text{-}5\text{-}1)$$

and the withdrawal rate (1.0 minus the recession rate), i.e. the LZPK parameter value, is:

$$LZPK = 1.0 - K_p \quad (7\text{-}5\text{-}2)$$

During winter periods when there is snow on the ground, the computed withdrawal rate could be less than the value of LZPK due to small amounts of melt at the snow-soil interface which can be providing a steady slow recharge to the lower zone storages.

LZSK

LZSK is the withdrawal rate from the supplemental baseflow aquifers. As with LZPK, the only method for obtaining reasonable values for LZSK is by analyzing the observed daily flow hydrograph. The effect of this parameter can be isolated by finding relatively dry periods when no recharge is occurring beginning several days after intervals of significant runoff and recharge. During such periods both supplemental and primary baseflow are being generated. Thus, in order to determine the supplemental recession, the primary baseflow component must first be removed. When primary baseflow is subtracted from the total flow, periods of supplemental baseflow should plot as a straight line on a semi-log plot. This is illustrated in Figure 7-5-6.

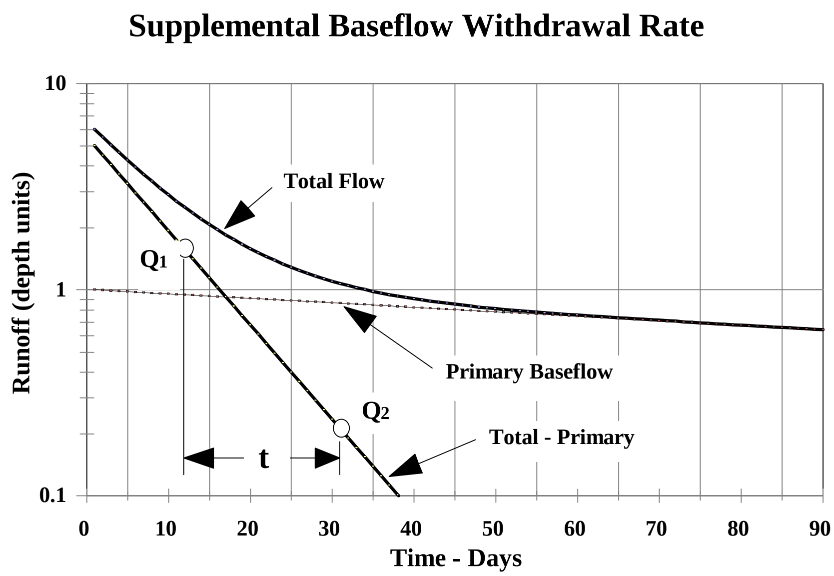


Figure 7-5-6. Hydrograph values needed for deriving LZSK.

Two points can then be picked off this straight line and by using time, t, in days, the supplemental recession rate can be computed as:

$$K_s = \left(\frac{Q_2}{Q_1} \right)^{1/t} \quad (7\text{-}5\text{-}3)$$

and the withdrawal rate, i.e. the LZSK parameter value is:

$$LZSK = 1.0 - K_s \quad (7\text{-}5\text{-}4)$$

As one gains experience, the two runoff values needed to compute the supplemental recession can be obtained by subtracting primary baseflow from total flow for two days during the supplemental recession without having to generate a plot of total flow minus primary baseflow.

LZFPM

There are two ways of computing an estimate of LZFPM from a hydrograph analysis. The first is to find a nice recession period following several months of significant runoff and recharge during which the primary baseflow aquifer has a chance to accumulate a substantial amount of storage. The largest primary contents will typically occur during the very wettest years. If the recession period is of sufficient length to reach the point where only primary baseflow remains, then the primary recession can be extrapolated backwards to find the amount of primary baseflow at the end of the recharge period, Q_x, as shown in Figure 7-5-7.

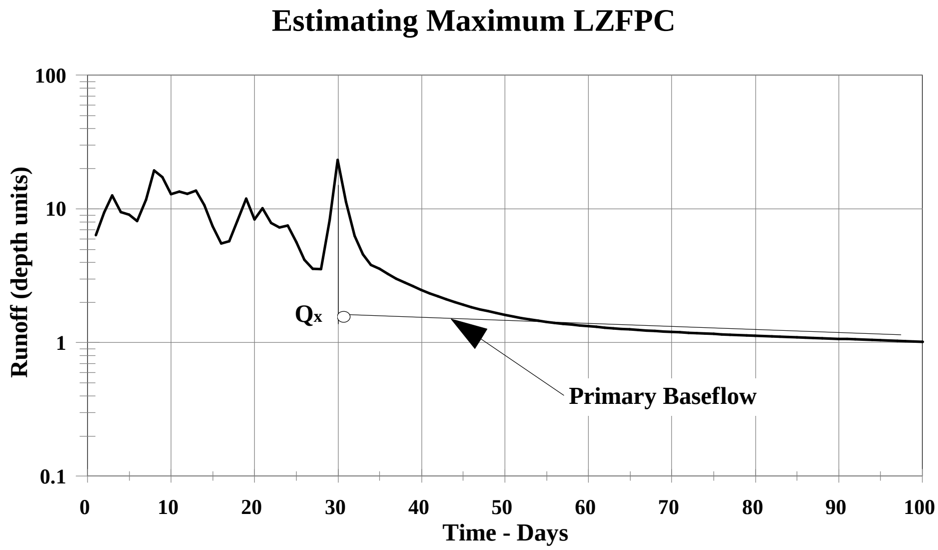


Figure 7-5-7. Back extrapolation to estimate maximum LZFPC.

The initial estimate of LZFPM can then be computed from:

$$LZFPM = \left(Q_x + \left(\varepsilon \cdot Q_x\right)\right) / LZPK \qquad (7\text{-}5\text{-}4)$$

where ϵ is a decimal fraction typically in the range of 0.1 to 0.25. The ϵ term is needed since the contents of the lower zone primary storage never actually become completely full. Generally the greater the withdrawal rate, LZPK, the larger the value of ϵ since it is harder to fill a storage the faster it drains.

If a backwards extrapolation is not possible during any of the wet years to get an estimate of Q_x, then the second way to estimate Q_x and then LZFPM is to attempt to sketch on a semi-log plot the primary baseflow component during some of the wettest years. This can be done if periods when primary baseflow is dominant exist prior to and after a prolong period of recharge. With these tie in points and having an estimate of LZPK, one can sketch the primary baseflow contribution and come up with a value of Q_x to use in Equation 7-5-4.

LZFSM

An estimate of LZFSM can also be derived by back extrapolation. This can be done when the baseflow recession can clearly be determined after a very large storm event. If the supplemental withdrawal rate, LZSK, is relatively slow, then a recession period after a series of storms is likely needed to have as much water as possible in supplemental storage. Figure 7-5-8 illustrates how to estimate the maximum amount of supplemental runoff, Q_x, by extrapolating the supplemental recession back to when the contents of this storage are at their fullest. It is best to subtract primary baseflow from total flow in order to clearly find the supplemental recession, though with experience the plotting of the total minus primary line is not needed to estimate a reasonable value for Q_x

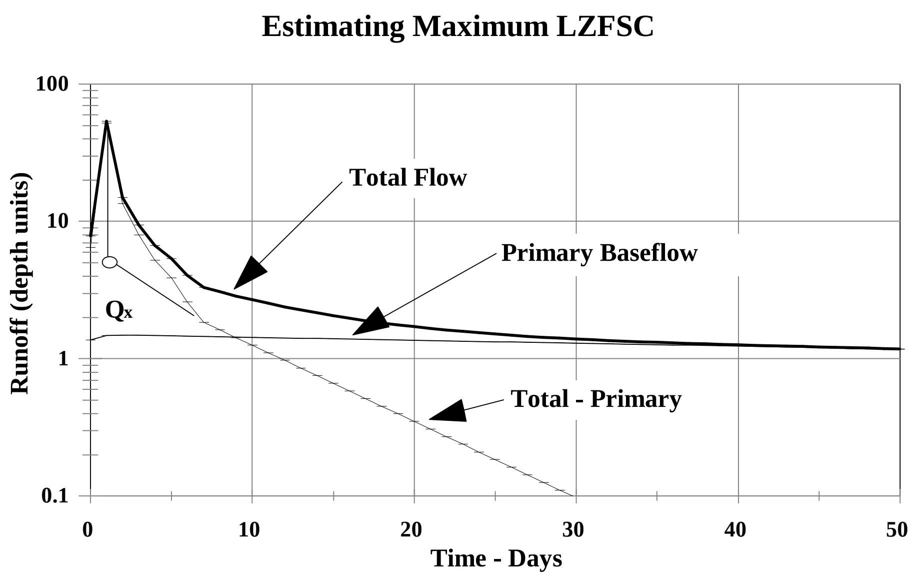


Figure 7-5-8.
Back extrapolation to estimate maximum LZFSC.

Once Q_x is determined an estimate of LZFSM can be computed from:

$$\text{LZFSM} = \left(Q_x + \left(\varepsilon \cdot Q_x\right)\right) / \text{LZSK} \qquad (7\text{-}5\text{-}5)$$

where ϵ in this case typically varies from about 0.5 to 1.0. Larger values of ϵ are needed for supplemental baseflow than for primary since the supplemental storage drains faster, thus the supplemental contents seldom get close to capacity. Also the value of ϵ should be greater for larger values of LZSK.

PCTIM

The PCTIM parameter represents the part of the area that always produces some runoff no matter what soil moisture conditions exist. The value is generally not the same as the portion of the area covered by surfaces such as pavement, roofs, and rock outcrops since runoff from many of these surfaces encounter areas of soil before reaching the stream channel. PCTIM represents impervious areas that are directly connected to the channel system.

An good estimate of the amount of constant impervious area can normally be derived from a hydrograph analysis. The conditions needed to derive a value of PCTIM are a week or two of dry weather during late spring or summer that produce a significant upper zone tension water deficit, followed by a moderate rain event (typically 0.25 to 0.75 inches) which is not sufficient to fill this deficit (no recharge occurs). The amount of runoff produced during such events is then computed as shown in Figure 7-5-9.

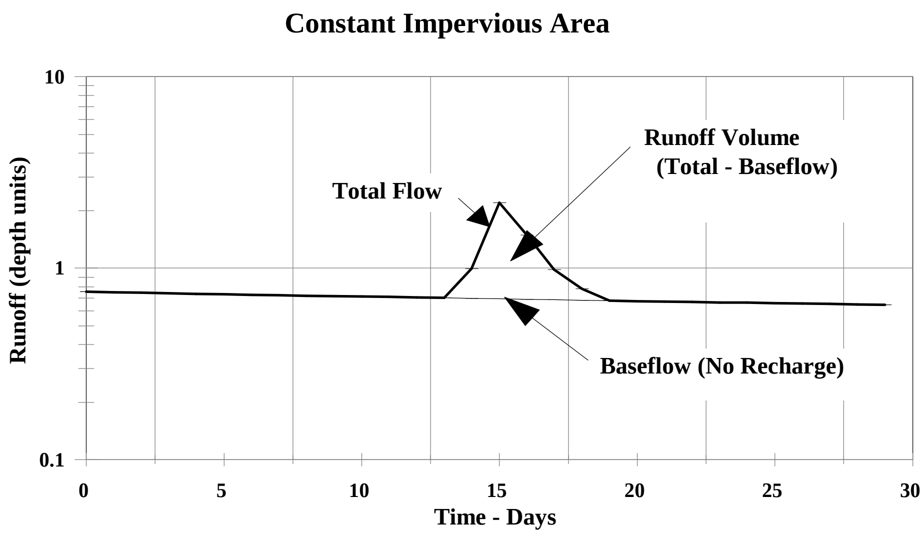


Figure 7-5-9. Runoff volume from the constant impervious area.

Then an estimate of the PCTIM parameter is computed by dividing the runoff volume, R_{imp}, by the amount of precipitation, P, as shown in Equation 7-5-6.

$$PCTIM = R_{imp} / P \qquad (7\text{-}5\text{-}6)$$

It is best to compute PCTIM for a number of events since rainfall under such conditions can be more uncertain since it is often from convective events with considerable spatial variability. Then take the average of these events after throwing out any with a significantly greater runoff percentage than the majority of the cases. The upper zone tension water may have filled during such events and thus, they could contain some interflow, or even variable impervious runoff, in addition to runoff from areas that always act as impervious.

UZTWM

The UZTWM parameter indicates the amount of rain that must fall after a long dry period before any runoff, other than that from constant impervious areas, is produced. The upper zone tension water comprises water held in the pervious surface soil, plus interception (by vegetation and forest litter) and depression storage. In agricultural regions with many farm ponds, the effect of these ponds is typically implicitly absorbed by the UZTWM parameter.

If the right conditions occur, a good estimate of UZTWM can be computed from an analysis of the hydrograph. The conditions needed are several weeks or more of quite dry weather in the late spring or summer, followed by a significant rain event that generates a small amount of recharge and more runoff than specified by PCTIM to indicate that the upper zone tension water deficit has been filled. Such an event is shown in Figure 7-5-10.

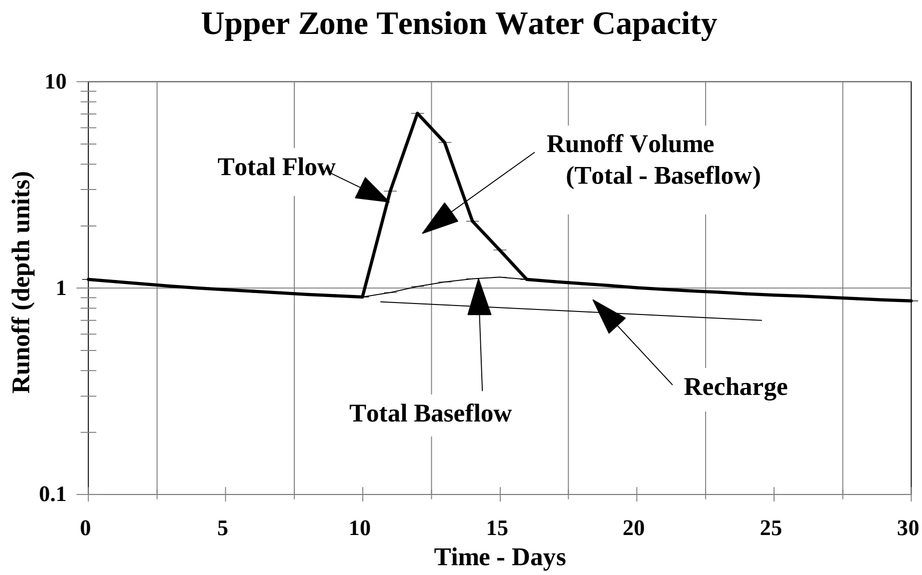


Figure 7-
5-10. Runoff from event that just fills UZTW storage.

The amount of rain that falls during such an event can be used as an estimate of UZTWM. Rainfall amounts that produce no additional runoff after a summer dry period can also be used as a lower limit for UZTWM. A number of events should be examined.

In regions where such situations don't occur, typically wet regions with frequent summer precipitation, it would probably be best to use the soil based value of UZTWM as an initial value. This should produce spatial consistency in UZTWM values over such a region. It should be verified that the soil based value is greater than any rainfall amounts that produce little or no recharge or additional runoff after the limited dry periods that may occur in these regions.

LZTWM

The LZTWM parameter indicates the maximum moisture deficit that can occur in the lower soil layers. Tension water is only removed from the lower zone by evapotranspiration via the vegetation in the watershed. Thus, this parameter is primarily a function of the depth of the root zone and not of the depth of the soil layer, though in shallow soils, the root zone may be controlled by the depth to bedrock. This was clear when modeling a watershed that had been transformed from a rural, forested landscape to a mostly suburban area with the primary vegetation being grass. The main parameter change needed to account for the effects of this transformation was to significantly reduce LZTWM. The grass cover produced runoff much earlier in the fall after a dry summer than when the watershed was forested.

The LZTWM parameter can be derived from a hydrograph analysis when the right conditions occur. The conditions needed are very dry conditions from late spring to late fall followed by a 2 to 3 week period with sufficient rain to fill the soil moisture deficit that has been generated. The water balance equation can then be used on the period from just after UZTW fills to just after LZTW fills (can be detected by a large increase in recharge) to compute the lower zone deficit that existed prior to the rain. Such a period is illustrated in Figure 7-5-11.

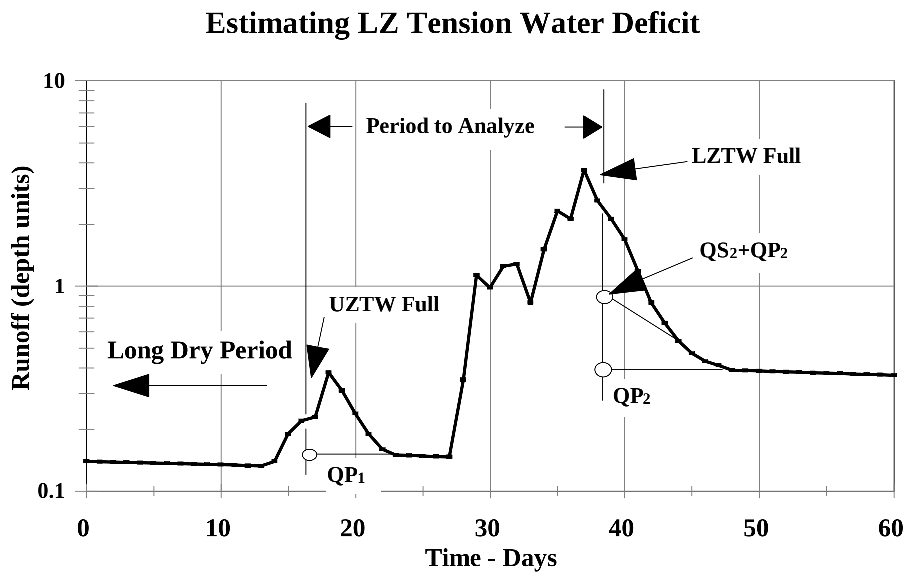


Figure 7-
5-11. Period for computing LZTW deficit via water balance.

By assuming UZTW is full and UZFW is empty at the beginning and end of the period, that LZFSC=0.0 at the start, and that deep recharge equals zero, the LZTW deficit is computed as:

$$\Delta \mathbf{LZTWC = P - R - ET - QS_2/LZSK - (QP_2 - QP_1)/LZPK} \qquad (7\text{-}5\text{-}7)$$

LZTWM (Continued)

where: P = precipitation, R = runoff, and ET = evapotranspiration. The ET for each day during the period should be close to the ET-Demand rate since UZTW should remain full or nearly full due to the periodic rainfall that generally occurs and the fact that evaporation rates are low at this time of year. The initial estimate of the LZTWM parameter should be somewhat greater than the maximum deficit that occurs after such a long dry period. If the LZTW deficit was ever equal to LZTWM it would indicate that the wilting point was reached throughout the watershed which is an unlikely situation.

In regions where a sufficiently long dry period never occurs and thus the LZTW deficit never approaches its maximum, the initial value of LZTWM should probably be obtained from the soil based derivation. It would be an improvement if this derivation also took vegetation type and coverage into account, however, the use of the current soil based value would insure some spatial consistency in wetter regions. When large lower zone deficits never occur, the effect of this parameter is difficult to isolate during calibration and fairly large variations in its value can be compensated for in many cases by reasonable changes to other parameters and the ET-Demand curve.

UZK

The withdrawal rate from upper zone free water, i.e. the UZK parameter, cannot be derived like the lower zone withdrawal rates, LZPK and LZSK, because water percolates from this zone in addition to draining out as interflow. It is possible in many cases when doing a recession analysis for a major storm event to compute the overall recession rate for the upper zone free water. The steps in a recession analysis are described in Section 7-6 as part of the procedure for deriving a unit hydrograph for use with the Sacramento Model. This overall recession rate is based on both the interflow withdrawal rate and the percolation rate. The percolation rate of course varies with soil moisture conditions. If the recession analysis is being done for a storm during a time when soil moisture conditions are close to saturation and the watershed has a very low percolation rate under these conditions, the upper zone free water recession rate derived from the analysis should be only slightly greater than the interflow withdrawal rate and can be used to estimate the initial value of UZK. In a case with such low percolation rates, the watershed should produce very little baseflow in general and almost all the storm runoff from the event should be surface runoff. The combination of all these conditions is quite rare, thus normally it is not possible to derive an good initial value for UZK from a hydrograph analysis.

When UZK cannot be derived from a hydrograph analysis, it is recommended to start with a nominal value of UZK = 0.3. The soil based derivation of UZK assumes that the interflow withdrawal rate is related to soil texture, with the more clay particles, the slower the withdrawal rate. Texture is indexed by the ratio of field capacity to porosity with the more clay, the higher the ratio. This seems logical, however, for the watersheds used by the author to test the soil based parameter derivations, the empirical equation used to compute UZK from this ratio produced unrealistically high UZK values in most cases. For this reason it is suggested that the nominal value of 0.3 be used as an initial estimate of UZK.

UZFWM

When a reasonable initial estimate of the UZK parameter can be derived from a hydrograph storm recession analysis as mentioned on the previous page, then an estimate of the capacity of the UZFW storage can also be computed. The maximum amount of interflow runoff can be determined by extrapolating the total minus baseflow line segment back to the time when the hydrograph peak occurred to obtain Q_i in depth units. Since surface runoff must be generated from such an event in order to determine a reasonable value for UZK, the UZFWC must be completely full at this point. Thus, UZFWM can be computed as:

$$UZFWM = Q_i / UZK \qquad (7\text{-}5\text{-}8)$$

If UZFWM cannot be derived from a hydrograph analysis, which is the most common case, the initial value of the parameter can be based on some general guidelines depending on how frequently surface runoff occurs. Surface runoff can be detected prior to running the model by comparing the amount of immediate storm runoff to the amount of rain+melt for a given event. When the immediate storm runoff exceeds about 50% of the rain+melt, it is likely that surface runoff occurred. The guidelines are given in Table 7-5-1. Estimates of UZFWM derived from soil data could also possibly be used as initial estimates. The soil based UZFWM values from the evaluation by this author were generally in the same ballpark as the calibrated values for most watersheds, though most of the watersheds examined generated surface runoff infrequently. For the one watershed that had frequent surface runoff (woon3 - 6-10 times/year), the soil based value of UZFWM was over twice as large as the calibrated value.

Table 7-5-1. Guidelines for initial estimate of UZFWM.

Frequency of Surface Runoff	Suggested Initial Value of UZFWM
Every moderate to heavy rainfall event (i.e. very frequently)	10 - 20 mm
Every large rainfall event	15 - 30 mm
Only during the largest flood events	30 - 60 mm (upper end of range for very wet regions)
Never or only during a record flood event	40 - 100 mm (upper end of range for very wet regions)

ADIMP

The ADIMP parameter indicates the maximum amount of variable impervious area within the watershed. These are portions of the watershed that become completely saturated and thus act as impervious areas as the soil moisture increases. The variable impervious area portion of the model is related to the variable contributing area concept that has been described in hydrology literature. The portions of the watershed that can be modeled using this feature are areas adjacent to the stream channels and areas along ravines that drain directly into the channel system. If such areas generate fast response runoff when the soil is wet no matter what is the rainfall intensity, then the ADIMP parameter is needed.

Generally it is recommended to initially set ADIMP to 0.0 and then determine during the calibration if a non-zero value is needed. However, in some cases the need for ADIMP and the computation of an initial estimate can be determined from a hydrograph analysis. What is required is a watershed with a quick response time for the channel system (i.e. unitgraph peaks in 6-12 hours). In this case an estimate of ADIMP can be made by examining moderate intensity rainfall events that occur when the soil is very wet (generally use moderate intensity storms that occur within a few days after a major event). Such a case is shown in Figure 7-5-12.

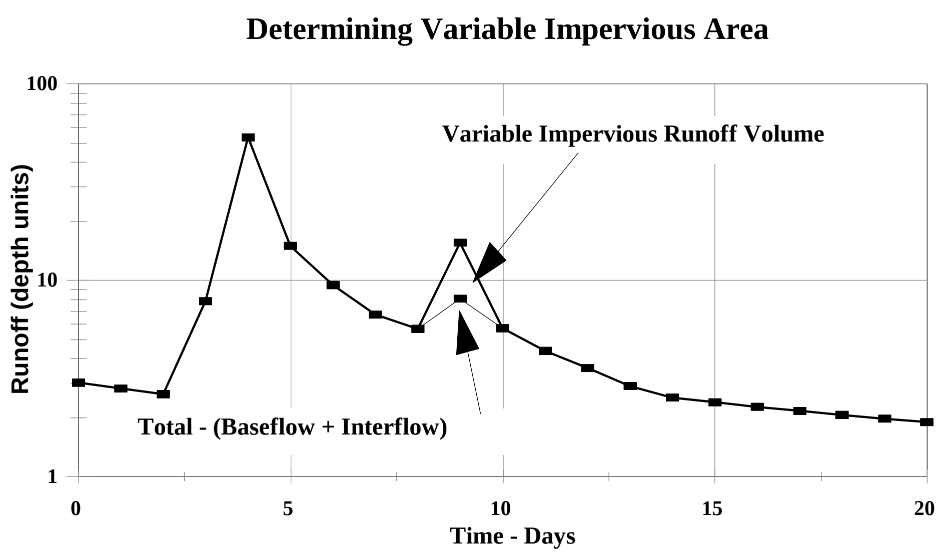


Figure 7-5-12. Determination of variable impervious area runoff volume.

An estimate of ADIMP can be computed from the runoff volume, R_v, and the precipitation, P, for this event as:

$$ADIMP = \left(R_v / P\right) - PCTIM \qquad (7\text{-}5\text{-}9)$$

PFREE

The PFREE parameter specifies what decimal fraction of the percolated water goes directly to lower zone free water storages when the lower zone tension water is not full. While this parameter would not be required if one were modeling a column of soil, it is needed when the model is being applied to a watershed. Over an entire drainage area the capacity of the lower zone tension water varies due to variations in soil properties and the depth of the root zone. This results in the tension water storage filling in some parts of the watershed before the capacity is reach over the whole area. In reality the fraction of percolation going to free water should not be a single value, but should be a curve with no percolation going to free water storages when LZTWC=0.0 and nearly all the percolation recharging baseflow as LZTWC approaches LZTWM. However, the developers of the model decided that given the simplified nature of the algorithms that a single value was adequate.

A general idea of the initial value of PFREE can be obtained by examining the hydrograph when moderate rains occur during otherwise dry periods or when the baseflow is first being recharged after a long dry summer. The amount of recharge that occurs during these periods is an indication of the magnitude of PFREE. This is illustrated in Figure 7-5-13.

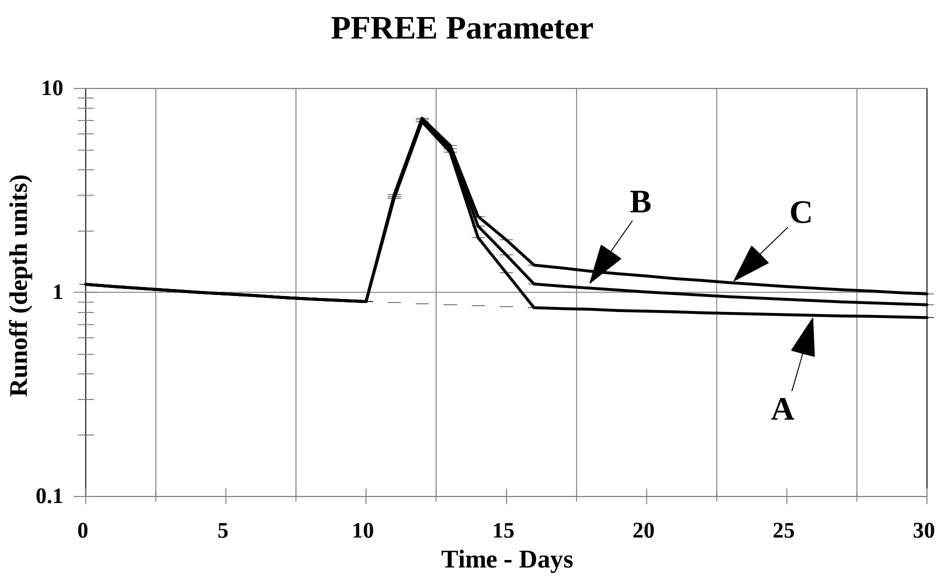


Figure
7-5-13. Evaluation of baseflow recharge during dry periods to estimate PFREE.

No baseflow recharge occurs in case A indicating that either UZTW never filled during the event or that PFREE should be 0.0. Case B shows some recharge occurring and would suggest using an initial value of PFREE in the range of 0.1 to 0.25, while case C has more recharge and would indicate setting PFREE to a value in the range of 0.3 to 0.5.

ZPERC and REXP

When considering the variation in percolation rates from dry to wet conditions, one should be thinking in terms of what the curve should look like instead of dealing with ZPERC and REXP as individual parameters. The shape of the percolation curve should be based on the type of soil that exists over the area. For example, a predominately sandy soil would have a large permeability when wet, but the ratio of dry to wet percolation rates would be relatively small and there wouldn't be much curvature to the relationship, whereas a clay soil would have a much larger permeability when dry than the low percolation rate that would exist when the soil was wet and there would be much more curvature to the relationship. This is illustrated in Figure 7-5-14.

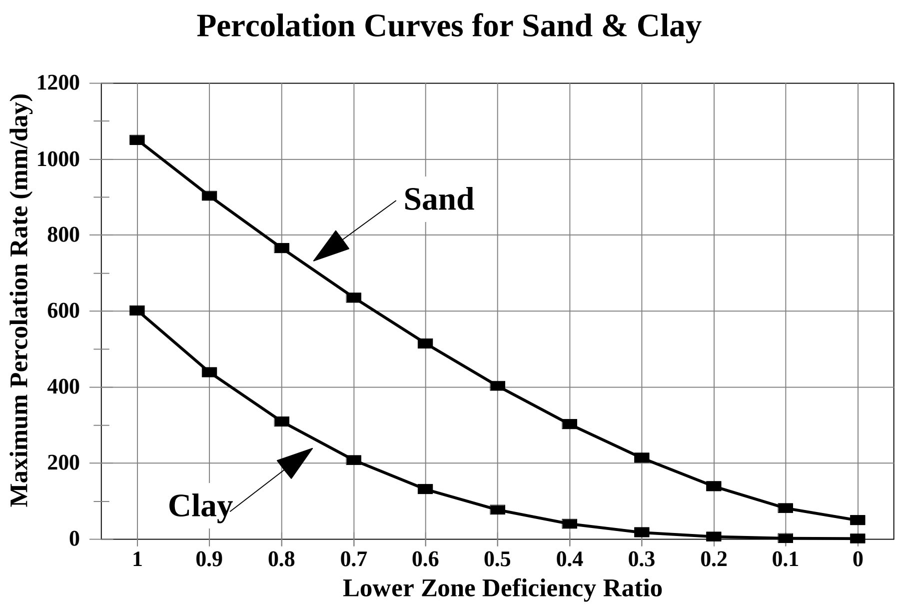


Figure 7-5-14. Sample percolation curves for sand and clay soils.

Hydrograph characteristics, as well as soils information, can indicate the general soil type and its permeability and thus can be used to obtain an initial estimate of the ZPERC and REXP parameters. Guidelines for estimating these parameters are given in Table 7-5-2. These guidelines are based primarily on logic considerations and not on actual calibration results. The relationship between ZPERC and REXP values from calibrations and soil types or hydrograph characteristics is not well defined. This is because for most watersheds the range of lower zone deficiency ratios for most significant runoff events is quite small (generally in the order of 0.2 to 0.3). Over such a small range, various values of ZPERC and REXP can produce similar percolation rates. When using real data with most of the significant events occurring at similar moisture levels, the ZPERC and REXP parameters are not very sensitive, thus the calibrations end up with a variety of values.

ZPERC and REXP (Continued)

The value of REXP derived from soil properties using the Koren method should give similar values for REXP as shown in the table. Soil based values of ZPERC may not be as useful due to questions concerning the assumption that the maximum daily percolation rate is equal to the combined capacity of all the lower zones, both tension and free water, as well as uncertainty in the capacity of these zones derived from soil data. From a physical standpoint, the value of REXP should always be greater than 1.0 as the shape of a percolation curve should always be concave.

General soil type	Hydrograph characteristics	Initial ZPERC and REXP
Clay	Frequent surface runoff, Little baseflow (max of 1 mm/day), PBASE: 2 - 4 mm/day	ZPERC: 150 - 300 REXP: 2.5 - 3.5
Silt	Some surface runoff - especially during larger storms, Moderate amount of baseflow (max of around 2 mm/day), PBASE: 4 - 8 mm/day	ZPERC: 40 - 150 REXP: 1.8 - 2.5
Sandy	No surface runoff or only during the very largest storm events, Considerable baseflow (max greater than 2.5 mm/day), PBASE: greater than 8 mm/day	ZPERC: 20 - 40 REXP: 1.4 - 1.8

Table 7-5-2. Guidelines for initial values of ZPERC and REXP.

OTHER PARAMETERS

Suggestions for initial values of the other Sacramento model parameters are as follows:

• RIVA – the need for RIVA should be determined when examining the hydrographs to decide how to assign runoff components as discussed earlier in this section, but the initial value should be set to 0.0. The final value of RIVA will be determined near the end of the calibration as discussed in Section 7-1.

• RSERV – this is a very insensitive parameter and in almost all cases a value of 0.3 is reasonable.

• SIDE – the initial value of SIDE should be set to 0.0.

• Seasonal PE adjustment or ET-Demand curve – recommendations and guidelines for these curves are given in Section 6-5.

• EFC – this parameter is only used when the snow model is included and an areal extent of snow cover time series is passed from the snow model to the Sacramento model. In that case the ET-Demand is modified when snow is present using the equation:

$$D_s = \left(\mathrm{EFC} \cdot \mathrm{D_{ns}}\right) + \left[\left(1 - \mathrm{EFC}\right) \cdot \left(1 - \mathrm{S_c}\right) \cdot \mathrm{D_{ns}}\right] \qquad (7\text{-}5\text{-}10)$$

where: D_s is the ET-Demand with snow, D_{ns} is the ET-Demand without snow, and S_c is the decimal fraction areal extent of the snow cover. The initial value of EFC should be the portion of the area covered by conifer trees times the average cover density of the conifers expressed as a decimal fraction.

• Preliminary (Frost Index) frozen ground model – based on limited use of these algorithms the following initial values are suggested:

- ◦ CSOIL - 0.1 for open areas and 0.05 for forested areas
- ◦ CSNOW - 0.08
- ◦ GHC - 0.1
- ◦ RTHAW - 0.0 (don't use unless clearly needed)
- ◦ FRTEMP - -3.0
- ◦ SATR - 0.0 (with SATR=0.0 the frost index will have no effect on interflow withdrawal and percolation rates – start with SATR=0.4 once it is determined that the use of the frozen ground model may be helpful)
- ◦ FREXP - 8.0

Typical Range for Parameter Values

Based on experience with the Sacramento model over a wide range of physiographic conditions, Table 7-5-3 gives the typical range of values for each of parameters. In some cases the value could fall outside this range, but if so, there needs to be clear evidence that such a value is required. For example, in some watersheds the value of LZPK may be greater than the upper limit shown in the table, but in most cases when LZPK is greater than this limit, it is very likely that what should be modeled as supplemental baseflow is being treated as primary baseflow.

Parameter	Lower Limit	Upper Limit
LZPK	0.001	0.015
LZSK	0.03	0.20
LZFPM	40.	600.
LZFSM	15.	300. (highest values associated with low values of LZSK)
UZTWM	25.	125.
LZTWM	75.	300.
UZK	0.2	0.5
UZFWM	10.	75.
PFREE	0.0	0.5
PCTIM	0.0	0.05
ADIMP	0.0	0.20
ZPERC	20.	300.
REXP	1.4	3.5
RIVA	0.0	0.20

Table 7-5-3. Typical range of values for the Sacramento model parameters.

Section 7-6

Unit Hydrograph Application for the Sacramento Model

Introduction

A number of methods could be used to convert runoff generated by a rainfall-runoff model into a discharge hydrograph at a location on the channel system. The only current method included in NWSRFS is the unit hydrograph procedure. This section describes how a unit hydrograph should be applied with the Sacramento model and methods for determining an initial estimate of the unit hydrograph for a drainage area. Also discussed are items to consider when using a unit hydrograph including the time interval of the ordinates, application to watersheds that are divided into multiple zones, and how to handle watersheds where the shape of the response varies considerably depending on the flow level.

Function of a Unit Hydrograph for Use with the Sacramento Model

The Sacramento model generates runoff into the channel system. Delays that occur as water moves through the soil, either as interflow or baseflow, are accounted for within the model. Time delays associated with surface and impervious runoff are not included in the Sacramento model as these runoff components are added to the channel runoff during the same period as the rain or melt occurs. Thus, when a unit hydrograph is used with the Sacramento model, the unit hydrograph must account for the delay and attenuation that occurs as surface and impervious runoff moves over the land surface and, most importantly, the delay and attenuation that occurs as the water moves through the channel system. Typically the response time of the channel system is much more significant than the overland flow response time and thus dominates the unit hydrograph.

In more traditional applications of the unit hydrograph method, such as with an API type rainfall-runoff model, the procedure must account for storm runoff delays both through and over the soil, as well as the effect of the channel system on watershed response. For a watershed where surface runoff dominates storm events and there is very little interflow produced, the function of a traditional unit hydrograph is basically the same as the unit hydrograph that would be used with the Sacramento model. However, for a watershed where interflow, or possibly even supplemental baseflow, is a major contributor to storm runoff, the delay time for the water moving through the soil needs to be included in the unit hydrograph and thus a traditional unit hydrograph is not appropriate for use with the Sacramento model. Figure 7-6-1 shows a traditional, i.e. API model, unit hydrograph for a watershed that has a considerable interflow contribution during most storm events. The figure also shows the interflow component of the API unit hydrograph and the appropriate Sacramento model unit hydrograph for this watershed. The Sacramento model unit hydrograph is derived by subtracting the interflow component from the API unit hydrograph and adjusting the ordinates so that they add up to the correct sum.

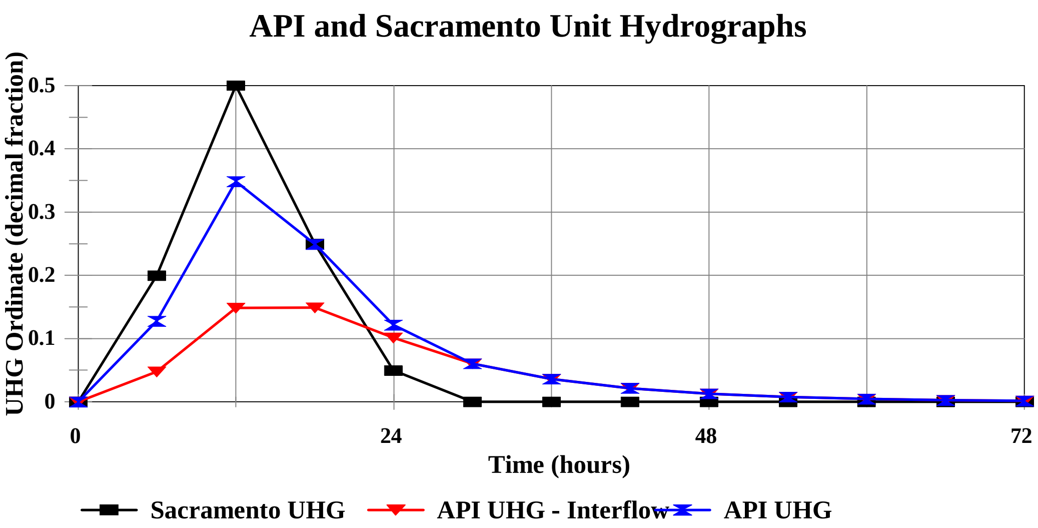
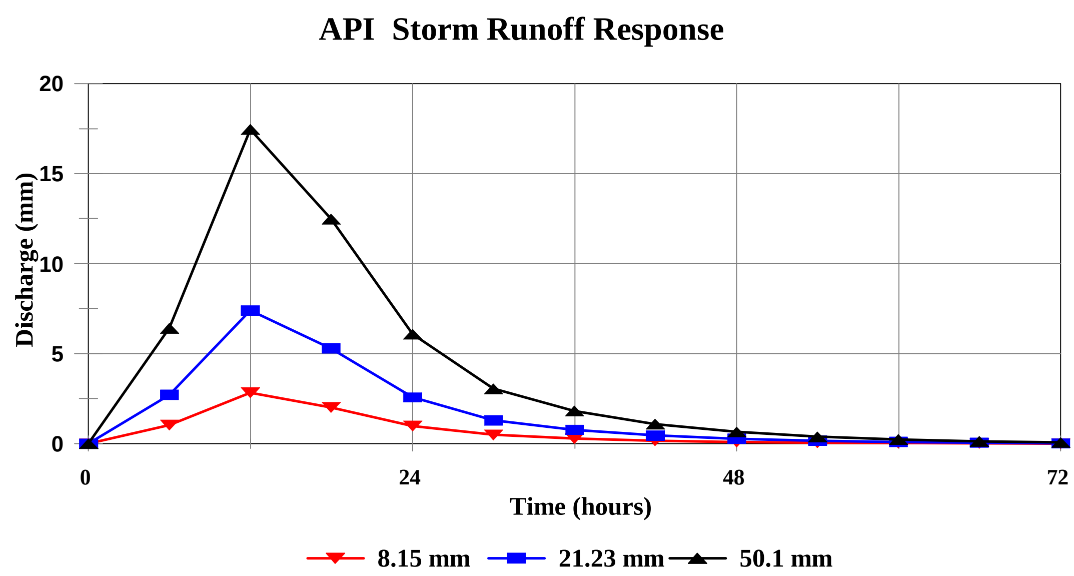


Figure 7-6-1. Unit hydrographs for a watershed with considerable interflow.

When using the unit hydrograph method with an API model, the shape of the storm response is always the same no matter how much storm runoff is generated since the unit hydrograph is a linear function and the storm runoff is all applied to the same time interval when the rain or melt occurs. When the unit hydrograph is used with the Sacramento model, even though the unit hydrograph is a linear function, the watershed response is nonlinear because the breakdown of total storm runoff into interflow and surface runoff varies depending on the amount of rain, the rainfall intensity, and the soil moisture conditions. With the Sacramento model only the fast response runoff, i.e. surface and impervious, is all produced at one time. Interflow and baseflow contributions are made available to the unit hydrograph over a number of time intervals after the rain or melt occurs. Using the unit hydrographs shown in Figure 7-6-1, the next two figures illustrate how the Sacramento model response differs from an API model response for synthetic storm events of different magnitudes. Figure 7-6-2 shows a watershed response to various amounts of storm runoff when an API model is used. The shape of the response is the same for all three cases. Figure 7-6-3 shows the response of the watershed when using the Sacramento model for the same three events. The event with 8.15 mm of storm runoff only generates interflow, while the 21.23 mm event has 57% surface runoff and 43% interflow, and the 50.1 mm case is produced by 81% surface runoff and only 19% interflow. When comparing these two figures one can see that by using the unit hydrograph to model only the channel system and not interflow response with the Sacramento model, that small events can have a lower peak and more damped response, while large events will have a higher peak and quicker response than when using an API model with a unit hydrograph.

It is very important to clearly understand what the unit hydrograph is being used to represent when working with the Sacramento model. If unit hydrographs derived for use with an API model are to be used with the Sacramento model, any interflow or baseflow contribution must first be removed so that the resulting unit hydrograph only represents the delay and attenuation of water through the channel system and over the land surface.



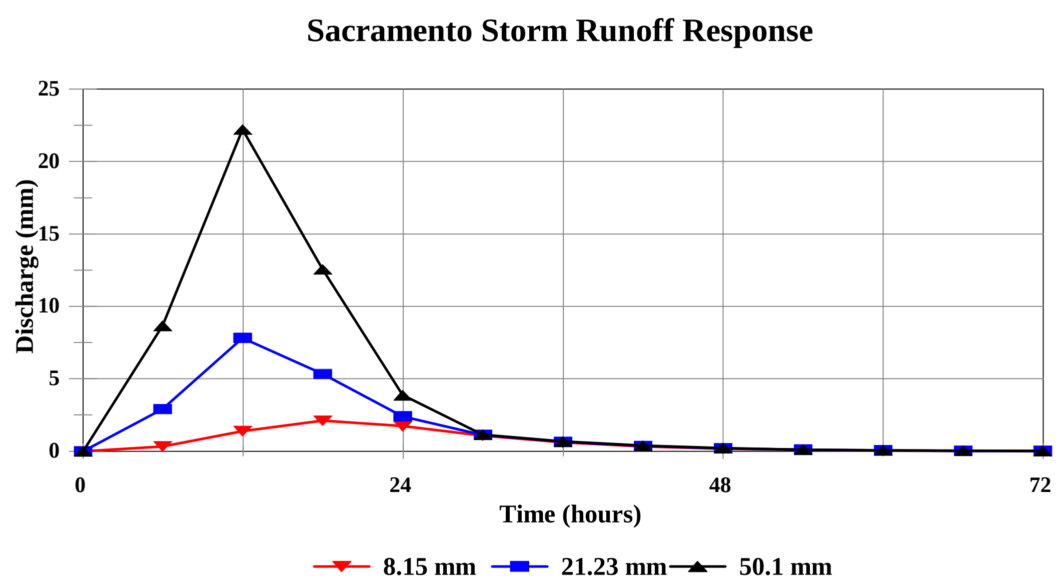


Figure 7-6-2. API model response to different size storm events.

Figure 7-6-3. Sacramento model response to different size storm events.

Derivation of an Initial Unit Hydrograph for the Sacramento Model

There are two basic methods for deriving an initial estimate of the unit hydrograph for use with the Sacramento model. The first is to use data from actual storm events for the watershed and the second is to use one of a number of techniques to derive a synthetic unit hydrograph. If the proper conditions exist it is much better to derive the unit hydrograph using actual storm data.

Derivation of a Sacramento Model Unit Hydrograph from Storm Events

The procedure to derive a Sacramento model unit hydrograph from actual watershed data involves separating the fast response runoff contribution, i.e. surface and impervious, from the other runoff components prior to doing the unit hydrograph computations. In order to do this the following conditions must be met:

- the storms used must produce a significant amount of fast response runoff,
- there must be a reasonably clean recession period for some time after each event, typically in order of several weeks, and
- the precipitation causing the storm response should occur within a few time intervals; all within one period is best, but up to 3 or 4 time intervals are okay (complex storms and snowmelt periods should be avoided as when deriving a traditional unit hydrograph).

In order to separate out the fast response runoff contribution so that the effect of the channel system and overland flow can be isolated, a recession analysis is used. The recession analysis should allow one to remove the baseflow and interflow contribution. This is analogous to separating out baseflow when deriving a traditional unit hydrograph only in this case the interflow contribution must also be removed. Once the watershed response to surface and impervious runoff is determined, then the remainder of the process is exactly the same as when computing unit hydrograph ordinates in the traditional case. If one is not familiar with these steps, they are described in many textbooks.

In order to perform a recession analysis, a semi-log plot is generated for the receding portion of the hydrograph. Such a case is shown in Figure 7-6-4. This figure contains an idealized case generated with synthetic data so that the steps in the procedure can easily be described. The steps in the recession analysis are:

- Identify the primary baseflow component if possible. This component will plot as a straight line on the semi-log plot after interflow and supplemental baseflow storages have been drained completely. In the figure, the plot is not extended all the way out to this point. Extend the primary baseflow contribution back to under the peak of the hydrograph and then subtract the primary flow component from the total flow. The result is shown as 'total - primary' in the figure.

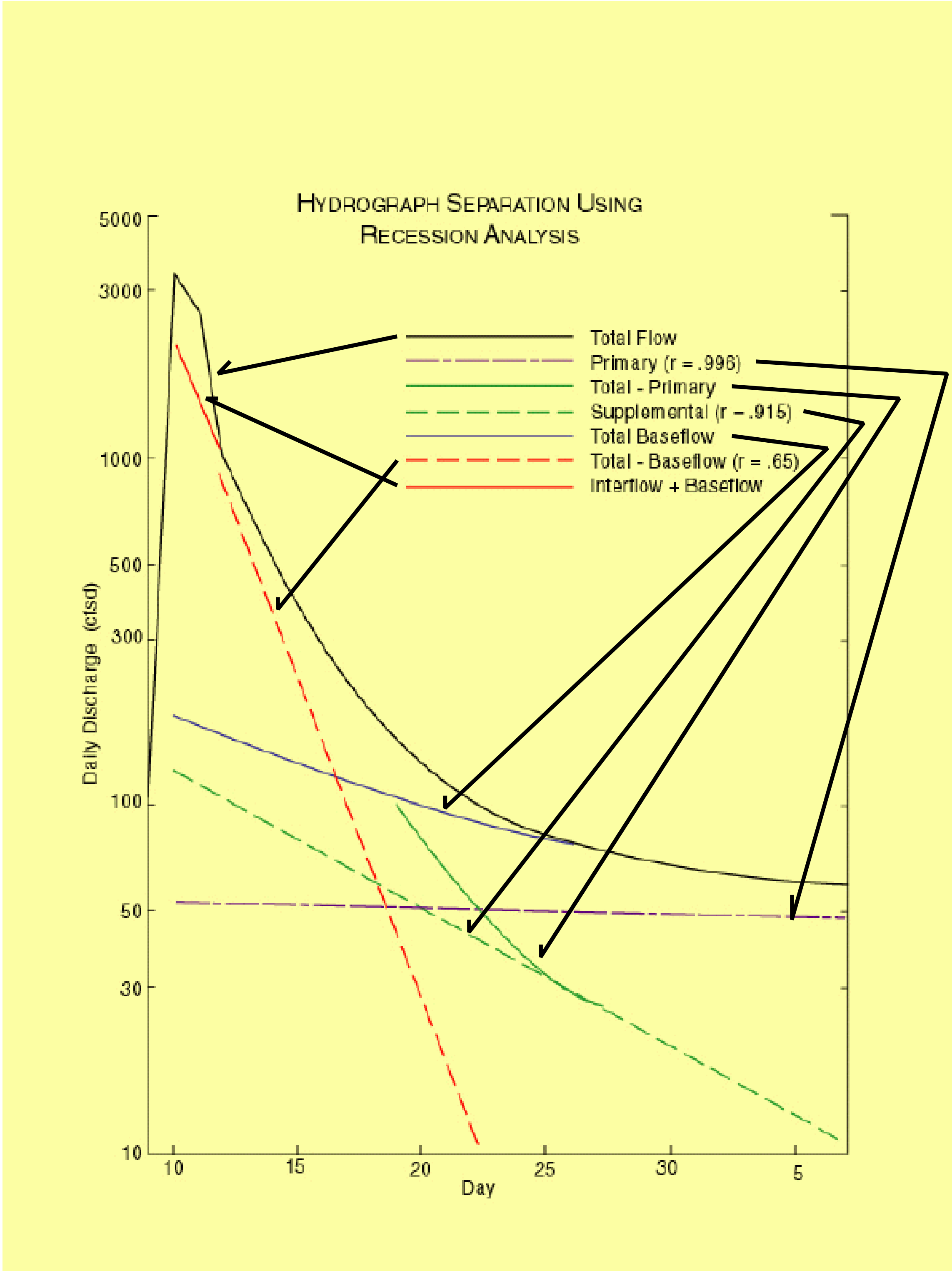


Figure 7-6-4. Illustration of a recession analysis using synthetic data.

• The straight line portion of the total minus primary line on the plot identifies the supplemental baseflow component. Extend the supplemental baseflow contribution back to under the hydrograph peak and then add the supplemental baseflow to the primary amount to get the total baseflow for this event. Then subtract the total baseflow from the total flow to get the ‘total - baseflow’ contribution. The total minus baseflow portion is shown on the plot starting at about the point where fast response runoff ceases though it could be extended back under the peak. In many real cases it is difficult to separate out primary and supplemental baseflow contributions, especially when the recession period is not very long or the supplemental withdrawal rate is quite slow. In these cases one would try to identify the total baseflow contribution, rather than dealing with primary and supplemental separately. The total baseflow recession will not plot exactly as a straight line on a semi-log plot since it is comprised of flow from two aquifers with different recession rates.

The ‘total - baseflow’ line will normally plot as a straight, or nearly straight, line on the semi-log plot. A recession rate can be computed for this segment. This is not the interflow recession rate, but instead an indication of how fast water is draining from the upper zone free water storage both as percolation and interflow. If soil moisture conditions are nearly saturated and this is a watershed with very low percolation rates under wet conditions, the amount of percolation should be small and thus, the total minus baseflow recession rate would be only slightly greater than the interflow recession rate and could be used to calculate an initial estimate of the Sacramento model UZK parameter. In most cases the ‘total - baseflow’ recession rate will be considerably greater than the interflow recession rate and can only be used as an extreme upper limit for UZK.

• The straight line portion of the ‘total - baseflow’ amount indicates the interflow contribution to the storm. This straight line segment is then extended back under the hydrograph peak and the total baseflow is added to the interflow contribution to obtain the amount of ‘baseflow + interflow’ for the event. This amount is only less than the total flow for a short time after the rain that produced the rise. During the remainder of the recession all the flow is either interflow or baseflow.

• The last step is to plot the total baseflow and the baseflow plus interflow amounts on an arithmetic plot as shown in Figure 7-6-5. Some subjectivity is needed when drawing the recharge portion , i.e. the period from when the hydrograph starts to rise until these flow components start to recede. The upper zone free water storage and thus interflow should typically peak a time interval or two after the storm peak, while baseflow recharge generally will take longer and thus, the baseflow contribution will not peak until a day or two after the storm peak.

The sum of interflow and baseflow can then be subtracted from the total instantaneous discharge amount to get the fast runoff, i.e. surface plus impervious, contribution to the storm. The surface plus impervious discharge is then used to derive the unit hydrograph .

to be used with the Sacramento model using textbook methods.

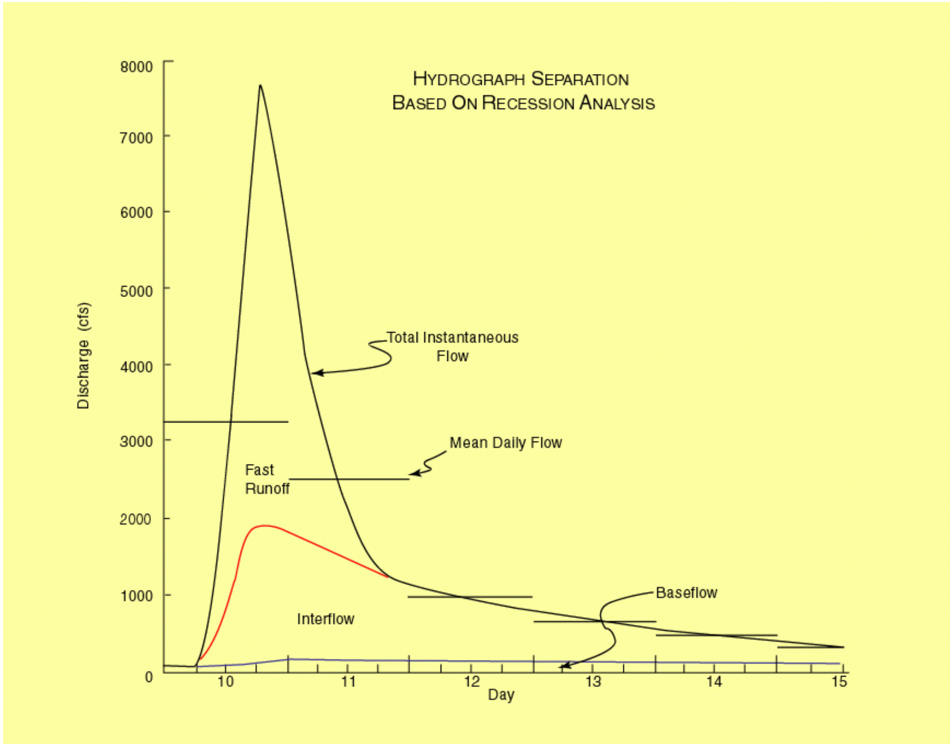
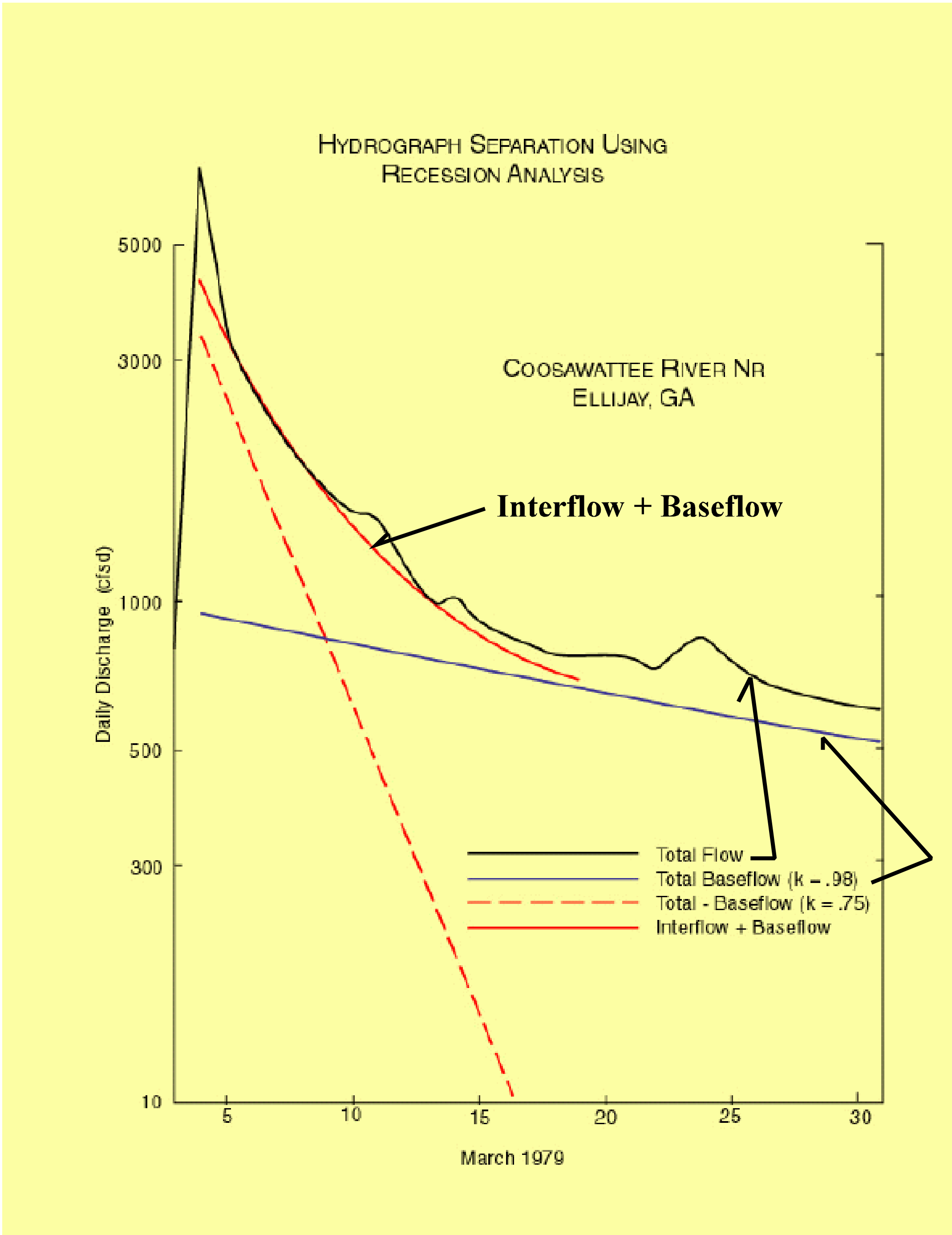


Figure 7-6-5. Separation of fast resonse runoff for deriving a unit hydrograph.

Figure 7-6-6 shows a recession analysis for an actual watershed. In this case there are several small events that occur in the period after the main storm, thus making it more difficult to determine the baseflow contribution. By looking at a low flow period further out in time than shown on the plot, the total baseflow contribution could be reasonably estimated. Then baseflow was subtracted from total flow to obtain the 'total - baseflow' amount and the straight portion of this line indicates the interflow contribution. 'Interflow + baseflow' was then computed and plotted for the storm event. Differences between total flow and 'interflow + baseflow' for the storm event that occur during the recession are the result of interflow and baseflow recharge from the subsequent small rainfall events. The total baseflow and 'interflow + baseflow' amounts are then plotted on an arithmetic plot as shown in Figure 7-6-7 to determine the fast runoff contribution to the storm hydrograph. Observed instantaneous discharge data were not available for this event so the total instantaneous flow was estimated by knowing the mean daily discharge amounts and the instantaneous peak flow. The rainfall for this event is also shown in the figure. The period of rain that generated most of the runoff was between 6 and 12 hours in length. Thus, the Sacramento model unit hydrograph computed from the fast runoff contribution to this event will be between a 6 and 12 hour unitgraph. An "S" curve analysis could be used to try and determine the appropriate time interval and then to compute a 6 hour unitgraph to be used with the model. If the storm event doesn't contain any fast response runoff, which was the case most of the time for the Ellijay watershed (surface runoff only occurs 3 times during the period of record), then the recession analysis should show that the entire rise is primarily from interflow and the event can't be used to determine an estimate of the unit hydrograph to use with the Sacramento model.



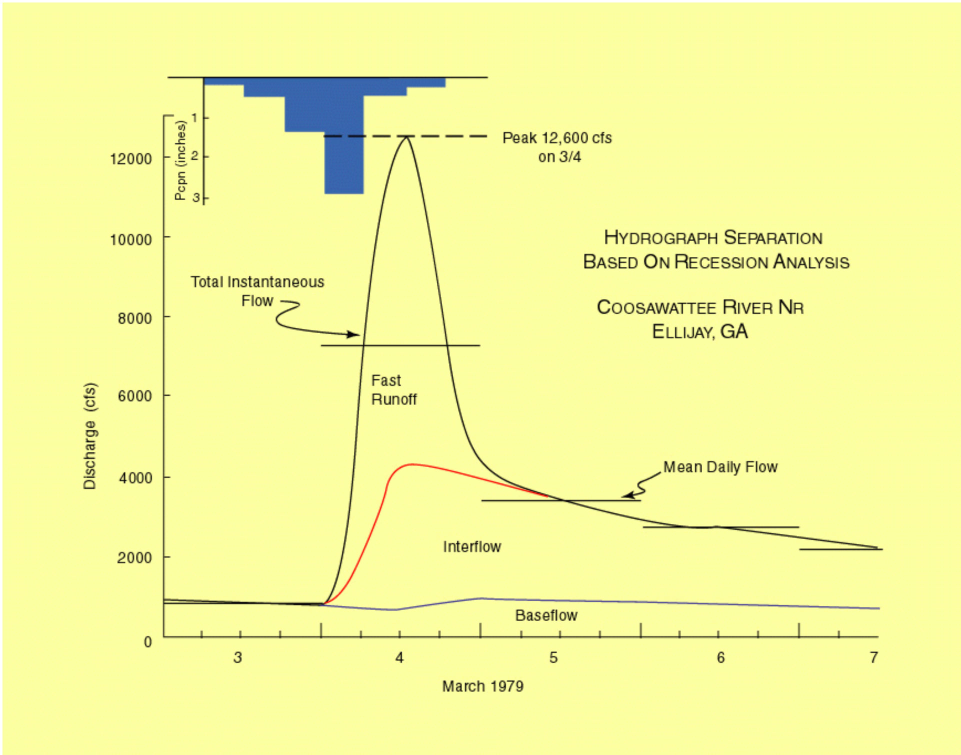
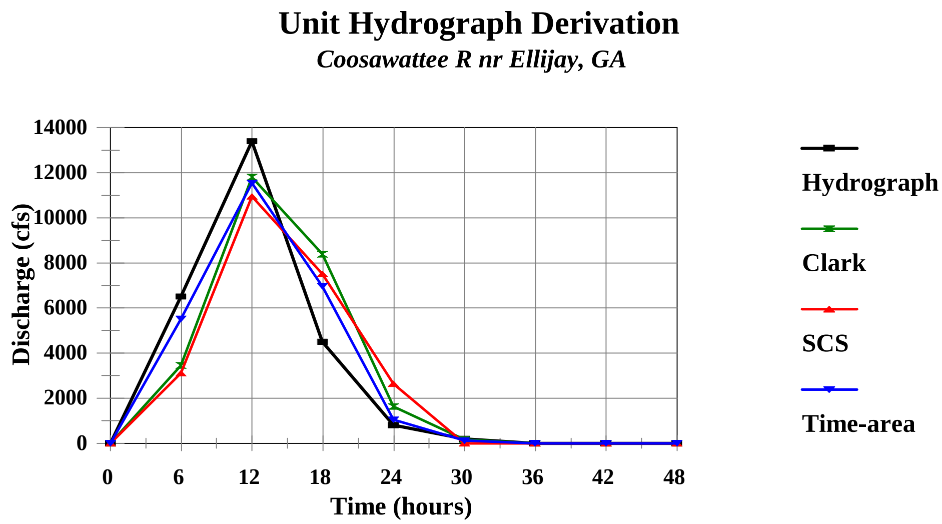


Figure 7-6-6. Recession analysis for the Ellijay watershed for March 1979 storm.

Figure 7-6-7. Fast runoff contribution to March 1979 storm for the Ellijay watershed.

<u>Derivation of an Initial Unit Hydrograph using Synthetic Methods</u>

If a unit hydrograph for use with the Sacramento model cannot be derived from precipitation and discharge data for the watershed, then there are a number of synthetic methods that have been proposed that are available. These methods generally fall into two categories. First



there are time of travel methods which compute the portion of the watershed contributing each time interval based on travel time estimates. Second there are methods that use watershed geometry to estimate the peak discharge, the time to peak, and the base of the unit hydrograph. These methods contain coefficients that are determined from unit hydrographs derived from actual watershed data though in many cases the coefficients may only represent a specific region and could be more appropriate for a traditional, i.e. API model, unitgraph. In addition to using a synthetic method, in some cases it is adequate to subjectively estimate the initial unit hydrograph to use with the Sacramento model based merely on typical time to peak information for major events, though this requires a certain amount of experience.

This author is not an expert on synthetic methods for deriving a unit hydrograph. Thus this manual will not include a discussion of the pros and cons of each procedure. The only warning offered when using a synthetic method is for slower responding watersheds where the storm hydrograph doesn't typically peak until days, rather than hours, after the rainfall or snowmelt occurs. For fast responding watersheds, most of the synthetic methods will give similar results, but for slower responding watersheds, none of the methods may produce the proper time delay. Figure 7-6-8 shows initial unit hydrographs generated from several methods for the Coosawattee River near Ellijay, Georgia which peaks quite quickly. Three

Figure 7-6-8. Unit hydrographs derived with different methods for Ellijay, GA.

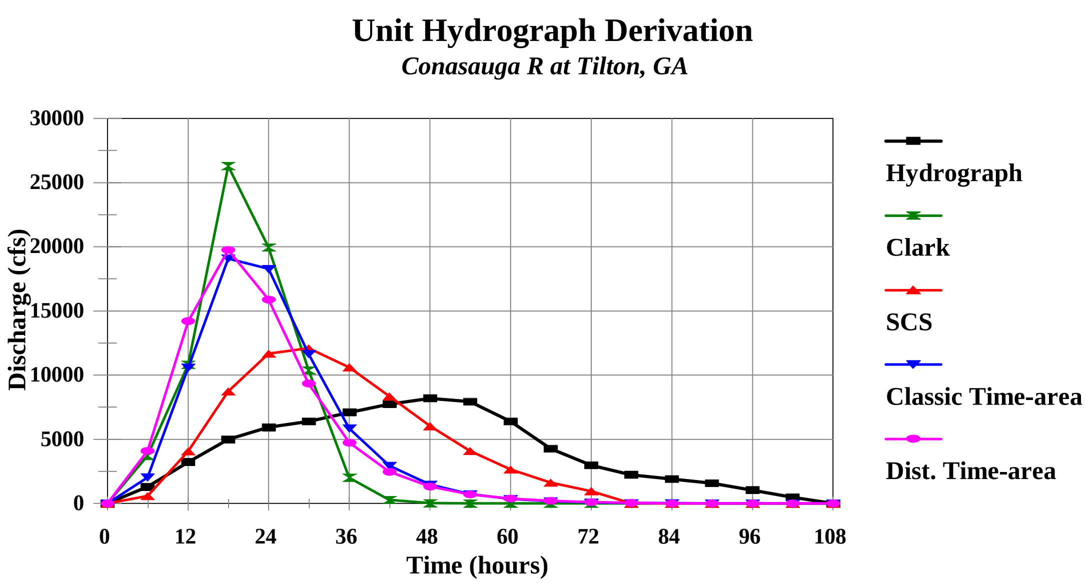
Figure 7-6-9. Unit hydrographs derived with different methods for Tilton, GA.

synthetic unit hydrographs are compared to one derived from actual hydrograph data. For this watershed that peaks in 12 hours, all the unitgraphs are quite similar. Figure 7-6-9 is for the Conasauga River at Tilton, Georgia. For this watershed that takes a couple of days to peak, the synthetic methods all produce unit hydrographs that peak much quicker than the one derived from actual storm data. The unitgraph generated by the SCS method is more delayed than the other synthetic ones, however, the person who generated the synthetic unitgraphs was warned prior to running the SCS method that the time delay was quite a bit longer than the other synthetic methods were showing and thus the coefficients were changed based on this information to produce a longer delay. For watersheds that don't have a unit hydrograph with the typical shape associated with most drainage areas, generally due to the geometry of the drainage area, the time-area methods should have a better chance of having the proper shape than other synthetic methods, though there still may be problems with the timing for slow responding watersheds.

Other Considerations when Deriving Initial Unit Hydrographs

There are several other items that should be considered when deriving and using unit hydrographs. These include:

Watersheds with Multiple Zones - When a watershed is divided into several zones, typically



either based on elevation or travel time, for rainfall-runoff computations, there are two basic sequences that can be followed when applying a unit hydrograph. First, the runoff from each zone can be weighted and the resulting mean watershed runoff can be applied to a single unit hydrograph for the drainage area. Second, the runoff from each zone can be applied to a separate unit hydrograph and then the results combined to produce the instantaneous flow hydrograph for the watershed. If separate unitgraphs are to be used for each zone, it is generally not possible to derive the response for each zone from a hydrograph analysis unless events can be found where all of the runoff comes from only one zone per event. Typically in this case one of two approaches are followed. One approach is to derive a total watershed unit hydrograph from storm data and then divide it into unitgraphs for each zone in such a way that the combined response is the same as the unit hydrograph derived for the total area taking into account that the runoff contribution from each zone may not have been the same. Another approach is to use a synthetic method to derive the unitgraph for each of the zones individually. For zones where no runoff reaches the designated river location for some period of time, i.e. there is some distance between the river location and the closest part of the zone, either zero ordinates can be inserted at the beginning of the unitgraph or the LAG/K operation can be used to lag the unitgraph by the required amount.

For watersheds that are divided into multiple zones based on travel time, separate unit hydrographs should be used for each zone or it defeats the purpose for subdividing the watershed. For watersheds with multiple elevation zones, it depends largely on the distribution of the elevation zones as to whether single or multiple unit hydrographs should be used. When the elevation zones are significantly related to distance from the river location, then separate unitgraphs are recommended for each zone. However, when the higher elevation zone has sort of a horseshoe pattern around the watershed divide (thus some portions of the upper zone are closer to the gage than a large part of the lower zone) then the use of a single unit hydrograph for the watershed is generally adequate. Also, in these cases it is typically very difficult to derive separate unitgraphs that can be verified as to their timing and shape.

<u>Time Interval of Ordinates</u> – Unit hydrographs are designated with a time interval that represents the time interval associated with the runoff being applied to the unitgraph. Thus, if 6 hour runoff data are being calculated and passed through a unit hydrograph to obtain discharge at a point on the river, a 6 hour unit hydrograph must be used. The time interval associated with the unit hydrograph has nothing to do with the ordinate spacing that is used to define the unitgraph. A unit hydrograph is a continuous curve that defines the instantaneous hydrograph produced by one unit of runoff over a specified time interval. The ordinates that are used to define that curve can be at whatever time interval is necessary to adequately define the shape of the curve. Thus, for example, if a 6 hour unit hydrograph for a watershed typically peaks in 15 hours, 3 hour ordinate spacing should be used to define the unitgraph so that the peak will occur in 15 hours and not in 12 or 18 hours as would be required if the ordinates were defined at 6 hour intervals.

<u>Variable Channel Response</u> – For some watersheds the shape and timing of the unit

hydrograph is related to the flow level. This normally occurs when the channel width increases significantly as the flow goes over the bank and there is considerable roughness in the flood plain. This is the same physical situation that exists for channel reaches that require variable routing parameters at different flow levels. This situation is quite common in areas with only a slight amount of channel slope, a fairly broad flood plain that contains a lot of vegetation, and flood levels that can be considerably higher than the flood plain elevation. Typically for such watersheds the channel response has much more attenuation when the stream first goes out onto the flood plain and then the attenuation decreases as the flow level increases and the effect of the flood plain roughness is diminished. This effect can be modeled by using a routing procedure that allows a variable amount of attenuation, such as a variable K in the LAG/K operation, as a function of the flow level immediately after the unit hydrograph is applied. The unit hydrograph defined is for the flow level with the minimum amount of attenuation and then attenuation is added as needed at other flow levels with the routing model.

Section 7-7

Effect of Snow Model Parameters on Model Response

Introduction

A critical aspect of interactive trial and error calibration is to understand the unique effect that each parameter has on model response and how to isolate that effect. This understanding allows the person doing the calibration to make educated decisions as to which parameter values should be changed as opposed to random guesses. Without this understanding, interactive calibration becomes an exercise in futility.

This section describes the unique function of each of the major snow model parameters and also discusses things to examine when deciding which, if any, parameters should be changed when simulated and observed flows don't agree at the beginning of the snowmelt season. The unique aspects of each parameter are illustrated by hydrograph plots for the appropriate time periods with different values of the parameter being considered. These plots are generated by running the models with everything exactly the same except for the value of the parameter being discussed. Under such conditions the unique effect of each parameter can clearly be shown. The actual problem of deciding on which parameters to change becomes much more difficult during calibration because of noise in the data and the fact that typically multiple parameters need to be adjusted. The combination of the effects of multiple parameters not having the proper value make it much more difficult to determine which parameter values need to be altered. To have any hope of making the proper changes in a reasonable amount of time, one must know what periods to examine and what to look for to isolate the effects of each parameter. It is also helpful to have a systematic strategy for checking the parameters for possible changes. Such a strategy is outlined in Section 7-1.

Besides plots showing the effect of changing each of the parameters, panels that show how the model states are changing and other results of the model computations are included in many of the figures. These panels are extremely helpful in determining when the conditions occur that are needed to isolate the effects of the parameter. An explanation of the items included in these panels is in the next section. Even though two hydrograph plots are included on each figure to show the difference in response with different values of the parameter, the panels showing the model states and computations can only be included for one of the parameter values for a single zone. This value and zone are indicated next to the panels on each figure.

Explanation of Panels Showing Model States and Computations

Figure 7-7-1 illustrates the panels which are part of the ICP WY-PLOT display for the SNOW-17 operation. The plots on these panels are for a daily time interval. Instantaneous values such a water-equivalent are for the end of the day and mean, average, or total values such as energy exchange and air temperature are the mean, average, or total for the day.

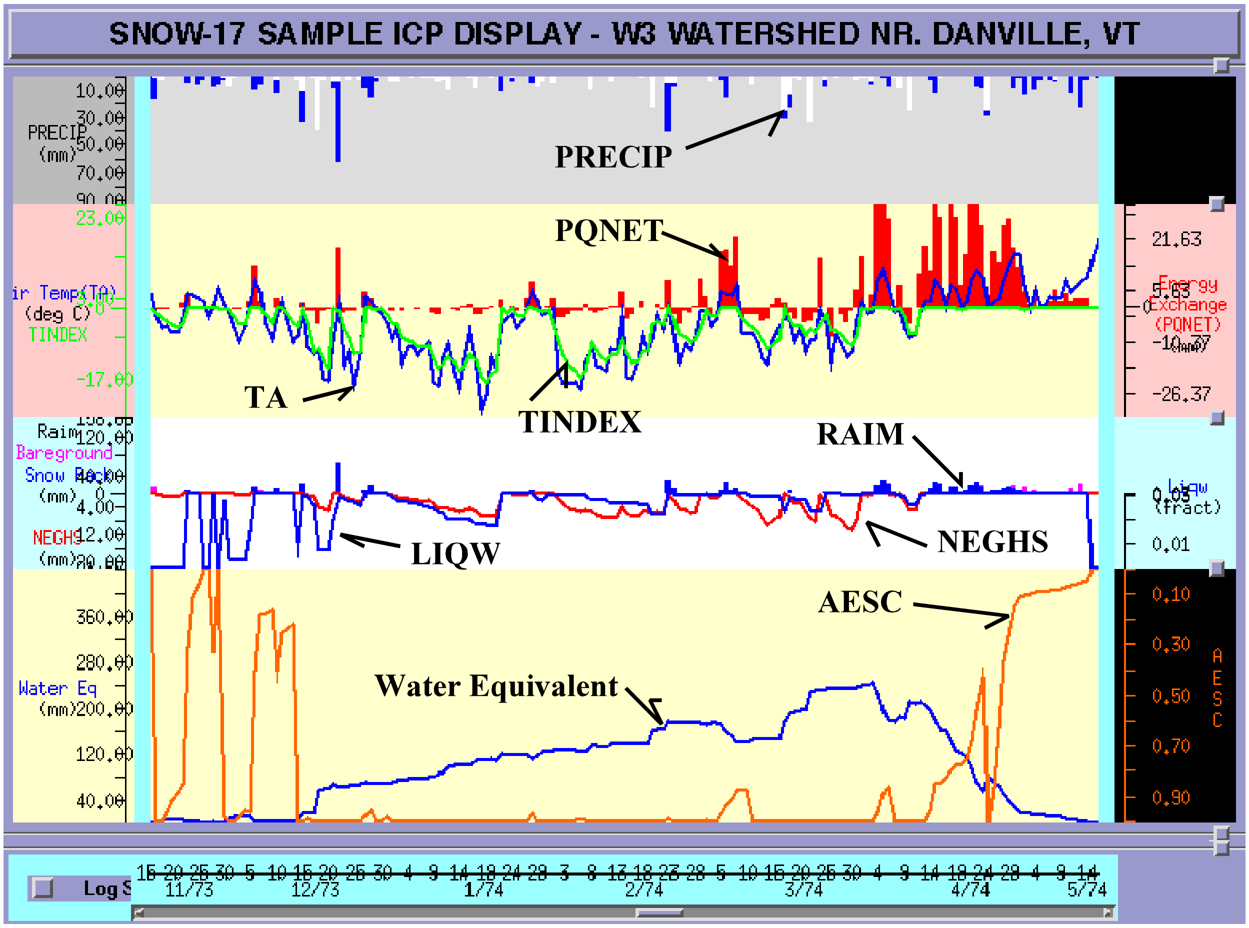


Figure 7-7-1. Sample ICP display for the SNOW-17 model.

• <u>Top Panel</u> – This panel shows the total amount of precipitation (PRECIP) for each day with the scale on the left side. The portion in blue indicates that the precipitation was rain, while the portion in white indicates snow. If the rain-snow elevation option is used, this panel will also contain the average elevation of the rain-snow line if it is within the elevation range of the zone. The rain-snow elevation scale will be on the right side.

• <u>Second Panel from Top</u> – This panel shows the average daily air temperature (TA) in blue and the average daily snow cover temperature index (TINDEX) in green with the scale on the left side. The gradient defined by these two variables indicates the direction of heat flow when the air temperature is below freezing. The panel also contains the total daily net energy exchange (PQNET) in red with the scale on the right side. The units of the energy exchange are mm (that is the energy needed to melt 1 mm of snow). The energy exchange is the combination of non-rain melt, rain-on-snow melt, and changes in the heat deficit of the snow cover during the day.

• <u>Third Panel from Top</u> – This panel shows the amount of liquid water (LIQW) in the snow cover in blue with the scale on the right side. The maximum amount of liquid water is controlled by the PLWHC parameter. The brown line shows the heat deficit or negative heat storage (NEGHS) in the snow cover at the end of each day with the scale on the lower left side. The units for NEGHS are mm, i.e. the amount of melt or rain that is needed to return the snow cover to isothermal conditions at 0°C. This panel also shows the total amount of rain plus melt (RAIM) for each day with the scale on the upper left side. When the RAIM is in blue it indicates water that came from the snow cover (either melt or rain water that passed through the snow), while when RAIM is in magenta, it indicates rain on bare ground.

Bottom Panel – This panel shows the total amount of water equivalent in blue with the scale on the left side. This is the sum of the ice portion of the snow cover, any liquid water, and water moving through the snow at the end of each day. The panel also shows the computed areal extent of the snow cover (AESC) in brown with an inverted scale on the right side (bottom of plot is 100% cover and the top is bare ground).

Major Snow Model Parameters

This section describes the unique effect of each of the major snow model parameters. Examples are included for a watershed with a single zone and for most parameters, examples are also shown for watersheds with multiple elevation zones.

SCF – The snow correction factor is the only snow model parameter that controls the amount of snow that accumulates and thus the volume of snowmelt runoff. This is assuming that significant errors in the form of precipitation have been corrected. The effect of SCF shows up in the later part of the snowmelt season, i.e. when either too much or too little snow may remain and thus continues the snowmelt period beyond when it should end or cause melt to stop too soon. This is the period to examine to determine if there is a problem with the amount of snow. The higher the value of SCF the more snow will accumulate and the longer snow will remain and vice versa.

Figure 7-7-2 shows the effect of changing the value of SCF on the volume of snowmelt runoff for a watershed with only one zone. There is no difference during the period when there is 100% cover with both values of the parameter. The difference occurs during the later part of the melt season when the increase in the amount of snow with SCF=1.4 results in more runoff volume. Once the snow is gone, the difference in response between the two values disappears over time. There is some difference in runoff from the large rain event near the end of May, since the soil is more saturated at that time when SCF=1.4 due to a longer period of snowmelt, but by the rain event in mid June, the difference is minimal.

Figure 7-7-3 shows the effect of changing SCF for just the upper elevation zone of a mountain watershed for a year with a large enough amount of snow that the upper area remains at 100% cover for some period of time after melt begins and there is no significant rain during the snowmelt season. The figure also shows what portion of the runoff is

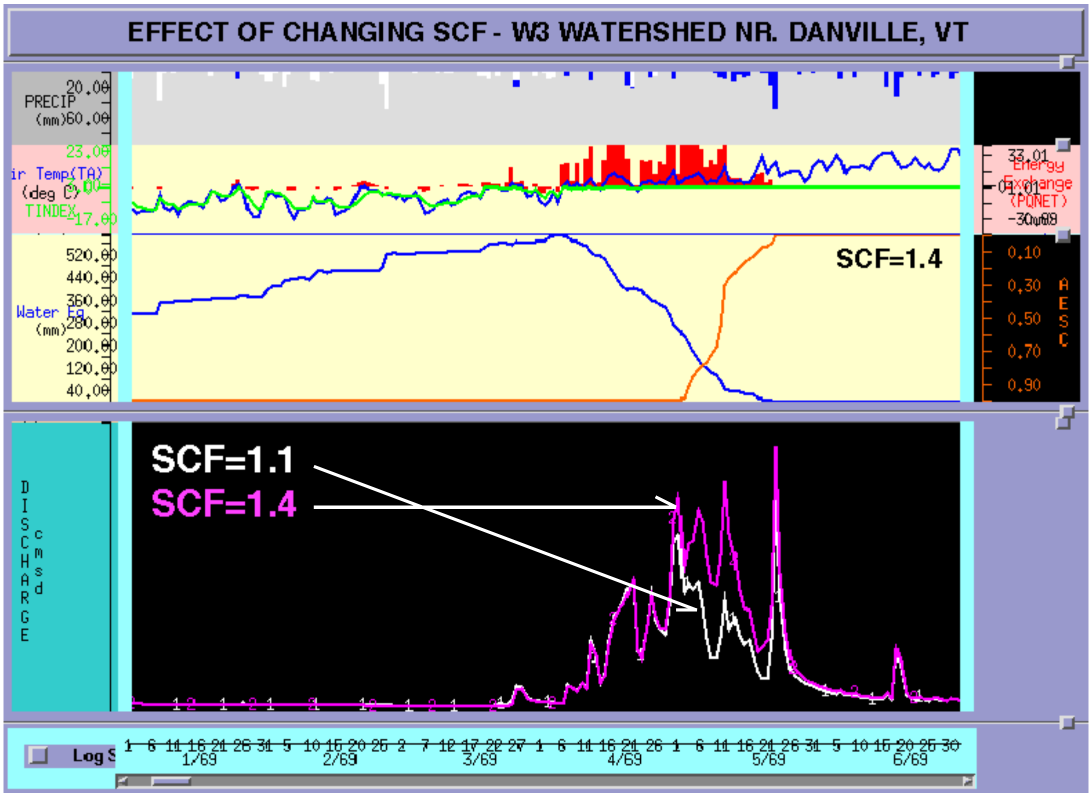
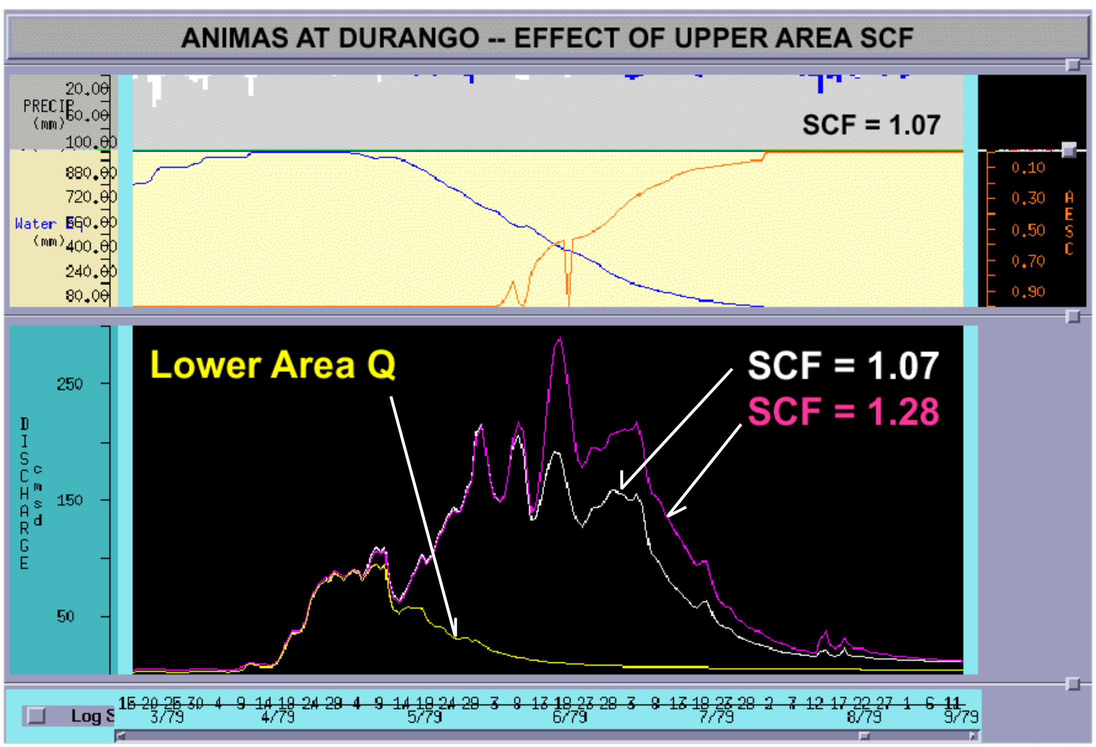


Figure 7-7-2. Effect of changing SCF for a watershed with one zone.



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e 7-7-3. Effect of changing SCF for an upper elevation zone.

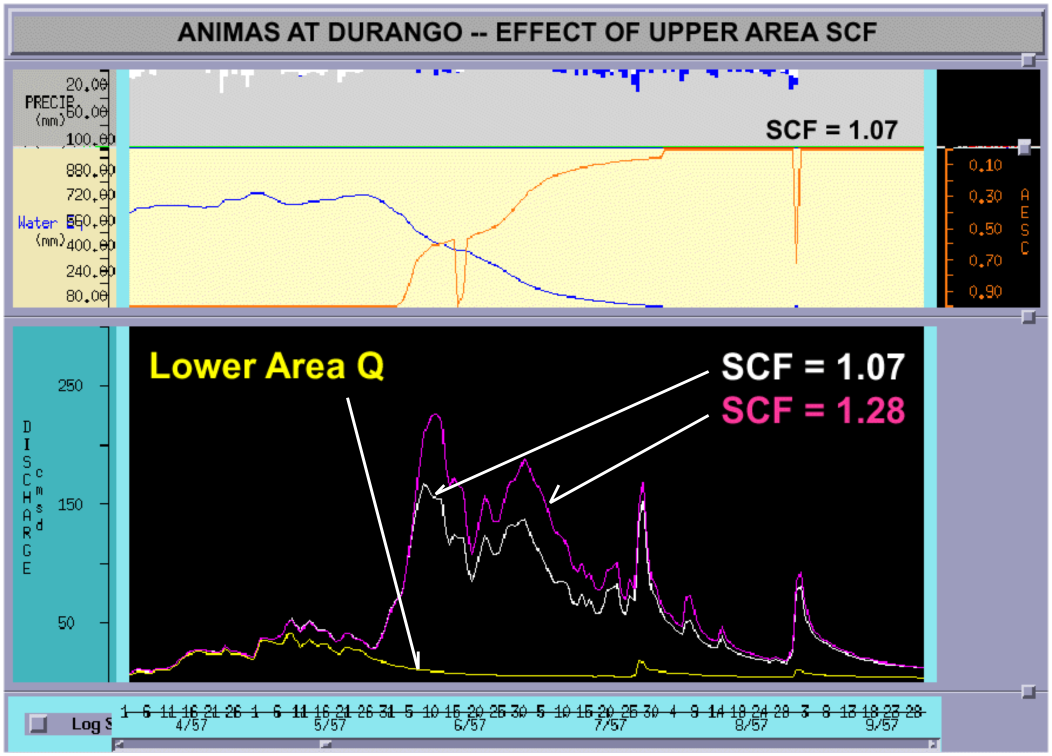


Figure 7-7-4. Effect of changing upper zone SCF with rain near the end of melt.

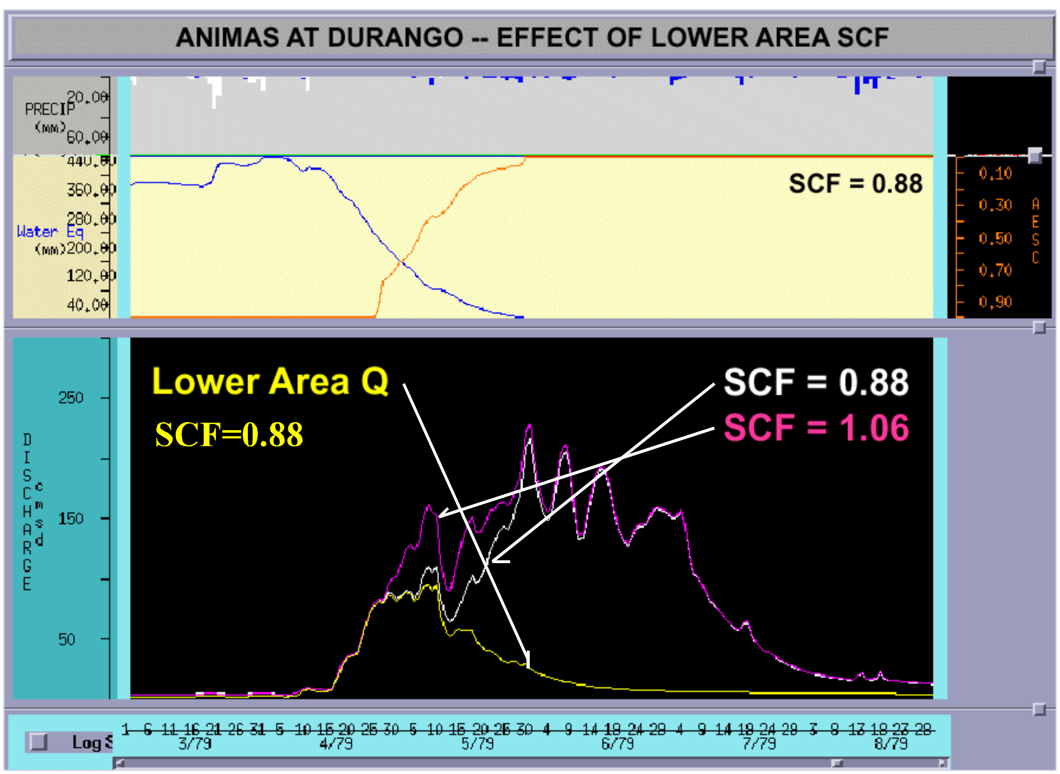


Figure 7-7-5. Effect of changing SCF for a lower elevation zone.

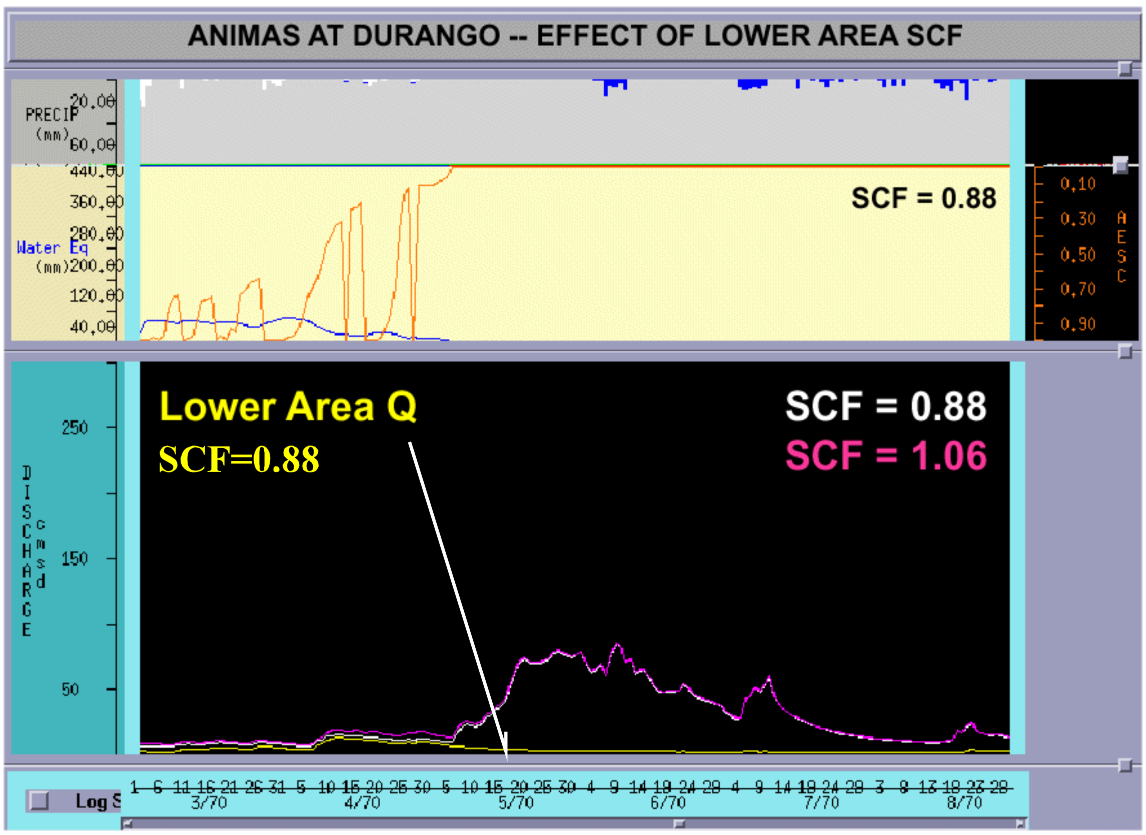
produced by the lower zone. It is very important when working with watersheds with multiple elevation zones to known the contribution of each zone. The response to snowmelt is the same as in the previous figure since the upper zone melts off last and there are several weeks with 100% cover after melt begins. Figure 7-7-4 shows the same case for another year for the same watershed. During this year the upper zone only remains at 100% cover for a short period after melt begins and the lower zone contribution is much less than in the previous example. Also during this year there is a significant amount of rain late in snowmelt season and for some time thereafter. Again the primary effect of changing SCF is to alter the amount of snow accumulation and thus the volume of runoff from snowmelt. There is some effect on the amount of runoff from the rain events, but this is small and diminishes with time. Figure 7-7-5 shows the effect of changing SCF for the lower zone for the same year as shown in Figure 7-7-3. This is a year when there is substantial volume of snowmelt runoff from the lower zone. Again by increasing the value of SCF, the volume of snowmelt runoff is increased, however, since the lower zone melts off well before the upper zone, the effect shows up toward the early part of the snowmelt season for the entire watershed. Figure 7-7-6 illustrates the effect of changing the lower zone SCF value on a year with little snowmelt runoff from the lower zone. In this case since the snowmelt runoff volume from the lower zone is minimal, the effect of changing SCF for this zone has little effect on the hydrograph.

Figure 7-7-6. Effect of changing lower zone SCF during a low snow year.

To repeat, the unique effect of the SCF parameter is to control the amount of snow accumulation and thus the volume of runoff from snowmelt. It is the only snow model parameter whose primary effect is to control the runoff volume.

Under the SCF parameter initial value discussion in Section 7-4 it was mentioned that when average annual precipitation is based on the water balance (determined by adding an estimate of actual annual ET to mean annual runoff) that the result could be too much rain and not enough snow. If this appears to be the case for such watersheds, the PXADJ factor in the SNOW-17 operation can be decreased below 1.0 to reduce the amount of rain and then SCF increased as necessary to obtain the correct amount of snow cover runoff.

MFMAX and MFMIN – These two parameters determine the maximum and minimum value of the non-rain melt factor. MFMAX has more effect when most of the melt occurs after March 21st, while MFMIN has more effect on melt that occurs prior to that date. The non-rain melt factor is used to determine the melt rate when the area is completely covered by snow, thus the effect of these parameters can be isolated when non-rain melt is occurring and



there is 100% or nearly complete areal snow cover. SCF and the areal depletion curve have no effect when there is 100% cover and UADJ is only used when there is rain-on-snow melt occurring. A variety of factors can affect when the onset of melt occurs and the response during the very early part of the melt season (these will be discussed later in this section), thus it is best to examine the period after melt is well underway and there is still complete or nearly complete areal cover to determine if the non-rain melt factor should be altered. Since the non-rain melt factor varies seasonally and melt can occur at different times, one technique that may prove useful is to plot the seasonal melt factor variation and then note when the results would be improved by changing the melt factor up or down and when it should be left the same. After examining a number of years, hopefully there will be a pattern to the suggested changes and a new seasonal melt factor curve can be drawn and new values of MFMAX and MFMIN determined for the next iteration.

Figure 7-7-7 shows the effect of changing both MFMAX and MFMIN. In this case MFMAX has the most effect since almost all the melt occurs after March 21st. The overall effect of changing these melt factors is to cause more melt to occur early in the melt season and thus less later because the snow will be gone sooner. To isolate the effect of these parameters the period to examine is from after melt begins to when bare ground begins to show, i.e. from late March until about the 21st of April. There is a difference in the hydrographs later in the melt season, but this is not the period to use to determine if the non-rain melt factor needs to be adjusted as other snow model parameters can also affect this later period.

Figure 7-7-8 shows the effect of changing MFMAX for both elevation zones of a mountain watershed during a big snow year when there is significant snowmelt runoff from the lower elevation zone. Again the overall effect of increasing MFMAX is to cause more melt to occur early in the melt period, in this case for both elevation zones. Figure 7-7-9 shows the same change for a small snow year when there is little snowmelt runoff from the lower

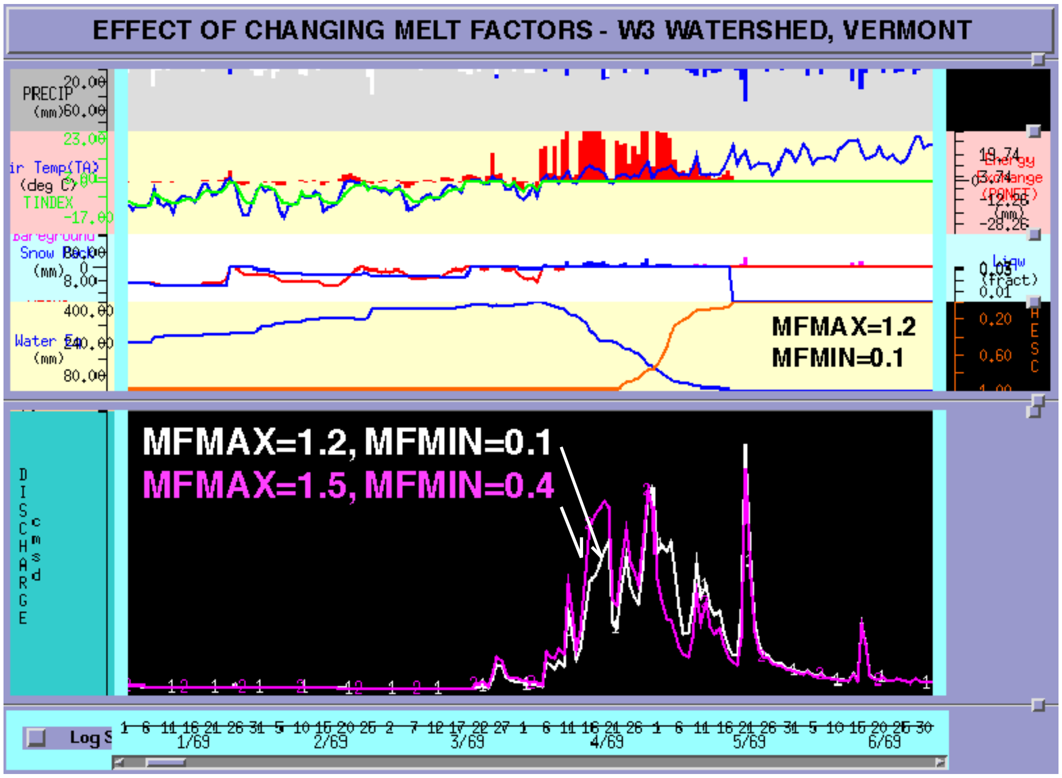


Figure 7-7-7. Effect of changing MFMAX and MFMIN for a watershed with one zone.

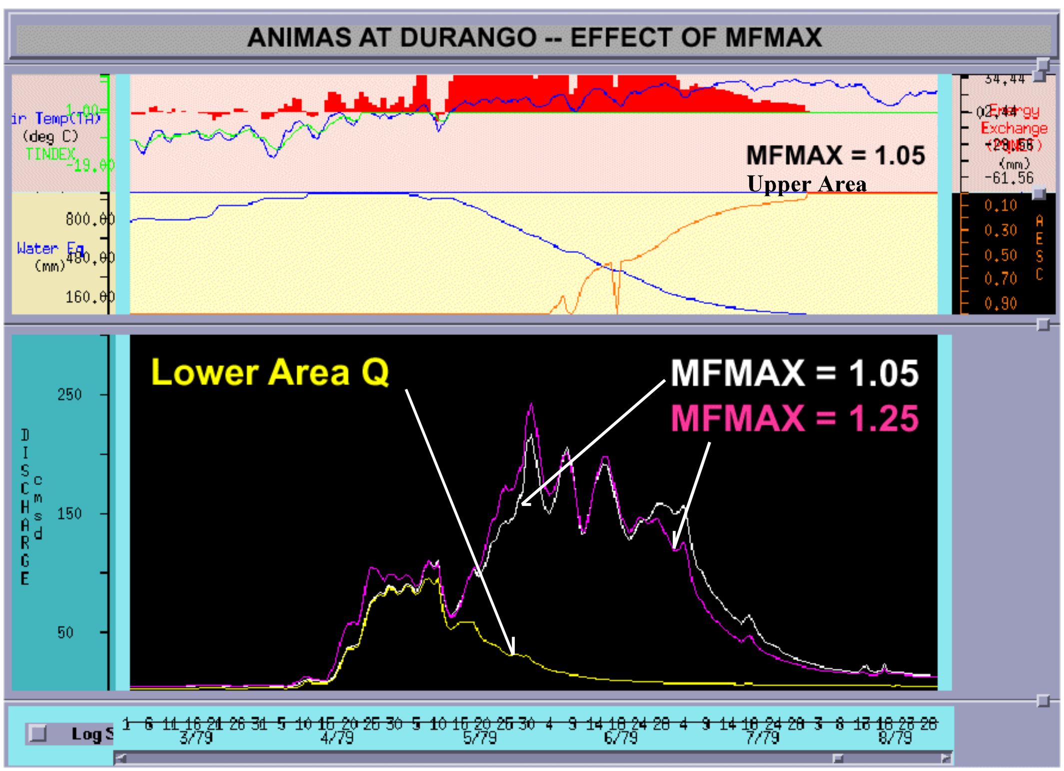


Figure 7-7-8. Effect of changing melt factors for 2 elevation zones during a big snow year.

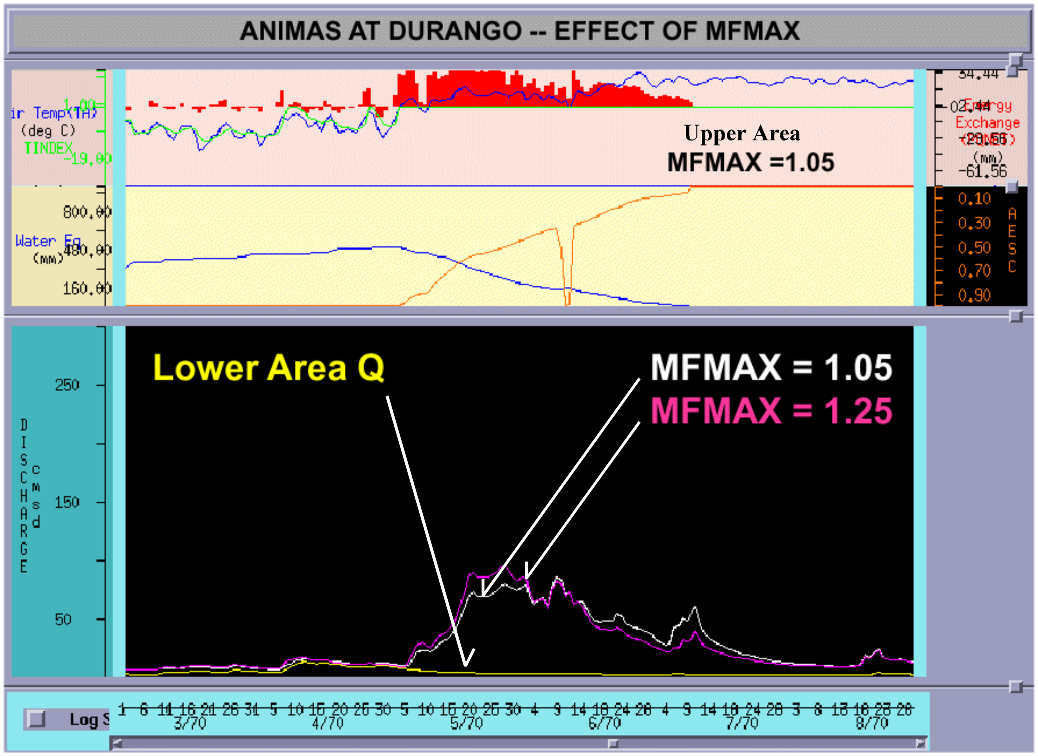


Figure 7-9. Effect of changing MFMAX for 2 elevation zones for a small snow year.

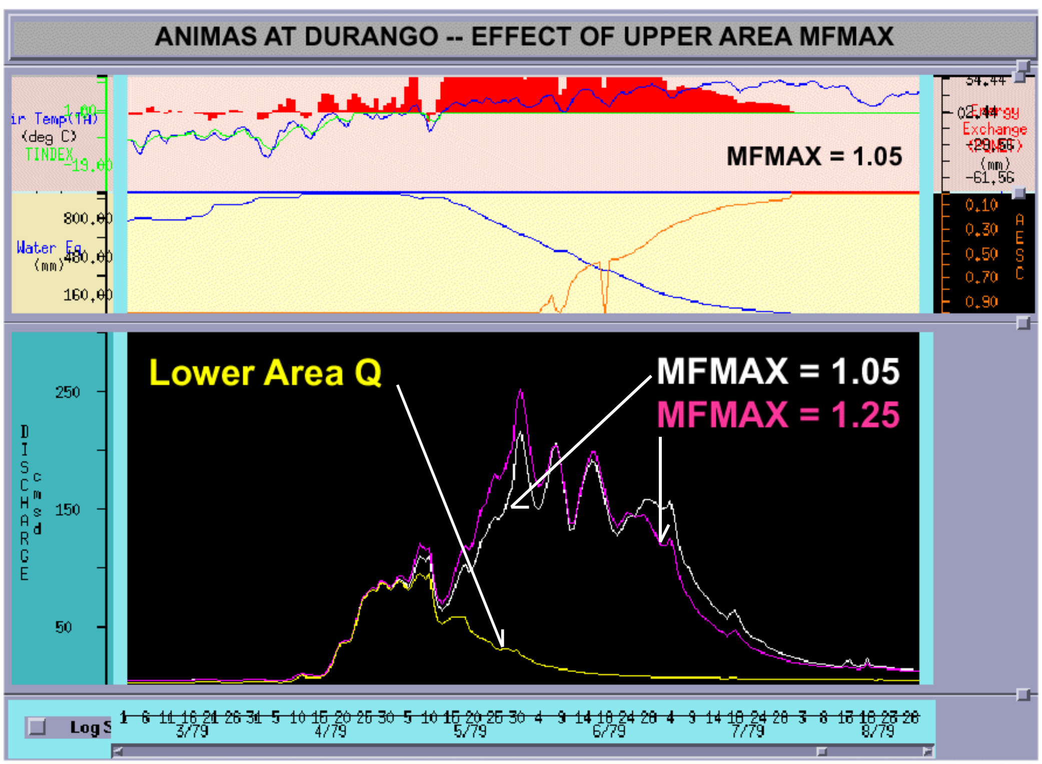


Figure 7-10. ect of nging MAX the per vation e only.

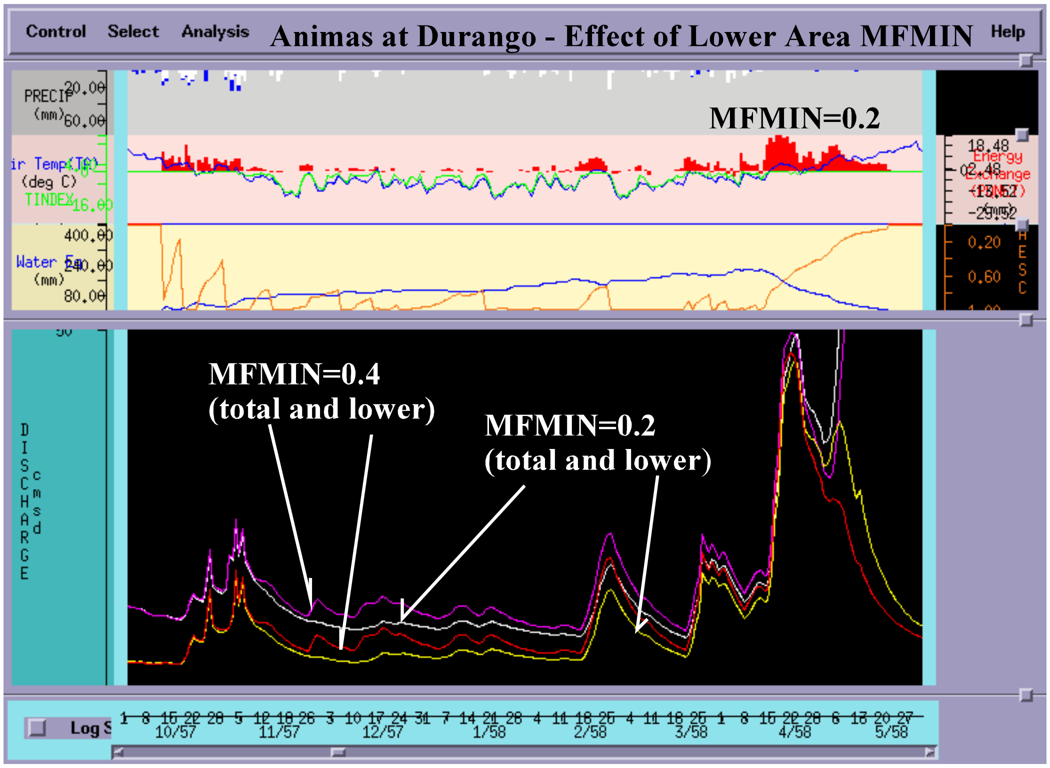


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Figure 7-7-11. Effect of changing MFMIN for the lower elevation zone.

elevation zone. In this case the effect of increasing MFMAX for the lower zone is not noticeable since this zone produces little runoff. For lower elevation zones the effect of changing snow model parameters will only be visible during years when these zones have sufficient snow to produce a significant amount of runoff. Figure 7-7-10 shows the effect of changing only the MFMAX parameter for the upper elevation zone during a large snow year. In this case the timing of the melt from the upper zone is affected which again underscores the importance of knowing where the runoff is coming from when multiple zones are being used. Figure 7-7-11 shows the magnified effect of changing the MFMIN parameter for the lower elevation zone for this same watershed. Increasing the MFMIN value causes more melt during mid winter periods when the temperature goes above freezing at the lower elevations. Changing MFMIN for the upper zone wouldn't affect these periods since the temperatures remain below freezing at the higher elevations. In many watersheds in the intermountain west, MFMAX is the most important melt factor parameter since most melt occurs in the spring, however, in some cases there is some winter melt at lower elevations which allows for checking the value of MFMIN for the lower zone. The value of MFMIN for the upper zone is fairly insensitive for these watersheds.

To repeat, the unique characteristic of the non-rain melt factor parameters is that they determine the melt rate when there is 100% snow cover, thus the effects of MFMAX and MFMIN can be isolated once melt has really started and the area is completely, or nearly completely, covered by snow.

<u>SI</u> – The SI parameter determines when and for how long the area remains at 100% areal cover. During small snow years, typically bare ground shows up as soon as significant melt occurs. During large snow years, most areas remain at or near 100% areal cover for some period of time after melt begins. Thus, the effect of SI can generally be isolated by examining the snowmelt patterns during years with different amounts of snow accumulation. In Section 7-4 it was recommended that the initial value of SI be set to a value greater than any mean areal water equivalent that will occur during the period of record. If this is done, the initial run will show bare ground showing up as soon as melt begins for all years. Then one can examine the larger snow years to see if more melt is needed for some period into the snowmelt season. By tabulating the water equivalent values above which more melt is needed, one can determine a reasonable guess at a value of SI to try.

Figure 7-7-12 shows the effect of SI on a large snow year. When SI=999, bare ground shows up as soon as the snow begins to melt. When SI=200, the watershed remains at 100% areal cover until the mean areal water equivalent drops below 200 mm. This causes the entire area to contribute melt until the water equivalent (WE) drops below 200 mm. Figure 7-7-13 shows the same parameter combination for a small snow year. In this case there is almost no change in the response since the mean areal water equivalent barely exceeds 200 mm and thus, in both cases bare ground shows up soon after melt begins.

Figure 7-7-14 shows the effect of SI for the upper zone on a watershed with 2 elevation zones during a large snow year. When using a value of SI=600 mm, the melt continues over 100% of the area until the water equivalent reaches the SI value near the middle of June. When SI=999, the areal cover begins to deplete as soon as outflow is initiated from the snow cover in the upper zone in early May. This causes the mean areal melt to be less than what would occur if the zone had remained completely covered. Figure 7-7-15 shows the effect of SI for the upper zone during a small snow year. In this case there is no difference in the response since the mean areal water equivalent never exceeds 600 mm. Figure 7-7-16 shows the effect of using a value of SI that causes both zones to remain at 100% areal cover for a significant time after melt begins during a large snow year. This increases the snowmelt contribution from both zones during this period.

To repeat, the effect of the SI parameter can be isolated by examining the early part of the melt season, i.e. the same period as used to isolate MFMAX and MFMIN, only in the case of SI one is looking for differences in response between large and small snow years. SI allows for 100% of the area to contribute for some period during years with a large snow accumulation, but not during small snow years.

Areal Depletion Curve – The areal depletion curve controls the amount of snowmelt once bare ground begins to appear. Thus, it is the timing of snowmelt whenever the mean areal water equivalent is less than SI that is examined to determine if the shape of the areal depletion curve should be altered. The best way to determine how the curve should be changed is to plot the areal depletion curve and then go through each of the years in the

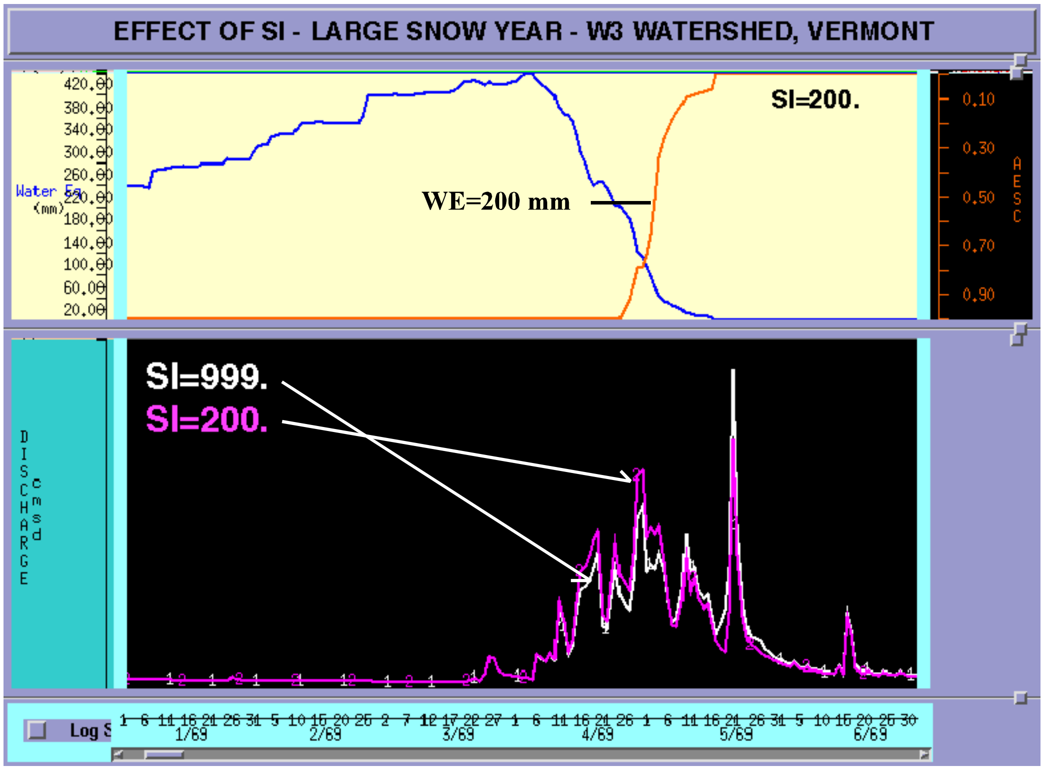


Figure 7-12. Effect of SI on a large snow year for a single zone watershed.

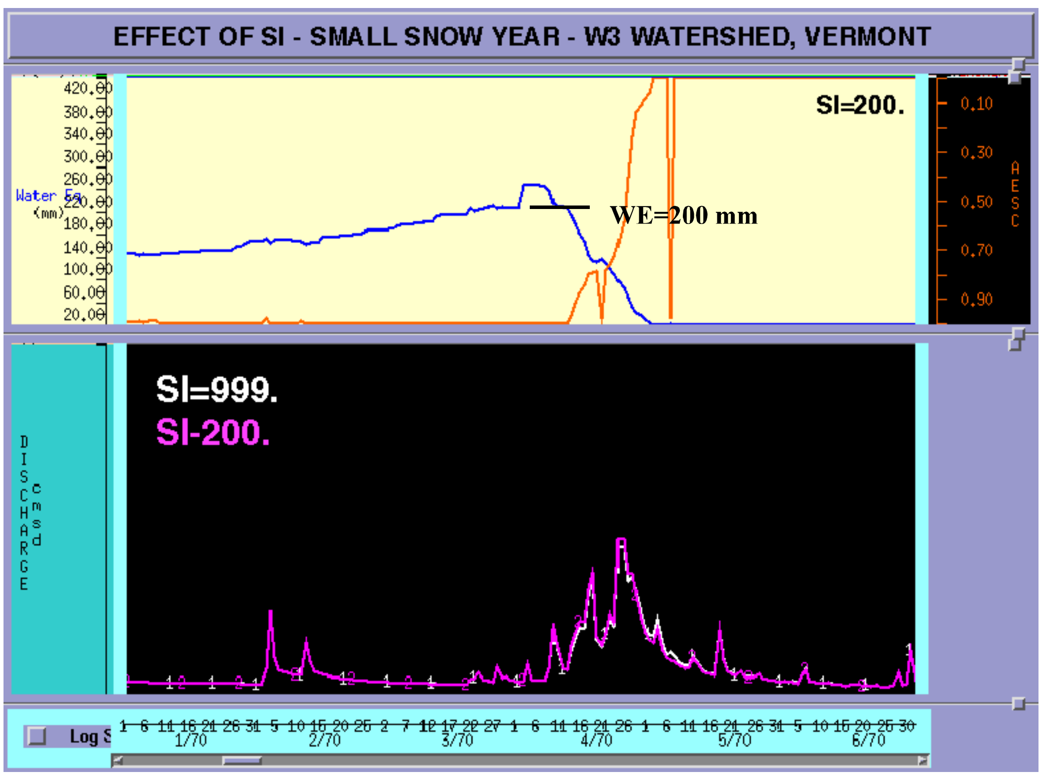


Figure 7-7-13. Effect of SI on a small snow year for a single zone watershed.

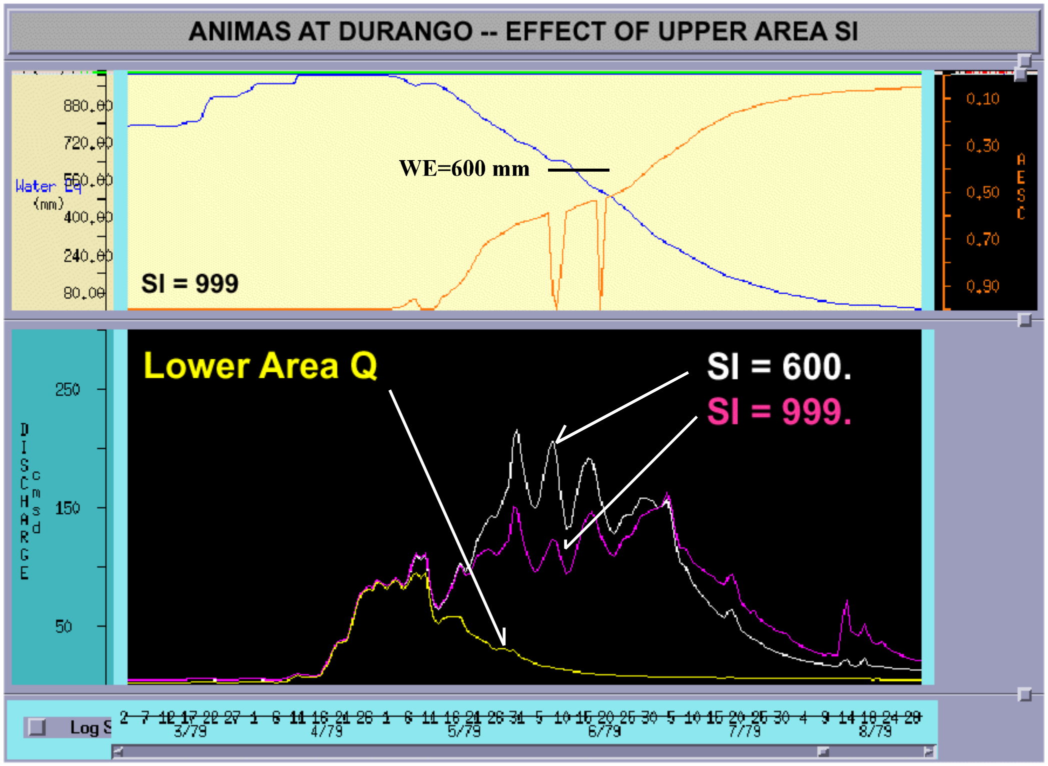


Figure 7-7-14. Effect of changing SI for a upper zone for a large snow year.

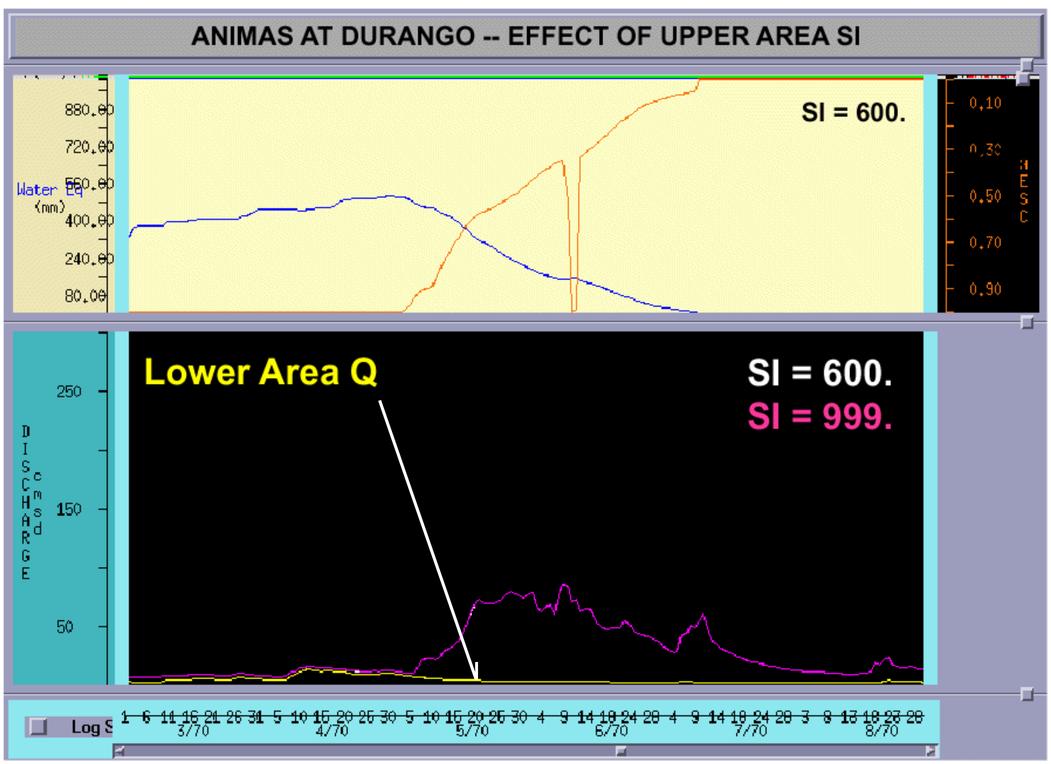


Figure 7-7-15. Effect of changing SI for a upper zone for a small snow year.

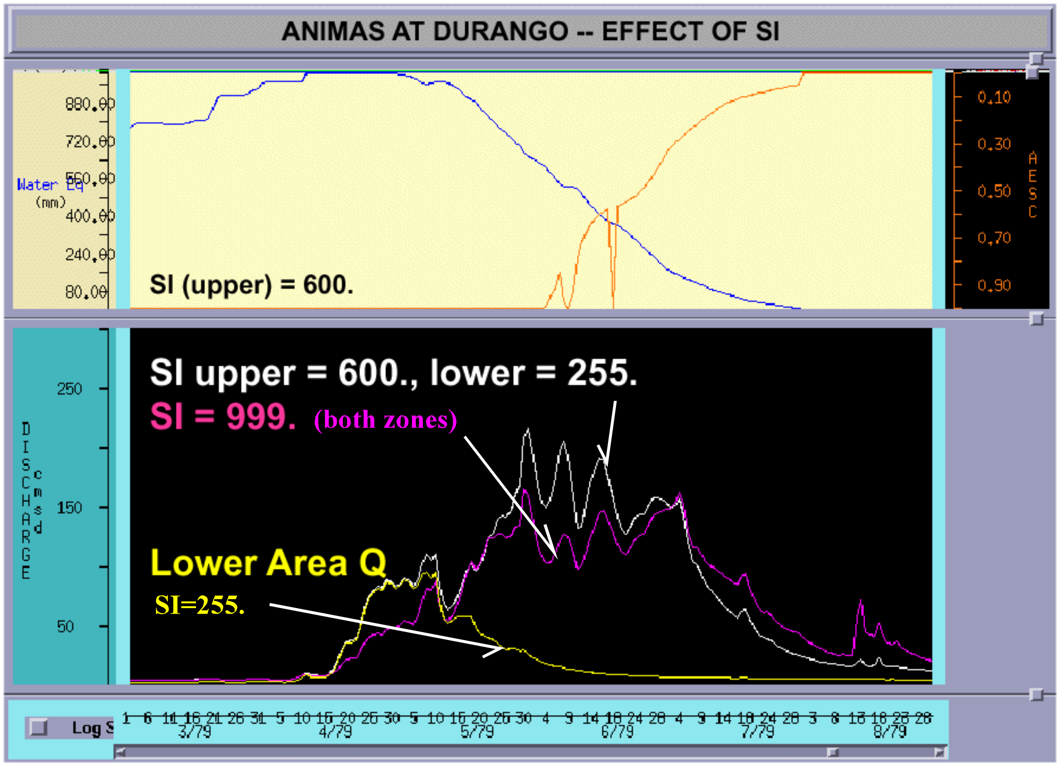


Figure 7-7-16. Effect of changing SI for both elevation zones during a large snow year.

calibration period and note what portion of the curve is being used at different times when some bare ground exists. If more melt is needed at a given time, it suggests that the areal cover should be increased for that WE/A_i ratio and vice versa. Hopefully a pattern will develop that indicates how the overall shape of the curve should be changed. In the following examples the sample initial value curves, curves B and C as shown on Figure 7-4-4, are used to illustrate the effect of changing the shape of the areal depletion curve.

Figure 7-7-17 shows the effect of changing the depletion curve for a watershed with no elevation zones. There is no difference in the hydrographs prior to when bare ground first begins to show. After that the 'B' curve melts off the snow quicker because the areal extent of the snow cover is significantly greater than for the 'C' curve for WE/A_i ratios above 0.4.

Figure 7-7-18 illustrates the effect of changing the areal depletion curve for the upper zone of a mountain watershed during a large snow year. Again the hydrographs are the same until bare ground begins to show up in the upper area. Again the 'B' curve melts off the snow quicker at first than the 'C' curve, however, due to the shape of the 'B' curve when only a little snow remains, there is still some snow left in this case in mid August to augment the summer rains that occur then. Figure 7-7-19 illustrates changing the areal depletion curve for both elevation zones for the same large snow year. Both zones remain at 100% cover for some period after melt begins. Changes to the depletion curve for the lower

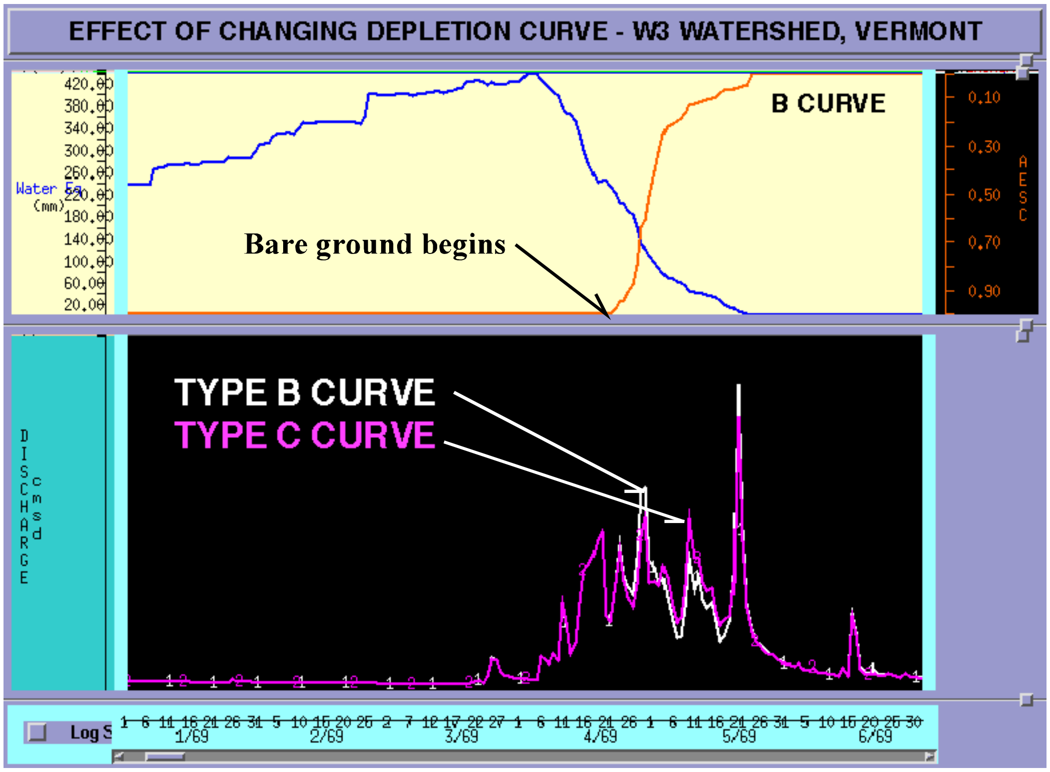


Figure 7-7-17. Effect of different depletion curves on a watershed with a single zone.

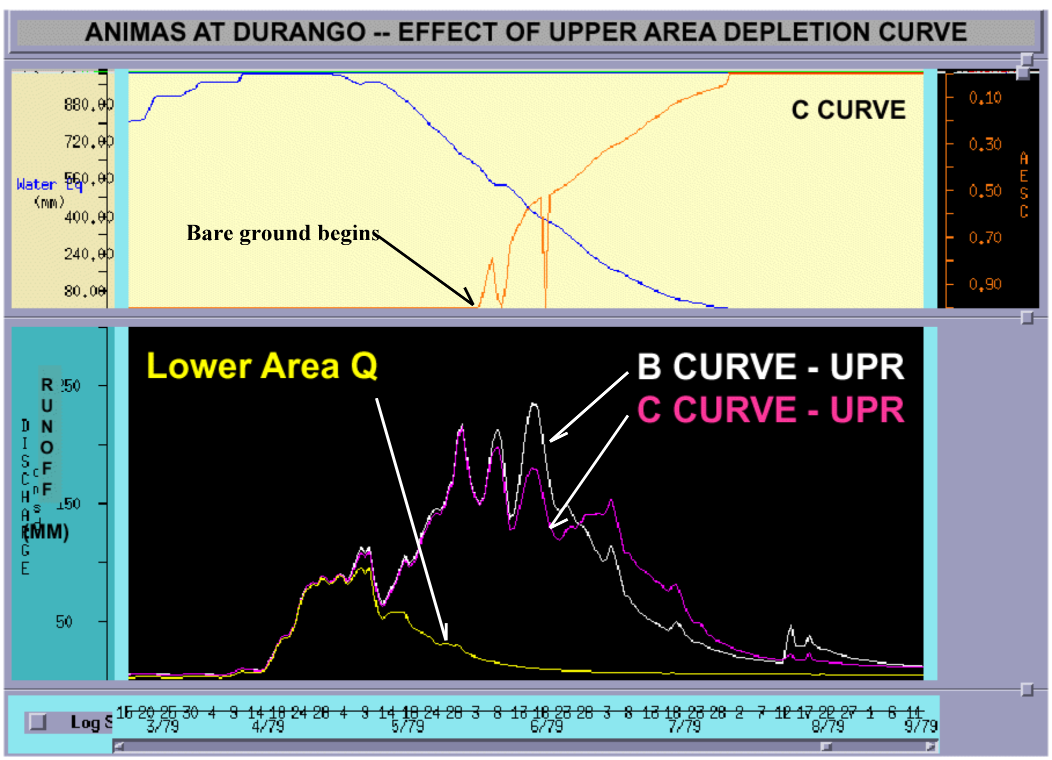


Figure 7-7-18. Effect of changing depletion curve for an upper elevation zone.

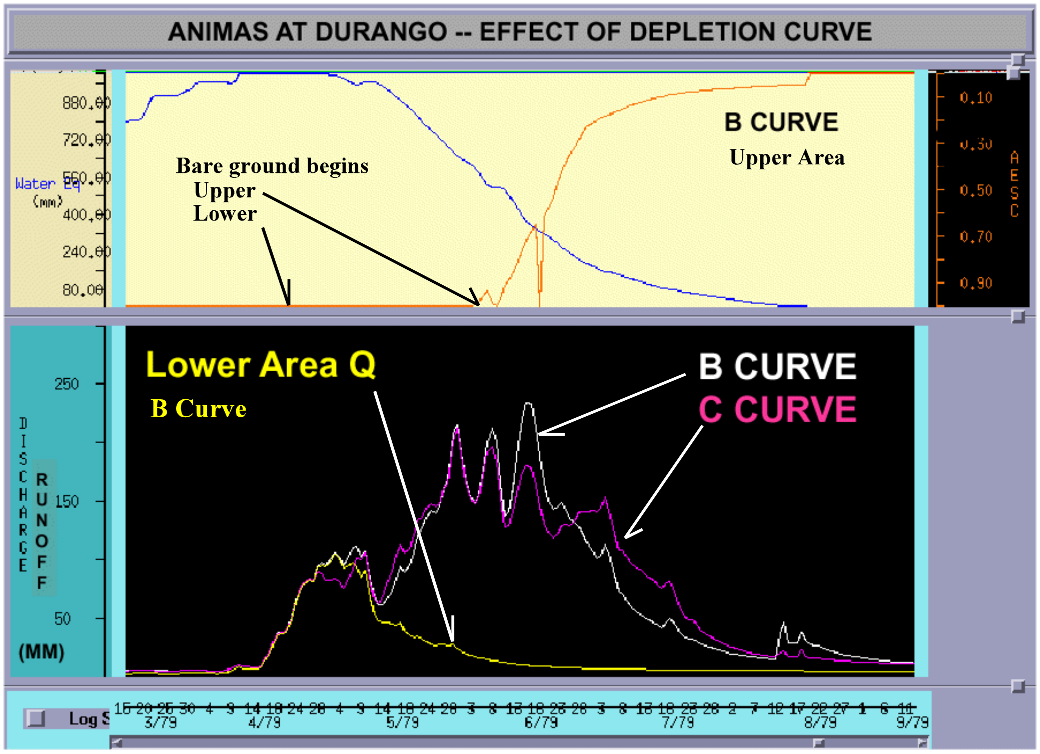
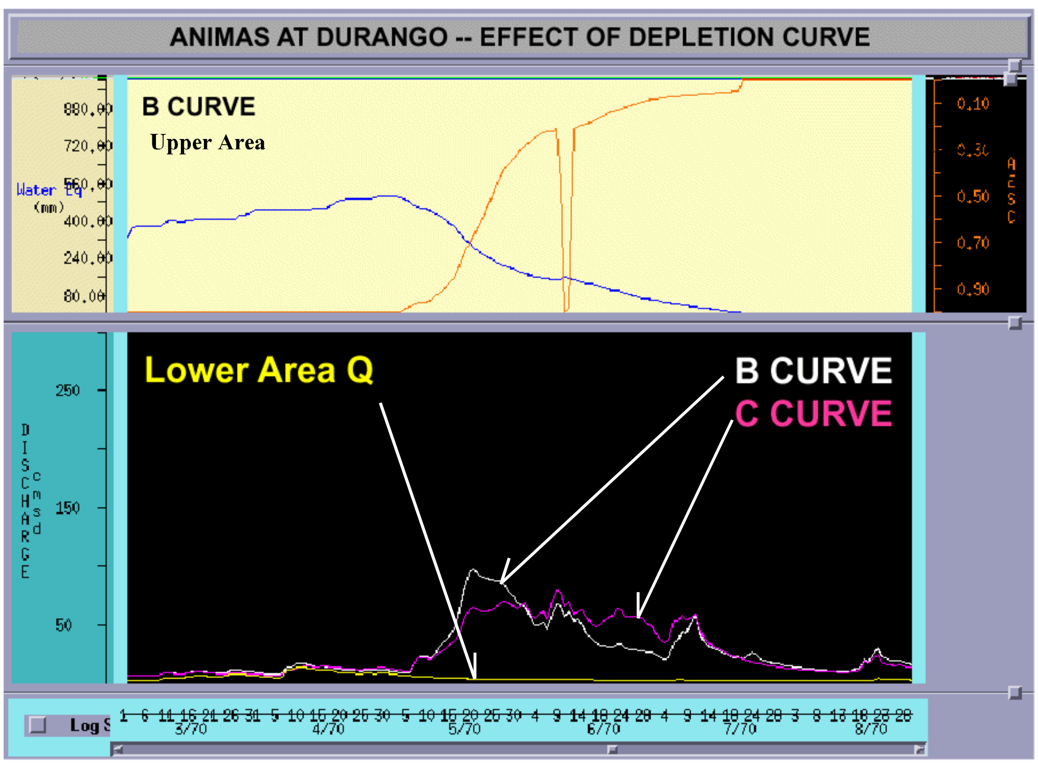


Figure 7-7-19. Effect of changing depletion curve for both elevation zones.



Figur e 7-

7-20. Effect of changing depletion curve for both zones for a small snow year.

zone persist long enough so that the portion of the hydrograph when the upper area is completely covered is affected. Figure 7-7-20 shows the effect of changing the depletion curve for this same watershed for a small snow year. During this year bare ground begins to show up as soon as active melt begins since the water equivalent for neither area exceeds SI, thus the entire melt season is affected. Only the upper zone shows much effect to the depletion curve changes because very little runoff is generated from the lower area.

<u>UADJ</u> – The rain-on-snow melt equation is only used when the rainfall rate exceeds 2.5 mm in a 6 hour period. Thus, to isolate the effect of the UADJ parameter, the rainfall rate must exceed that value. Also to have a significant amount of melt produced during rain periods, the air temperature must be well above freezing. If the temperature during rain is just barely above freezing, very little melt will be generated. It should be emphasized that the amount of rain is not a factor in isolating the effect of UADJ, but only that sufficient rain occurs to use the rain-on-snow melt equation when the air temperature is well above freezing.

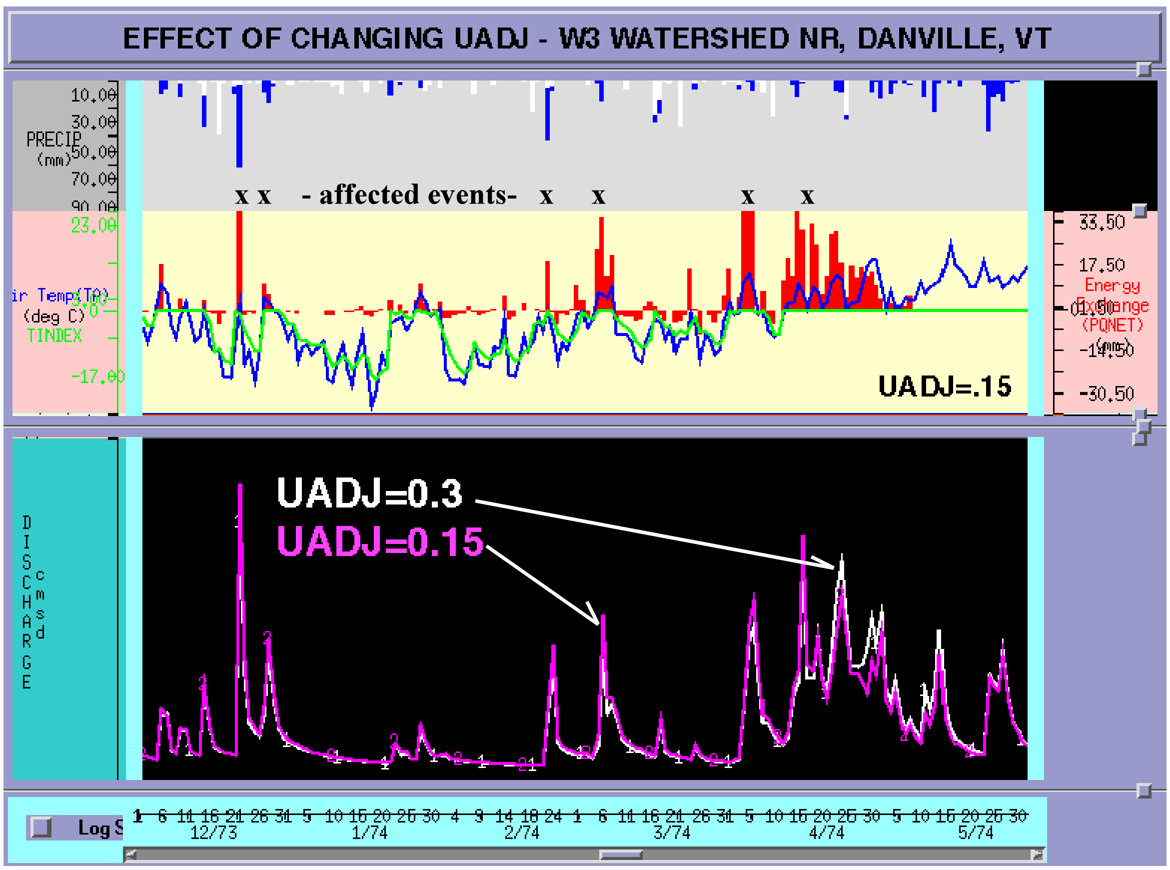
Figure 7-7-21 shows the effect of UADJ during a year with a number of rain-on-snow events. Increasing the value of UADJ resulted in more melt during many of the rain events as noted on the figure. Since these events were mostly in the winter, the additional snow

Figure 7-7-21. Effect of changing UADJ.

melted with UADJ=0.15 resulted in less snow being available for the main melt season in April. For a few of the rain-on-snow events there was little difference in the amount of melt computed because the air temperature was barely above freezing. These were the 3 events occurring between the 6th and 16th of December and the 2 events in late January.

Table 7-7-1 summarizes the primary effect of each of the major snow model parameters. It is critical to understand the primary effect of each of these parameters in order to isolate the periods to examine to determine if changes are needed to their values.

Parameter	Primary Effect
SCF	Controls volume of snowmelt runoff
MFMAX, MFMIN	Controls melt when at or near 100% areal cover
SI	Controls when 100% cover exists during large snow years



Depletion curve	Controls melt when areal cover less than 100%
UADJ	Controls melt when rain falls and the temperature is warm

Table 7-7-1. Summary of primary effect of major snow model parameters.

Discrepancies at the Beginning of the Snowmelt Season

Various parameters and conditions can affect when the onset of snowmelt runoff occurs after a long accumulation period. This section attempts to discuss those items that should be examined when snowmelt runoff starts too early or too late. The things to consider include:

- Snow Cover Heat Deficit – If the size of the heat deficit is too large or too small prior to a snowmelt period, this can result in the onset of runoff to occur a few days late or early. Typically the size of the heat deficit is only sufficient to cause the onset of runoff to be off by a period of days and not weeks. A significant heat deficit will only exist prior to melt when there has been an extended period of very cold weather followed by a quick warm up to melt conditions. A significant heat deficit cannot develop when temperatures are not well below freezing or when the temperature warms up slowly, even though remaining below freezing, after an extremely cold period. Also a large heat deficit cannot build up in a shallow snow cover because there is not enough heat storage capacity. The size of the computed heat deficit is controlled by the TIPM and NMF parameters. To develop a significant heat deficit, the value of TIPM should be fairly low, typically 0.05 or 0.1, in order to maintain a large gradient between the air temperature (assumed snow surface temperature) and the antecedent temperature index (TINDEX, indicates the temperature at some distance within the snow cover) during a long cold period. When the temperature at the snow surface is considerably less than the internal snow temperature, then the larger the value of NMF, the faster the heat deficit will grow. Thus, if the size of the heat deficit is thought to be the cause of problems at the onset of snowmelt runoff, then one should try changing the TIPM and NMF parameters. It should also be recognized that even though small TIPM values and large NMF values will cause a significant heat deficit to develop during an extremely cold period, this same combination will cause the heat deficit to more rapidly diminish during a warm up. Thus, in order to have a large heat deficit that will affect melt computations and the timing of runoff, there must be a rapid transition from an extremely cold period to melt conditions.

  Liquid Water Storage – The amount of liquid water that goes into storage within the snow cover when significant melt first occurs can have an effect on the onset of snowmelt runoff. If too much of the melt is held within the snow cover as liquid water, the runoff will be delayed and vice versa. For regions with a relatively deep snow cover during most winters, it is physically unrealistic to use a liquid water holding capacity for ripe snow (PLWHC parameter) outside the range of 0.02 to 0.05. In these regions liquid water storage is seldom the cause of problems related to the onset of snowmelt runoff. However, in regions with generally shallow snow cover, especially in the plains and north central regions, the overall amount of liquid water that can be held in the snow can be considerably greater than 5% due to the slush layer that typically builds up at the snow-soil interface. In these regions a PLWHC value of 0.15 to 0.30 is quite common and the PLWHC parameter is a likely candidate for correcting problems at the onset of runoff from melt.

Ice Blocking the Channel System – In some regions, especially portions of the north central area and parts of Alaska, ice may build up and block portions of the channel system, especially drainage outlets and culverts. This results in the initial melt water ponding in fields and low lying areas until the ice melts and frees the outlet. By neglecting this situation, computed snowmelt runoff appears sooner than what is observed. Currently there is no explicit way to model this effect. A separate procedure or modification to a channel response or routing model would be the most physically realistic way to address the problem. The use of a larger than normal PLWHC may implicitly account for some portion of this condition.

Soil Moisture Conditions – Soil moisture conditions can have a significant influence on runoff at the beginning of a snowmelt period in many regions. Two soil moisture model situations typically can cause problems during such periods. First, the magnitude of the tension water deficits when melt begins will have a large effect on the timing and the amount of the initial runoff. In some regions it is common during years with a dry summer and fall for large tension water deficits to still exist when melt begins. During other years the deficits will be full going into the winter and remain full until melt begins. If the tension water deficits are too large when melt starts, generally the onset of runoff will be delayed longer than it should and vice versa. Thus, it is important to check the size of the tension water deficits prior to snowmelt especially if problems exist with the onset of runoff from the melt.

Percolation problems can also affect the timing of runoff at the onset of snowmelt though these problems typically continue well into the melt season. If the percolation rate is too large when melt begins, too much water will initially go into lower zone storages, while if the rate is too low, the water will run off too quickly. Generally if a reasonable baseflow simulation is obtained prior to working with the snow model parameters this will not be a significant problem though if the lower zone deficiency ratio in the Sacramento model moves over a large range during the melt season, there could be a problem with the percolation rate for the drier conditions that exist when melt begins.

Temperature Bias – If snowmelt occurs well before or after the onset of observed runoff (typically a week or two) and none of the previously mention situations will explain the problem, it is very likely that the temperature values being used are too high or too low for the area they are representing. There can be two reasons for this situation. First, in some cases, especially in lower elevation zones of mountain watersheds, the elevation of the MAT time series is generally not the same as the mean elevation of the snow cover. The elevation of the MAT time series typically is selected as the mean elevation of the area being modeled, whereas in lower elevation zones, the snow may predominately be in the upper portion of the area. Thus, the mean elevation of the snow covered area is greater than the mean elevation of the entire zone. This situation can also occur during very low snow years in the upper elevation zone as described in Section 6-1. The solution to this problem is to use the lapse rates in the snow model to adjust the MAT time series values to the proper elevation. This is done by setting the mean elevation of the area to the mean elevation of the snow covered portion of the zone. Then the lapse rates will be used to adjust the MAT values by the elevation difference between that defined for the temperature data and that specified for the zone.

The second reason for the temperature values being off is that the MAT computations are producing biased values, typically due to improper monthly temperature-elevation relationships being used to extrapolate observed station data to the mean elevation of the area being modeled. Generally the problem involves extrapolating low elevation observations to higher elevations zones where most of the snow and runoff occur. In a few cases the problem is caused by an input error to the MAT program that causes the wrong stations to be weighted for one or more zones thus producing a biased temperature estimate. In order to see if adjustments to the temperature data will correct the problem, an elevation difference and lapse rate can be used to adjust the values or a non 0°C MBASE parameter value can be tried, however, once it is determined that the temperature data are biased, the MAT time series should be regenerated using the proper temperature-elevation relationships and station weights.

Section 7-8

Effect of Sacramento Model Parameters on Model Response

Introduction

It is critical to understand the most important function of each of the model parameters when performing interactive trial and error calibration. It is also essential to know what to examine to find the periods when the effect of each parameter can be isolated. This understanding allows the person doing calibration to make educated decisions regarding which parameters should be altered as opposed to random guesses. Without this knowledge, interactive calibration becomes an exercise in futility.

This section describes the most important function of each of the Sacramento model parameters and how to determine which periods to examine to isolate the effects of each parameter on model response. Besides their major function, many of the Sacramento model parameters also influence other aspects of the model computations. This is especially true with all the parameters that are involved in the percolation computations. The percolation equation in the model involves 8 parameters, ZPERC, REXP, LZFSM, LZFPM, LZSK, LZPK, LZTWM, and UZFWM. Two of these parameters are unique to the percolation computations, ZPERC and REXP, while all of the others are involved in other aspects of the model's algorithms. Thus, while these other parameters have a major function of their own, they also affect the percolation computations. Because of this, when the values of these parameters are changed, there are multiple effects. The user needs to anticipate these effects, but should concentrate on the major function of each parameter when performing interactive calibration.

The major function of each Sacramento model parameter is illustrated in this section by using mean daily flow hydrograph plots showing the response of two different values of the parameter for a period when the effects of the parameter can be isolated. The plots are generated by running the model with everything exactly the same except for the values of the parameter being considered. Under such conditions the unique effect of each parameter can clearly be shown. The actual problem of deciding on which parameters to change becomes much more difficult during calibration because of noise in the data and the fact that generally multiple parameters, perhaps involving several models, need to be adjusted. To have any hope of making the proper changes during calibration, one must know what periods to examine and what to look for to isolate the effects of each parameter. It is also helpful to have a strategy for checking parameters for possible changes. Such a strategy for the Sacramento model is outlined in Section 7-1.

Most of the parameters are discussed individually, however, the percolation curve and the parameters that primarily affect it are lumped together. When making changes to the percolation rate it is important to think in terms of the entire curve as opposed to the individual parameters that influence the curve. In addition to the hydrograph plots, panels that show how the model states are changing and other results of the model computations are included in each of the figures. These panels are extremely helpful in determining when the conditions occur that are needed to isolate the effects of each parameter. Even though two hydrograph plots are included on each figure, the panels showing the model states and computations can only be included for one of the parameter values. This value is specified next to the panels on each figure.

Explanation of Panels Showing Model States and Computations

Figure 7-8-1 illustrates the panels which are part of the ICP WY-PLOT display for the SAC-SMA operation. The plots on these panels are for a daily time interval. Instantaneous values such as zone contents are for the end of each day.

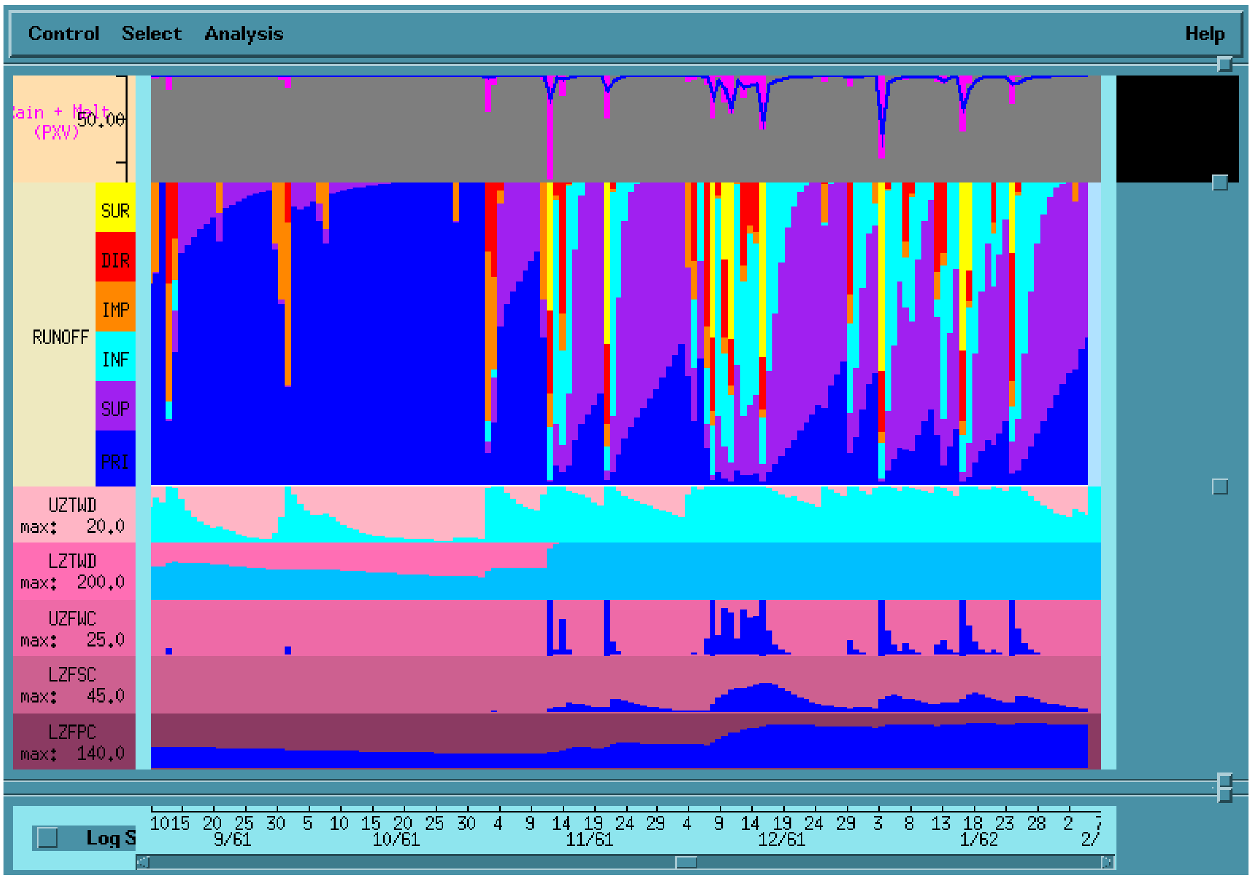


Figure 7-8-1. Sample ICP display for the SAC-SMA operation.

Top Panel - This panel shows the total amount of water coming into the Sacramento model for each day as a bar value in magenta with the scale on the left. These can be rain+melt values from the snow model or the direct input of rainfall when snow computations are not included. The dark blue line in this panel is the total amount of channel inflow, i.e. runoff, generated by the model for each day. This is the sum of all the runoff components. The scale is the same as for the precipitation input.

Middle Panel - This panel shows a breakdown of the runoff into components for each day. The total height of the panel is divided in proportion to the fraction of each runoff component that occurs on any day. Surface runoff is displayed in yellow, direct runoff (i.e. from the additional impervious area) in red, constant impervious runoff in orange, interflow in light blue, supplemental baseflow in purple, and primary baseflow in dark blue. This panel allows the user to see relatively how much runoff is being generated by each of the components on a daily basis.

Bottom Panel - This panel shows the states of each of the upper and lower zone moisture storages at the end of each day. The capacities of each zone are labeled on the left. The blueish tones represent contents and the pinkish tones deficits (i.e. capacity minus contents). If for a given day a zone is all blue, it indicates that the zone is completely full of water. Vice versa if the a zone is all pink, it indicates that the zone is empty. Generally when viewing this panel, the tension water storages are being thought of in terms of deficits, i.e. how much water is needed to fill the storage, while the free water storages are being thought of in terms of contents, i.e. how much water is available for runoff, or in the case of the upper zone free water storage, both for interflow and percolation.

Sacramento Model Parameters

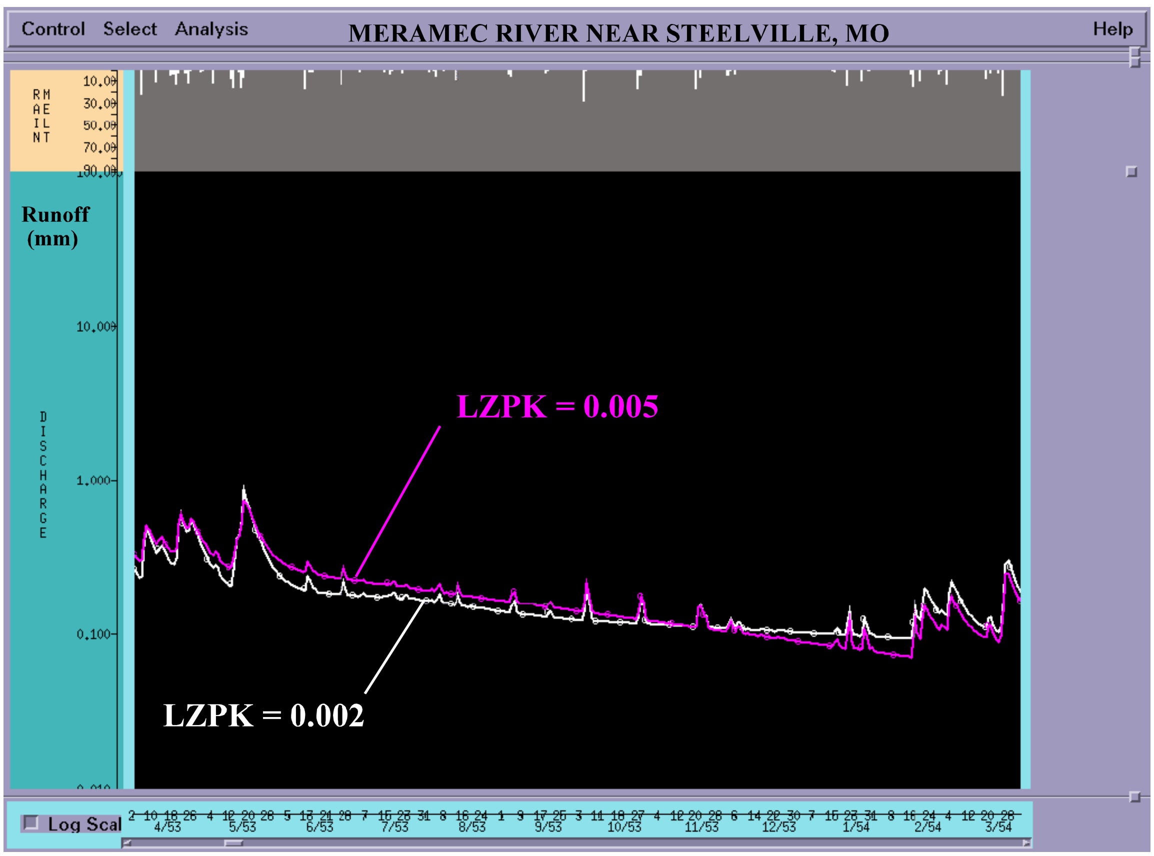
On the remaining pages in this section the major function of each parameter is described, as well as how to isolate the effect of the parameter. The order that the parameters are discussed is based on the strategy for examining the parameters during a calibration as suggested in Section 7-1. The parameters that primarily affect baseflow are described first, followed by tension water storages and PCTIM, storm runoff parameters, and lastly those that primarily affect evapotranspiration. Table 7-8-1, at the very end of the section, summarizes the primary function of each of the Sacramento model parameters.

Besides this material, the portions of Section 7-5 that describe how to derive estimates of parameter values from an analysis of the hydrograph provide considerable information that should assist in determining how to isolate the effect of each model parameter. That material should be reviewed even if one is not going to derive initial parameter values.

LZPK

The primary function of the LZPK parameter is to specify the slope of the primary baseflow recession. LZPK is not to be used to correct for problems with the magnitude of primary baseflow. As long as the simulated slope of the recession during periods when only primary baseflow is contributing to runoff is parallel to the observed recession, LZPK shouldn't be modified even if though the amount of primary baseflow is considerably high or low. Figure 7-8-2 illustrates how changing the value of LZPK alters the slope of the recession. For this illustration the percolation term PBASE was kept the same for both values of LZPK.

The value of LZPK is checked by examining periods when primary baseflow is basically the only source of runoff. Small amounts of constant impervious runoff may occur during such periods from rain that is not sufficient to fill the upper zone tension water storage, but no other runoff components should contribute significant amounts. Complications that can affect periods when primary baseflow dominates are discussed under the 'Assigning Runoff Components' portion of Section 7-5. Periods with riparian vegetation evaporation should be avoided when determining whether the value of LZPK should be changed. Also, during periods with a snow cover it should be recognized that ground melt may cause the primary recession to be slower than during snow free periods. Thus, it is best to use snow free periods whenever possible.



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re 7-8-2. Effect of changing LZPK on model response.

LZSK

The primary function of LZSK is the timing of supplemental baseflow runoff. This can be evaluated in terms of the slope of the supplemental recession or in terms of how long significant supplemental baseflow exists after the storage is recharged. The longer that supplemental baseflow exists, the slower the withdrawal rate. LZSK shouldn't be used in an attempt to change the amount of supplemental baseflow, but only the timing. The periods to use for determining if the value of LZSK should be changed are recessions after significant groundwater recharge has occurred. There should be no major runoff producing events during the recession in order to best evaluate LZSK. Such an ideal case may be difficult to find for watersheds with a very slow supplemental recession rate (see Section 7-5 for further information).

Figure 7-8-3 illustrates the how changing the value of LZSK alters the timing of the supplemental recession. The value of PBASE in the percolation equation is kept the same for both values of LZSK. The panel at the top is for LZSK=0.20. It shows for the October 1964 recession period that the supplemental baseflow contribution is essential gone by the end of the month. For the LZSK value of 0.10, supplemental baseflow lasts until the middle of November.

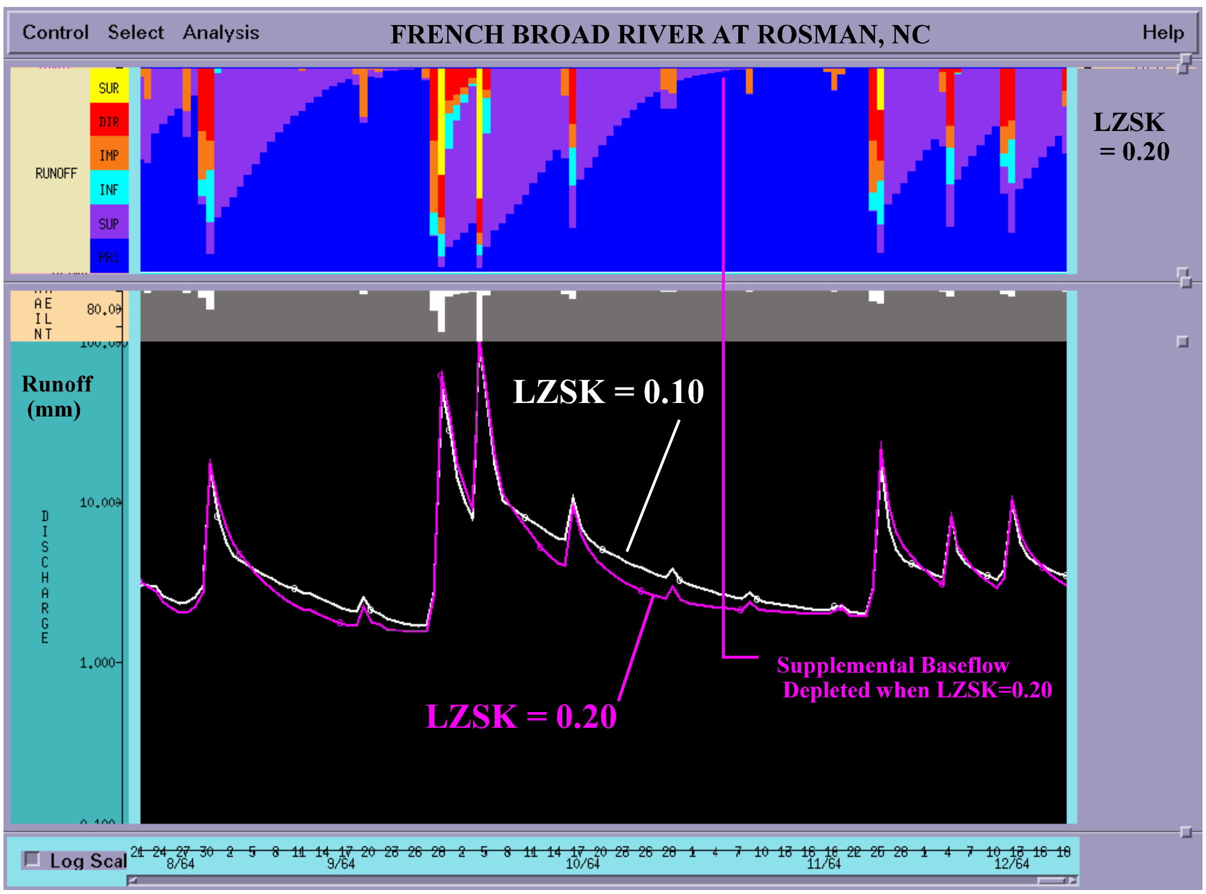


Figure 7-8-3. Effect of changing LZSK on model response.

LZFPM

The primary function of LZFPM is to control the amount of primary baseflow runoff. Whereas LZPK controls the withdrawal rate, i.e. the slope of the recession, LZFPM controls the magnitude. The greater the value of LZFPM the more water that can be stored in the primary storage, thus a greater overall contribution from primary baseflow. If the total amount of baseflow from both primary and supplemental contributions is too great or too small, the percolation rate will need to be decreased or increased to correct the problem. Once the total amount of baseflow is reasonable, then LZFPM can be changed so that the proper proportion is assigned to primary baseflow runoff.

The periods to examine for LZFPM are the same as were used to evaluate LZPK, i.e. periods when primary baseflow is the major source of runoff. Figure 7-8-4 illustrates how changing the value of LZFPM alters the magnitude of primary baseflow runoff. When LZFPM is altered, very little change occurs during periods when other runoff components dominate.

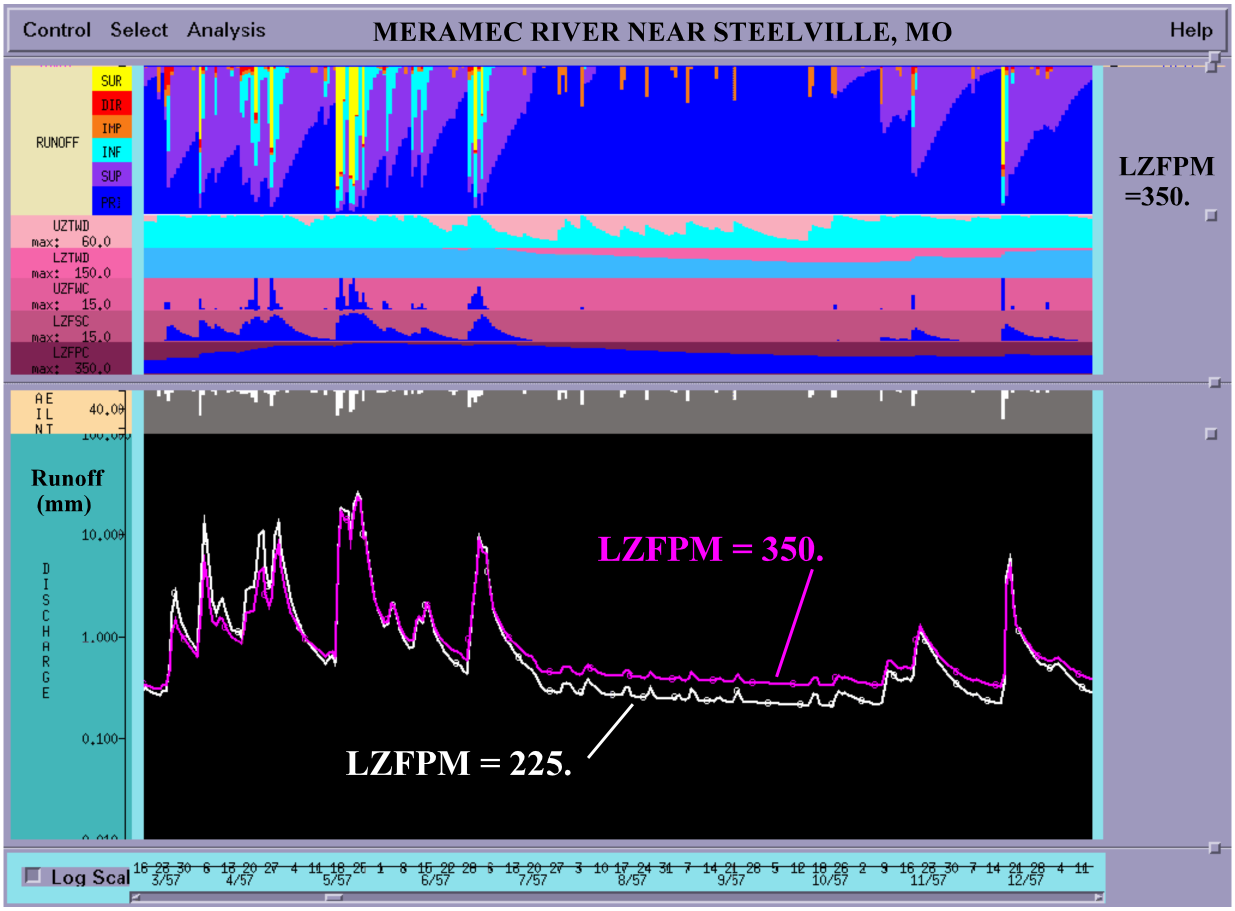


Figure 7-8-4. Effect of changing LZFPM on model response.

LZFSM

The LZFSM parameter is unusual in that it has 2 primary functions. The first, which is described on this page, is to control the amount of supplemental baseflow. The other is its effect on the percolation rate. This function is discussed, along with the role of other parameters on percolation, in the 'Percolation Rate' portion of this section.

Analogous to primary baseflow, LZSK controls the timing of supplemental baseflow and LZFSM controls the magnitude. The greater the value of LZFSM, the more water can go into supplemental storage. The periods to examine to isolate this effect of LZFSM are the same periods used to evaluate the LZSK parameter, i.e. recession periods after significant recharge when there is considerable supplemental baseflow contribution and very little storm runoff. It is especially important to examine recession periods after major events when the maximum amount of supplemental baseflow should occur. Figure 7-8-5 illustrates the effect of changing the value of LZFSM. It can be seen that besides affecting the magnitude of supplemental baseflow, altering LZFSM also changes the response during and immediately after the storm events. This change is due to the effect of LZFSM on the percolation rate. The larger the value of LZFSM, the greater the percolation rate and thus less storm runoff (i.e. surface runoff and interflow).

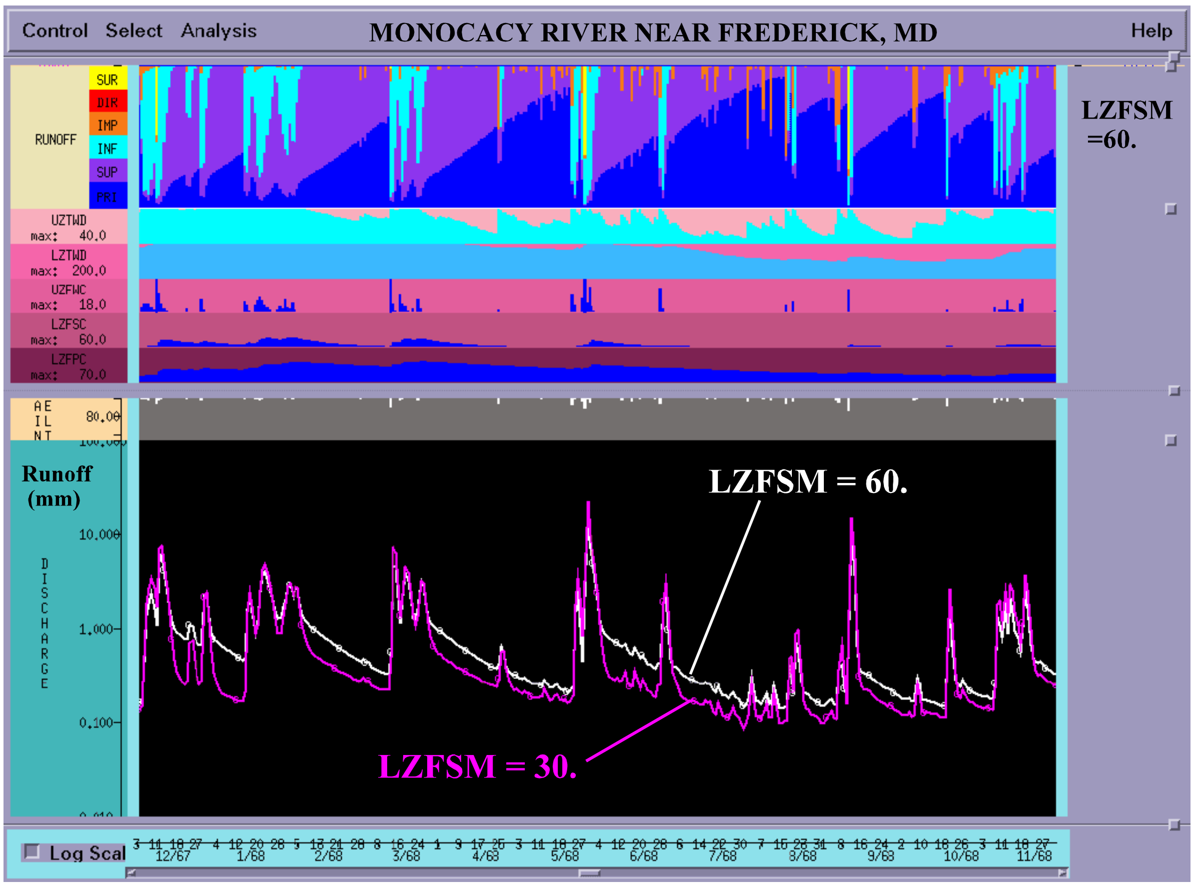
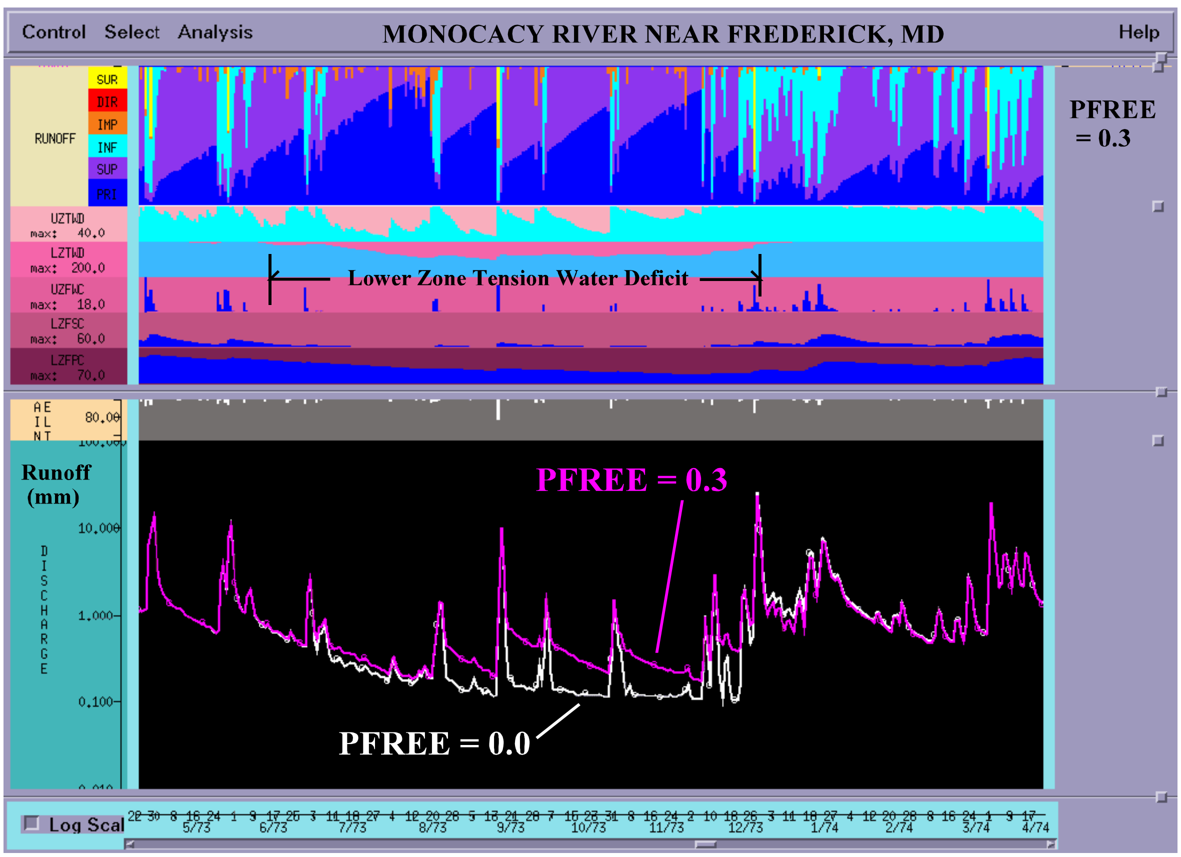


Figure 7-8-5. Effect of changing LZFSM on the magnitude of supplemental baseflow.

PFREE

The function of PFREE is to determine what fraction of the percolation goes directly to free water storages, i.e. how much baseflow recharge occurs, when there is a lower zone tension water deficit, i.e. LZTWC is less than LZTWM. Thus the only periods to examine when evaluating the value of PFREE are those when there is a lower zone tension deficit. Whenever lower zone tension water is full, PFREE has no affect. The amount of recharge is determined by how much the baseflow increases after an event that produces storm runoff (the upper zone tension water must fill in order to have any percolation or storm runoff). When there is a lower zone tension deficit, the relative amount of recharge will likely vary depending on the size of the deficit as in reality PFREE should be function of the dryness of the lower zone as discussed in Section 7-5. Generally it is preferable to use a PFREE value that works well during extended periods with a substantial lower zone tension deficit than to set the value of PFREE based on the shorter transition periods when the deficit first appears or dissipates, though this decision is left up to the user. Figure 7-8-6 illustrates how PFREE affects baseflow recharge after storm events when there is a lower zone tension deficit. Note that PFREE has essentially no effect when the lower zone tension water is full. In very wet regions lower zone deficits seldom occur. In such areas it may not be possible to determine the value of PFREE. Even though PFREE has little effect in such areas, spatial consistency in the parameter value should be maintained.



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igure 7-8-6. Effect of changing PFREE on model response.

SIDE

The function of the SIDE parameter is to have a portion of the withdrawal from baseflow storages go to deep groundwater recharge rather than appearing in the stream. The SIDE parameter allows the user to get rid of water by removing it from baseflow when storm runoff is being reproduced in a reasonable fashion and increasing the amount of evaporation or decreasing the precipitation seems physically unrealistic. The SIDE parameter should only be used when there is some collaborating evidence that significant deep groundwater recharge is an important part of the water balance.

Figure 7-8-7 illustrates the effect of using a non zero value for SIDE. The same fraction of the withdrawal from lower zone free water storages is removed every day from the water balance. Since the amount of withdrawal varies with the contents of the primary and supplemental storages, the amount of deep recharge is greatest when the amount of water in these storages is the greatest.

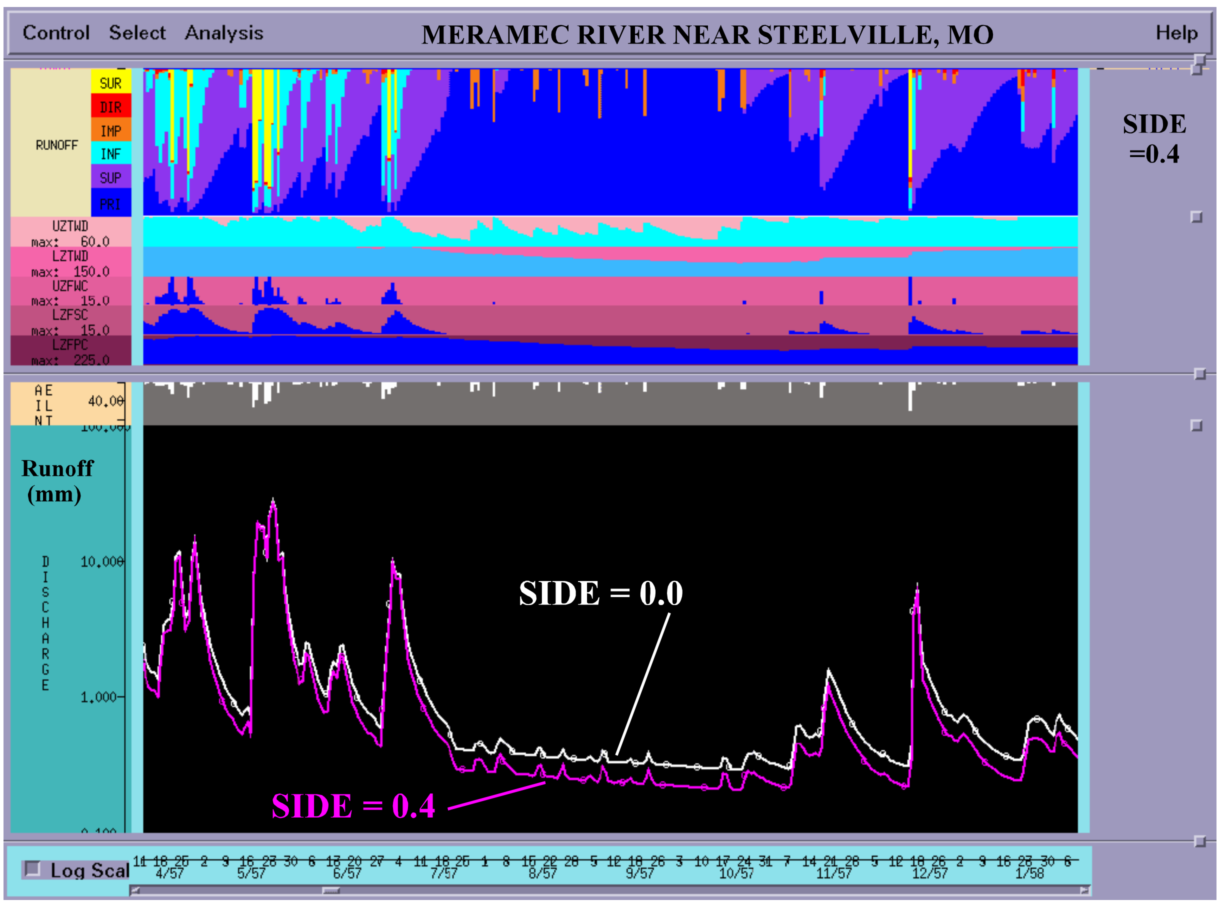
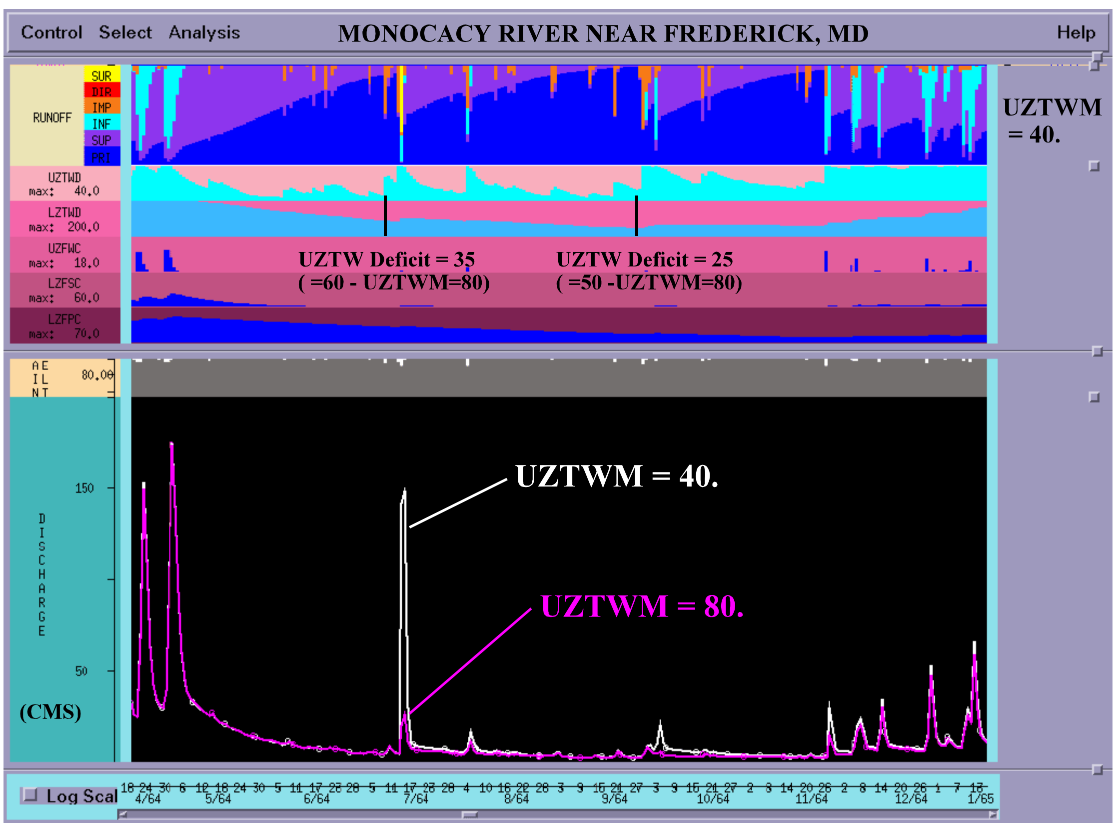


Figure 7-8-7. Effect of using SIDE on model response.

UZTWM

The primary function of UZTWM is to control the maximum upper zone tension water deficit that can be created. Remember no storm runoff, other than that from constant impervious areas, can occur when the upper zone tension water is not full. The value of UZTWM controls the time when the other storm runoff components (surface, interflow, and direct runoff) are suppressed during a dry period. Typically dry periods after a storm event during the summer are used to determine if changes are needed to UZTWM. Such periods allow for a sizeable upper zone tension deficit to develop. An evaluation can then be made as to whether the deficit is too large or not large enough based on the response from moderately large rain events that occur when the magnitude of the deficit approaches the value of UZTWM. Figure 7-8-98 illustrates the effect of changing UZTWM on the amount of storm runoff produced after a large upper zone tension deficit is generated. The deficits that exist prior to two storm events are noted on the figure. The first event had a much larger hydrograph response when UZTWM was equal to 40 partly due to more rainfall, but also the intensity was sufficient to generate surface runoff.

In very wet regions a significant upper zone tension deficit may never develop, thus it is impossible to determine the value of UZTWM. In such areas it is important to maintain a realistic spatial consistency in the values of UZTWM. Soil based estimates as discussed in Section 7-5 can provide this consistency in such regions.



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7-8-8. Effect of changing UZTWM on model response.

PCTIM

The PCTIM parameter is evaluated at the same time as UZTWM since the only source of new runoff during periods when an upper zone tension deficit exists is from constant impervious areas. During periods when there is a substantial upper zone tension deficit, the response from small to moderate rain events is examined to determine if the value of PCTIM should be changed. As with any parameter, changes should be based on the trend over many events. The periods used to evaluate PCTIM are typically in the warm season when convective rainfall is predominate, especially for smaller events. Since the MAP values from such events are quite uncertain, it is even more important in the case of PCTIM to base any decision on the response of many events. Figure 7-8-9 illustrates how changing the value of PCTIM affects the watershed response during periods when a upper zone tension deficit exists. PCTIM has only a small effect on the hydrograph during other periods unless the value of PCTIM is very large.

In very wet regions where significant upper zone tension deficits seldom exist, it may be very difficult to determine a unique value for PCTIM. In many cases in such regions it is best to set PCTIM to zero if constant impervious runoff can't clearly be shown to exist..

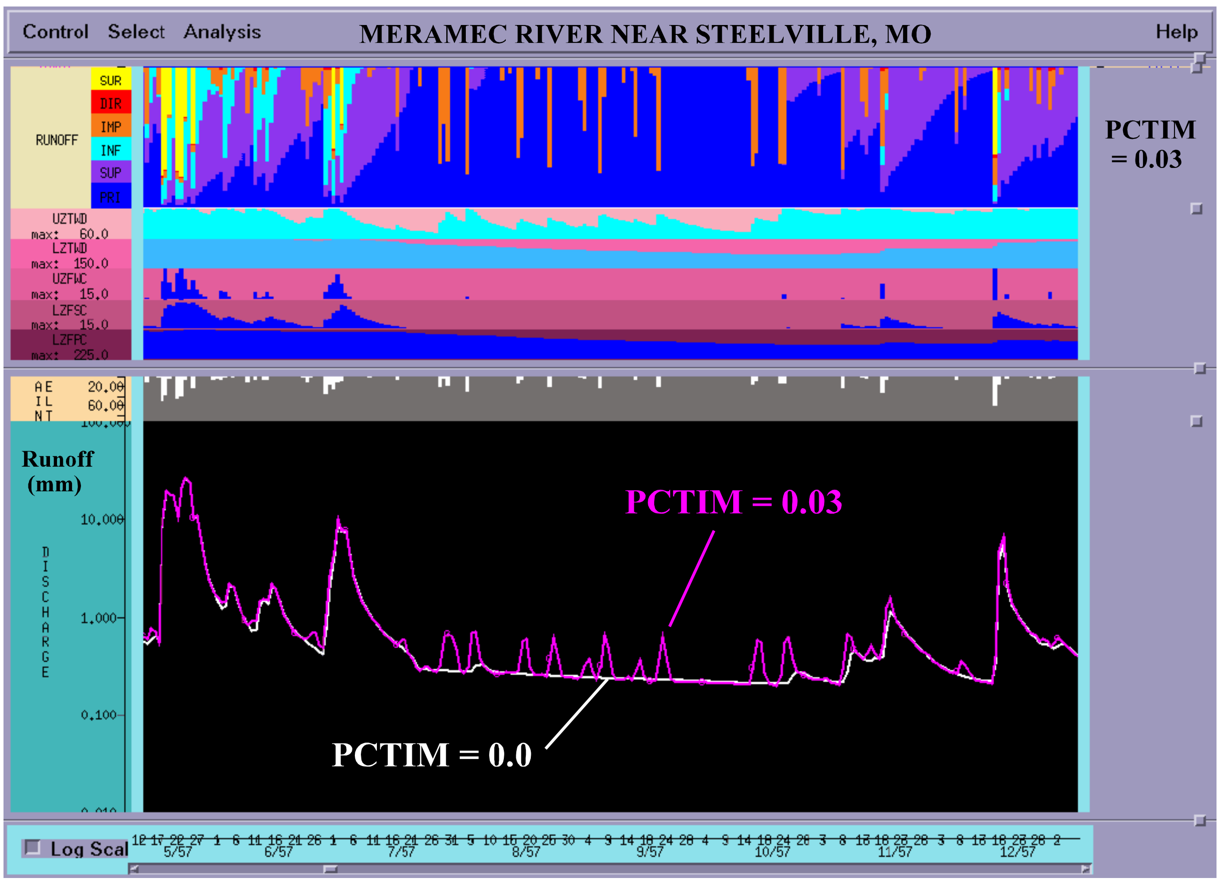
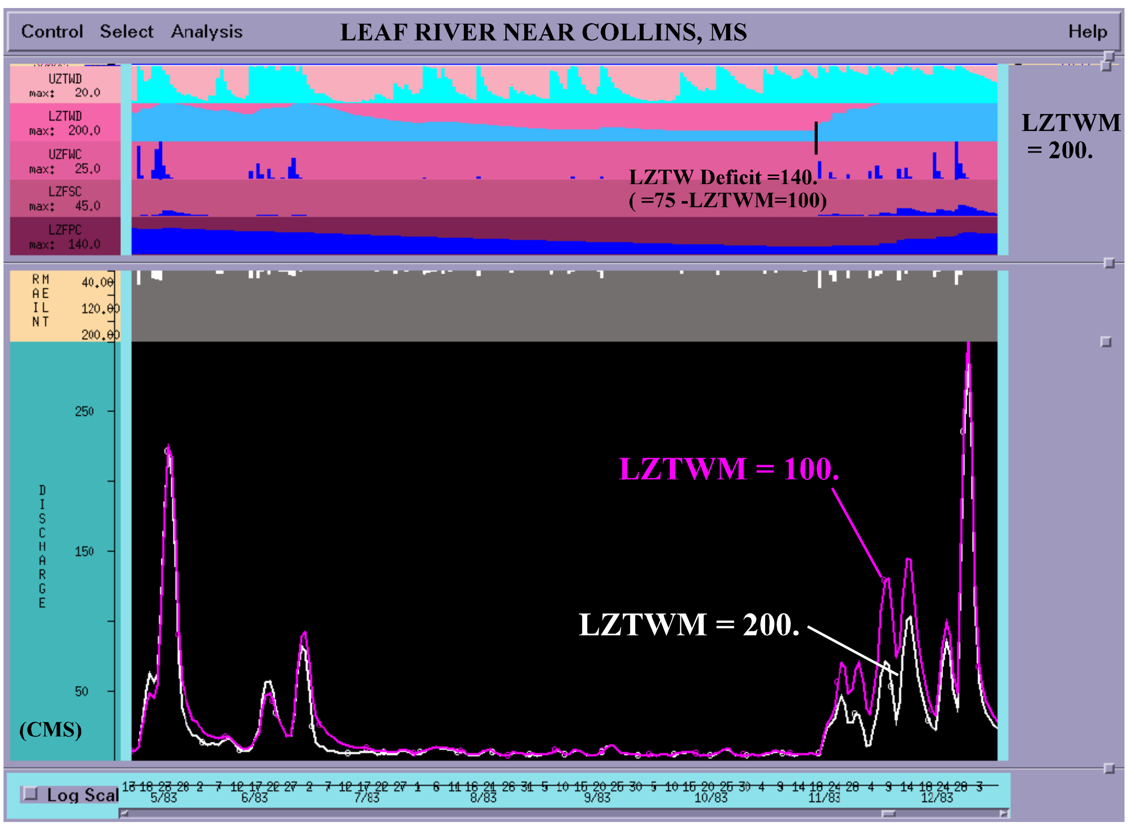


Figure 7-8-9. Effect of changing PCTIM on model response.

LZTWM

The primary function of LZTWM is to specify the maximum lower zone tension water deficit that can occur. The maximum possible deficit will occur after a long dry period when the vegetation withdraws all the moisture from the soil that the roots can reach. If the absolute maximum deficit occurred, all of the vegetation in the watershed would be wilted. Since such a situation seldom exists in nature, the lower zone tension water should never dry out completely. To determine if the value of LZTWM should be changed, the hydrograph response after long dry periods when the lower zone tension deficit approaches the value of LZTWM should be examined. The amount of runoff that occurs as the deficit is filled will indicate if the deficit was allowed to be too large or not big enough. In most areas, a large deficit that is built up over a very dry summer will be filled by fall rains, however, in watersheds where snowmelt dominates, such as in the intermountain west, the deficit is usually not filled until the spring melt season. In these cases the response in the early part of the melt season should be examined. Several factors can affect the model response at the beginning of the snowmelt season as discussed in the last part of Section 7-7. The value of LZTWM should only affect the response during years when a large deficit is carried through the winter. Figure 7-8-10 illustrates the type of period to use and the effect of changing LZTWM for the case when the deficit built up during the summer is filled by fall rains. Figure 7-8-11 illustrates the effect of LZTWM when a deficit is carried through the winter and not filled until the early part of the melt season.



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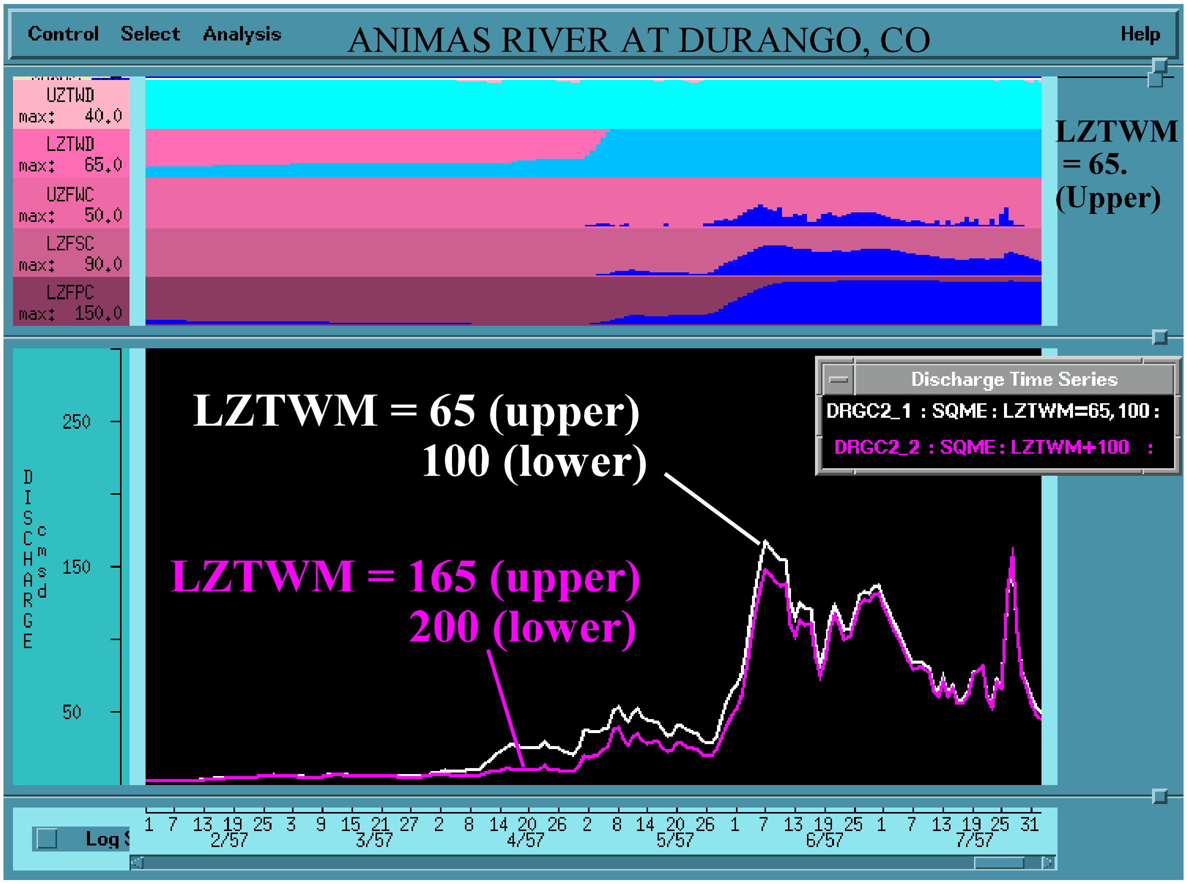


7-8-10. Effect of changing LZTWM for an area with fall rains.

Figure 7-8-11. Effect of changing LZTWM on a predominately snowmelt basin.

If the size of the lower zone tension deficit never approaches the value of LZTWM for watersheds where long dry periods periodically occur from late spring into the fall resulting in hydrologic drought conditions, the value of LZTWM should likely be reduced so that the maximum deficit is closer to the value of LZTWM. During extreme dry periods it is physically realistic for the deficit to approach its limiting value. In wet regions where significant lower zone tension deficits never occur, a true value for LZTWM can't be determined by calibration. In these regions changing LZTWM will alter the amount of computed ET since the LZTWM is part of the equation used to calculate evaporation from the lower zone tension water, however, LZTWM must be change by quite a bit to produce a significant change in ET (i.e. the parameter is not very sensitive in this situation). In wet regions it is probably best to use the soil based estimates of LZTWM to maintain spatial consistency though it would be better if the estimates were based on vegetation, as well as soils data. In very dry regions it may also be impossible to reliably determine the value of LZTWM since the lower zone tension deficit may seldom be filled. Simulation results using a lumped application of a conceptual model are generally poor such regions as shown in Figure 1-1.

Percolation Rate (ZPERC, REXP, LZFSM)

It is best to evaluate the entire percolation curve when determining whether changes are needed to the parameters that control amount of percolation. This is especially true in the case of ZPERC and REXP. Since LZFSM has two primary functions, changes can be made to alter the magnitude of supplemental baseflow without doing a full evaluation of its affect on the percolation curve. The thought process recommended when evaluating the percolation curve is to first determine how the curve needs to be changed at different levels of lower zone wetness and then decide on the combination of parameter values that will produce the desired curve. It is important to evaluate the whole curve before deciding on any parameter changes since percolation rates may be too high under some moisture conditions and too low under others. Only an examination of events that occur at various lower zone moisture conditions will indicate how the curve should be modified.

As indicated ZPERC, REXP, and LZFSM are the 3 parameters whose primary function is to control the percolation curve (LZFSM also affects the amount of supplemental baseflow). REXP determines the shape of the curve, ZPERC the percolation rate when the soil is completely dry, and LZFSM dominates the rate when the soil is saturated). Other parameters also affect the percolation rate, but that is not their primary function. This includes UZFWM, LZFPM, LZTWM, LZSK, and LZPK. The PBASE term in the percolation equation, which specifies the rate when the lower zone is saturated, is calculated based on the fact that water can’t enter the lower zone under saturated conditions faster than the lower zone free water storages can drain. PBASE is computed as:

$$\mathbf{PBASE = LZFSM \bullet LZSK + LZFPM \bullet LZPK}. \qquad (7\text{-}8\text{-}1)$$

The withdrawal rates, LZSK and LZPK, should never be changed in order to modify PBASE. Their only function is to specify the slope of the two baseflow recessions. Changes to LZFPM will alter the value of PBASE, however, generally the LZFSM • LZSK term of the equation is an order of magnitude greater than the primary baseflow term, thus LZFSM becomes the dominate parameter when changing the saturated percolation rate. When the division between supplemental and primary baseflow is correct, but changes to PBASE are indicated, both LZFSM and LZFPM can be changed in a manner that keeps their ratio the same.

Before evaluating the percolation curve, it is important to first know what to look for to decide whether a change in the percolation rate is needed. Figure 7-8-12 illustrates the model response that indicates there is an error in the percolation rate. When LZTWC is equal to LZTWM, i.e. lower zone tension storage is full, none of the percolated water can be stored in tension water. In that case the percolation curve controls the division between storm runoff, surface plus interflow, and baseflow, supplemental plus primary. A decrease in the percolation rate at any given lower zone moisture level will produce more storm runoff and less baseflow recharge. An increase in the percolation rate will do the opposite. When LZTWC is less than LZTWM, then much of the percolated water will go into tension water storage, thus reducing the amount of recharge (all of the percolated water will go into lower zone tension storage when PFREE is zero - some recharge will occur if PFREE is greater than zero). Thus, in this case, changing the percolation rate primarily alters the amount of storm runoff with only a minimal effect on recharge depending on the value of PFREE.

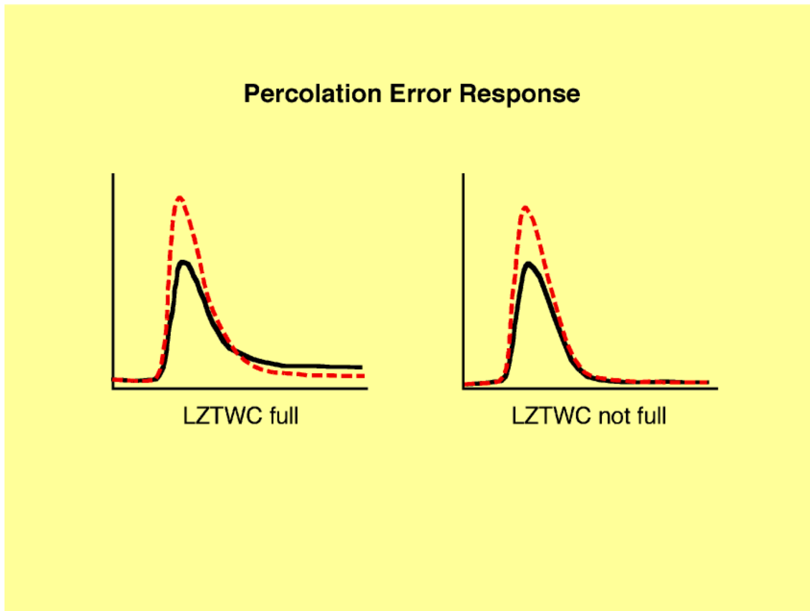


Figure 7-8-12. Illustration of model response to changes in the percolation rate.

The ICP has a percolation analysis feature built into the WY-PLOT display. This tool allows the user to go through many events, hopefully over a wide range of lower zone moisture conditions, and indicate the relative magnitude that the percolation curve should be altered to improve the simulation. If this analysis shows any trends in how the overall shape of the curve should be modified, then the parameters can be changed by trial and error until the desired curve is obtained. The steps to follow to perform a percolation analysis are:

1. In the main ICP window select ‘Water Year Plot’ under the ‘Display’ menu. Then choose ‘SAC-SMA’ under the ‘Select’ menu of the WY-PLOT display (the Sacramento model zone contents and runoff component breakdown must be included on the WY-PLOT display for the percolation analysis option to be active). Then choose ‘Percolation’ under the ‘Analysis’ menu. This will cause the current percolation curve to be displayed in one window and the current values of ZPERC, REXP, LZFSM and LZFPM to be displayed in another window.

2. In the window that shows a plot of the percolation curve choose ‘Points’ under the ‘Select’ menu and then choose ‘Build’. After this is done, whenever the right mouse button is clicked within the hydrograph plot portion of the WY-PLOT display, a dotted, red vertical line will appear on the percolation curve plot to indicate the lower zone deficiency ratio, LZDEFR, at that time and thus where you are on the percolation curve.

3. Go through the calibration period and select those events when the model response indicates a percolation error as shown on Figure 7-8-12. Events where other types of errors predominate, such as volume or timing errors, should be ignored. The SAC-SMA display is used to determine whether a lower zone tension deficit exists. Then determine where you are on the percolation curve during the event as described in step 2. You can determine where you are just prior to the event or can get the average percolation rate by checking on days just before and after the event. The main consideration is to be consistent in what you do from one event to another. For each event selected, click on the percolation curve plot where the vertical line appears to indicate whether the percolation rate should be higher, lower, or remain about the same. This will put a small red 'x' on the plot to indicate the relative change in the percolation rate that is needed to improve the simulation of that event (e.g. increase the rate significantly, decrease the rate slightly, or keep the rate the same). The amount that the curve needs to be changed is subjective. Over time you will become more skilled at anticipating the amount of change needed.

4. After going through the entire calibration period there should be many red x's on the percolation curve plot. If there is a trend in the suggested changes, it indicates that a new percolation curve is likely needed. If the points are scattered around the plotted curve, it indicates that no changes are needed to the current parameter values. If a new curve is suggested, the idea is to select changes to the parameter values to produce a curve that best fits the points. This is done by trial and error. Under the 'Select' menu of the percolation curve plot window choose 'Parameters'. This will bring up a new window that lists the current value of the 4 parameters. Make changes to the parameters and then click on 'Compute'. A new curve will be drawn on the percolation plot. Keep doing this until you get a curve that fits the points to your satisfaction. Then use those parameter values for the next calibration run. There is also a 'Solve' option under the 'Points' option of the 'Select' menu that will automatically fit a curve to the points. It is not recommended that this option be used.

In many situations going through the steps in the percolation analysis will not result in significant changes in the simulation results. By the time that a percolation analysis is performed, adjustments typically have been made to get a reasonable baseflow simulation and an overall water balance that is within a few percent. In order to for this to be the case, the overall amount of storm runoff should be realistic. Thus, most events will already have a reasonable percolation rate. The percolation analysis is primarily helpful in determining if the percolation curve adequately handles the full range of soil moisture conditions. Thus it is very important when doing the analysis to include as wide of range of LZDEFR values as possible. This is because over a certain range of LZDEFR values there are many combinations of PBASE, ZPERC, and REXP that will produce very similar curves. This is illustrated in Figure 7-8-13. For LZDEFR values from about 0.3 to 0.6 all of the curves on this figure look very much alike. For this example it would be very important to have events that occur under very wet conditions and especially cases when significant rain occurs when the soil is very dry in order to adequately define the percolation curve. In wet areas there may not be a wide range of LZDEFR values and thus it is impossible to get unique values for ZPERC and REXP. In these situations it is best to follow the guidelines in Section 7-5 and maintain spatial consistency. In some watersheds even though a wide range of LZDEFR values occur, the rain events that take place when the soil is dry are not of sufficient size to produce enough runoff to determine if the percolation curve needs to be modified. In these cases, if a good evaluation of the percolation curve can be achieved for some watersheds in the region, the values of ZPERC and REXP for those watersheds should be applied throughout the region with some possible modification for changes in soils.

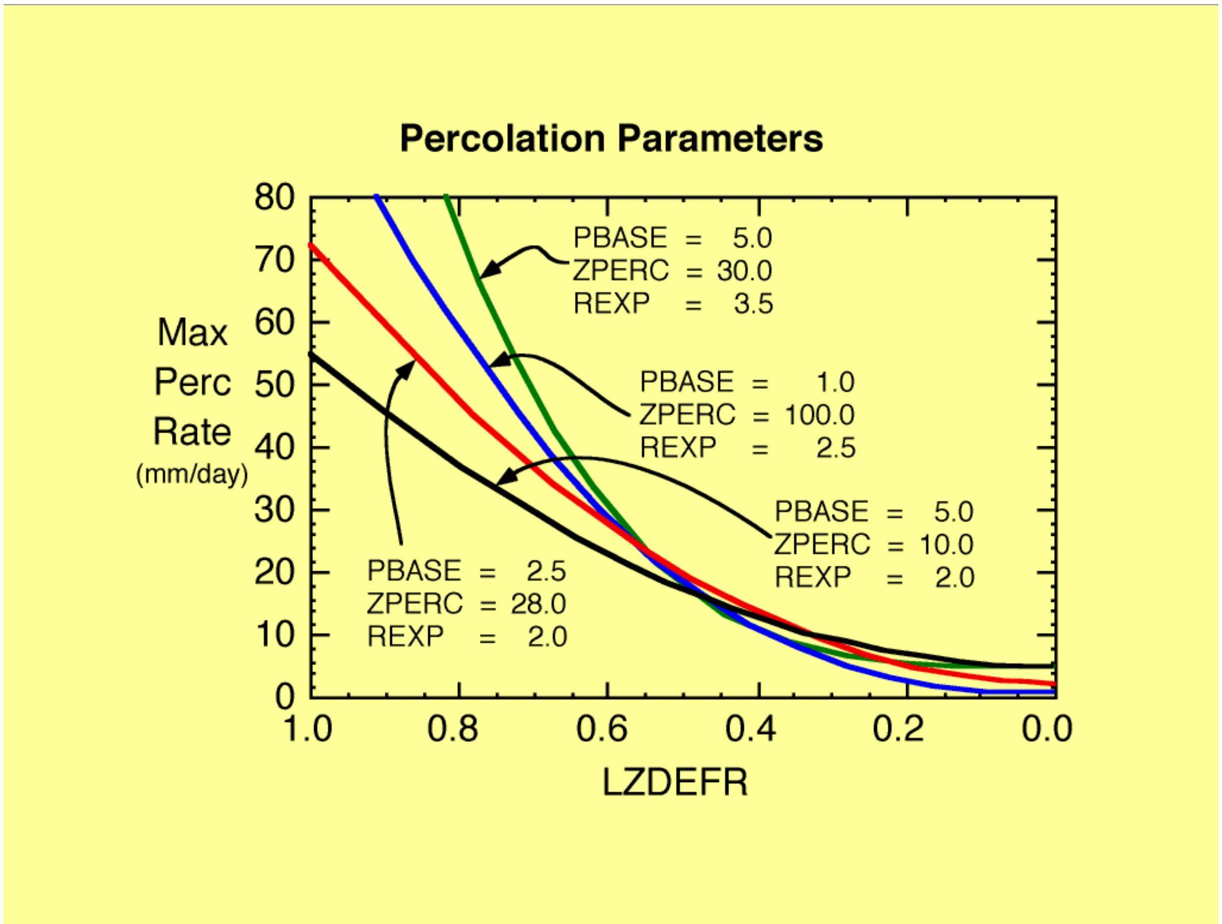


Figure 7-8-13. Illustration of how various parameter values produce similar percolation curves.

Figures 7-8-14 through 7-8-18 illustrate how changes to PBASE, ZPERC, and REXP affect model response. These figures should also reinforce what you are looking for when determining whether the percolation rate needs to be changed. In most of these figures the percolation analysis window that shows the percolation curves is included along with the main WY-PLOT display.

Figures 7-8-14 and 7-8-15 show the effect of PBASE on the model response. An arithmetic scale is used for the first figure to emphasize the high flow response and a semi-log scale is used for the second figure to accentuate the effect on baseflow recharge. When PBASE is 7.3, there is

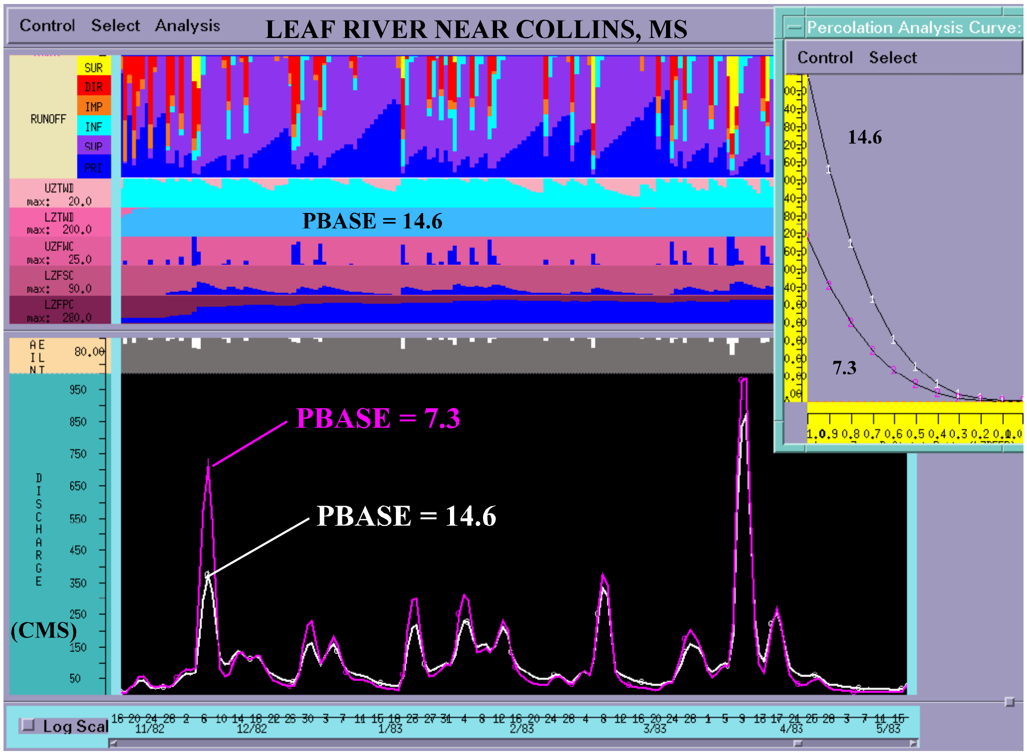


Figure 7-8-14. Effect of changing PBASE on model response (arithmetic scale).

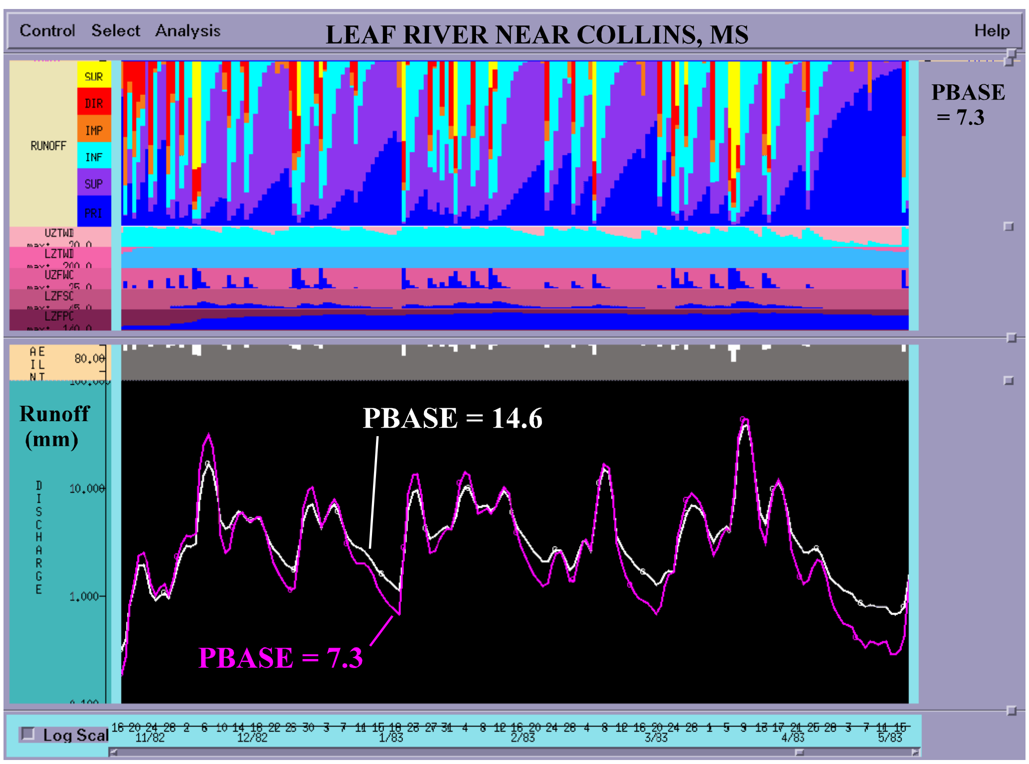


Figure 7-8-15. Effect of changing PBASE on model response (semi-log scale).

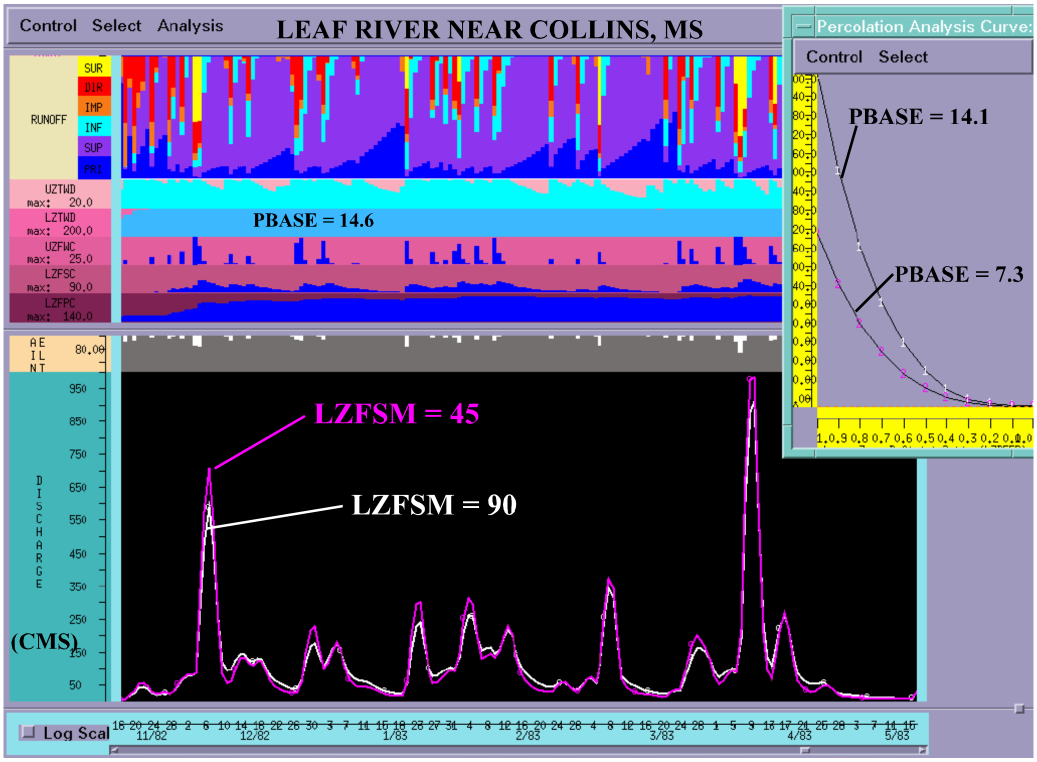


Figure 7-8-16. Effect of changing LZFSM on the percolation rate.

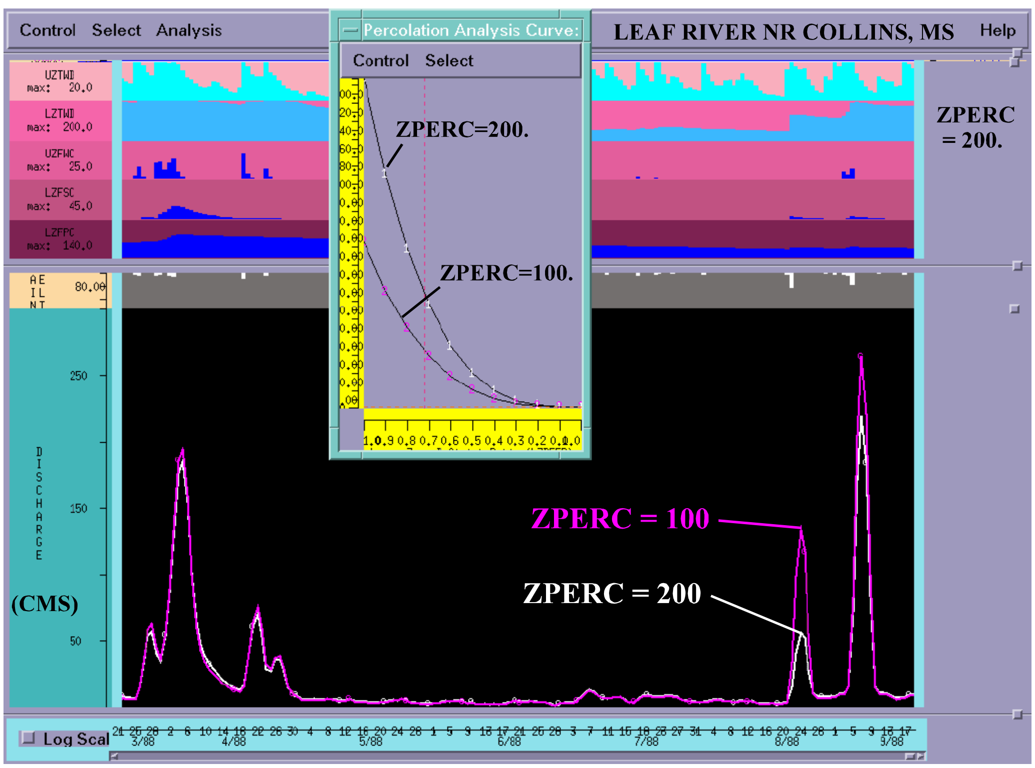


Figure 7-8-17. Effect of changing ZPERC on model response.

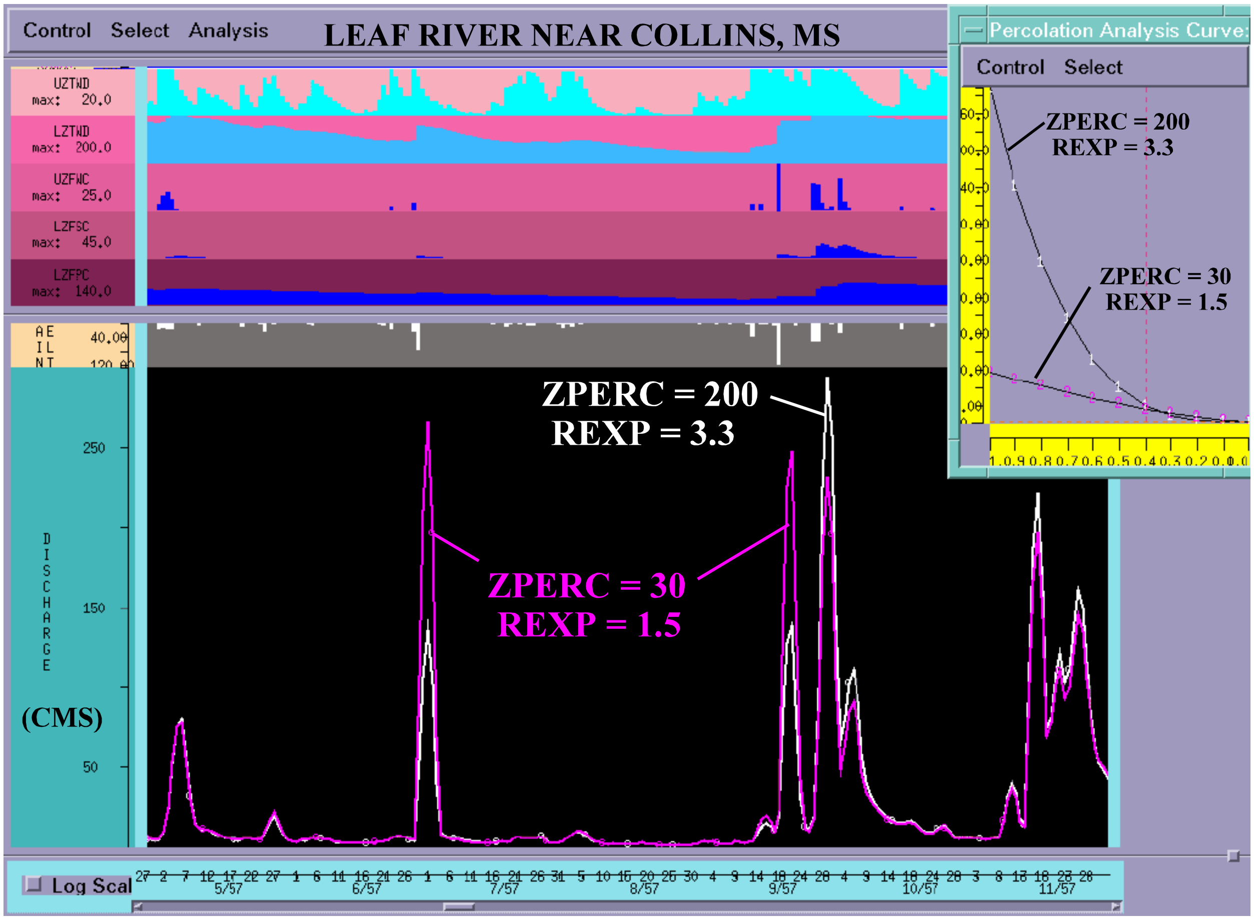


Figure 7-8-18. Effect of changing ZPERC and REXP on model response.

more storm runoff and less baseflow. This occurs for all events because a change in PBASE causes the entire percolation curve to increase or decrease by the ratio of the new PBASE to the previous value. Figure 7-8-16 is the same as Figure 7-8-14 except that only LZFSM is changed (in the previous 2 figures both LZFSM and LZFPM were altered by the same ratio in order to change PBASE). Doubling LZFSM from 45 to 90 mm causes PBASE to change from 7.3 to 14.1, thus showing how LZFSM dominates the PBASE value (doubling both LZFSM and LZFPM resulted in a PBASE of 14.6). The effect on percolation of doubling LZFSM is almost the same as the effect when both lower zone free water storages are doubled.

Figure 7-8-17 illustrates the effect of changing only ZPERC. Doubling ZPERC results in the maximum percolation rate under dry conditions to almost double while the rate under saturated conditions is not changed. Thus, the events in August and September, when the LZDEFR is quite large (i.e. dry soil due to a substantial lower zone tension deficit and little water in free water storages), are significantly more affected by changing ZPERC than the events in March and April when the soil is wet.

Figure 7-8-18 illustrates how events can be affected in different ways when the percolation curve is modified. In this case the two curves cross at a LZDEFR value of about 0.4. The maximum percolation rate is lower for the ZPERC=200, REXP=3.3 curve when the soil is wet, but greater when the soil is dry. This causes the model response to change as the soil becomes more saturated during the period shown. During the summer, the soil is quite dry, thus the ZPERC=30, REXP=1.5 curve produces much more storm runoff for the early July and mid September events. Right after the mid September event the LZDEFR value drops below 0.4, therefore the response of the remaining events is the opposite, i.e. the 30,1.5 curve produces the least amount of storm runoff. This example emphasizes why it is important to work with the entire percolation curve and to analyze the rate over a wide range of moisture conditions.

UZFWM

The primary function of the UZFWM parameter is to control when surface runoff occurs. Surface runoff can only occur when the intensity rate of the rainfall or rain+melt is sufficient to fill the upper zone free water storage. It is much easier to fill this storage when the percolation rate is low. This implies that surface runoff most frequently occurs under wet conditions and in regions where the soils have low permeability (baseflow amounts are low). Thus, the events to examine to determine if a change is needed to the value of UZFWM are those where surface runoff is already taking place with the current value of the parameter and those with large amounts of precipitation and near saturated soil conditions. Surface runoff can also occur for very high intensity events under dry conditions for watersheds with low permeability. The immediate response from these events is evaluated to determine whether more or less surface runoff is needed. The most important events to analyze are those that are just producing a little surface runoff and those that are currently not generating any, but the upper zone free water is close to being filled. An analysis of these events should suggest whether UZFWM should be increased or decreased. It should be noted that the UZFWC values shown on the ICP Sacramento display cannot always be used as an indication of how close an event was to producing surface runoff since the value shown is for the end of the day and free water contents can change quite rapidly for the upper zone.

Figures 7-8-19 and 7-8-20 illustrate how the model response is affected by changing the amount of surface runoff that is generated as the value of UZFWM is modified. The hydrograph plots on these two figures are exactly the same. The difference in the figures is the panel showing the runoff components. On Figure 7-8-19 the components are shown for the case when UZFWM=15. Figure 7-8-20 shows the components when UZFWM=30. When UZFWM=15 there are 4 events generating surface runoff. The first 3 produce quite a bit of surface runoff, while the early May event only generates a little. When UZFWM is changed to 30, the May event doesn’t generate any surface runoff and the other events produce much less. As UZFWM is increased and surface runoff decreases, the amount of interflow increases since there is more room to storage potential interflow runoff in the upper zone free water. Thus an effect of altering UZFWM is to change the relative division of storm runoff into surface and interflow. When less surface runoff occurs as in the case of UZFWM=30, not only is the immediate response reduced, but the timing is also modified. When there is more interflow, the peak occurs later because surface runoff enters the channel immediately while interflow is released from storage over some period of time.

For regions with highly permeable soils and those that never experience high intensity precipitation, at least at the spatial and temporal scales being used, surface runoff will never occur. In these cases it is impossible to determine the value of UZFWM. If UZFWM can be reasonably determined for a couple watersheds in such regions, these values could be used throughout the region. If not, a value great enough to surpress surface runoff should be selected and spatial consistency should be maintained.

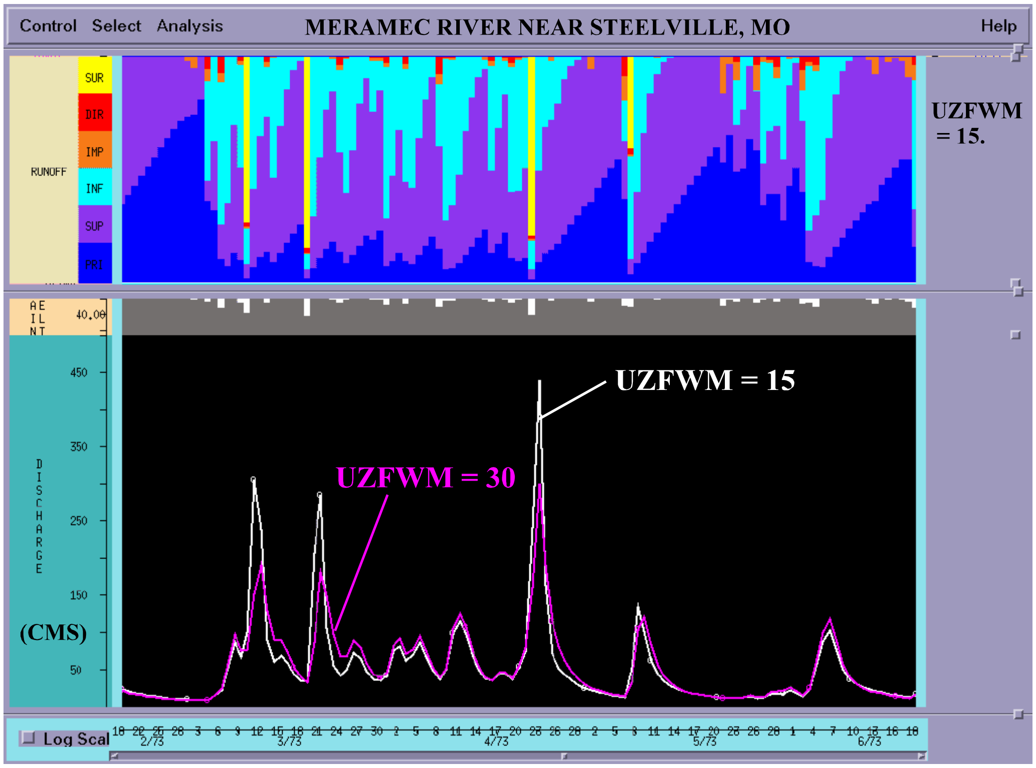


Figure 7-8-19. Effect of changing UZFWM on model response (UZFWM=15 components).

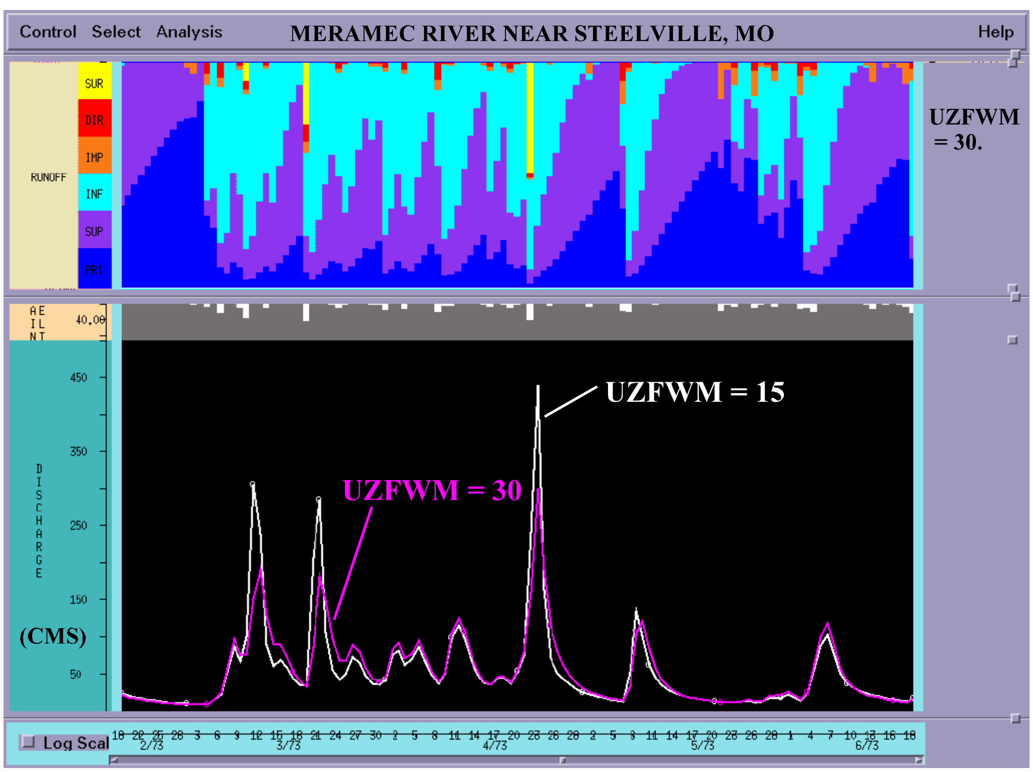


Figure 7-8-20. Effect of changing UZFWM on model response (UZFWM=30 components).

UZK

The primary function of the UZK parameter is to control the timing of interflow runoff. For most watersheds, interflow dominates small to moderate rises in the hydrograph. These are the events to examine to determine if the value of UZK should be modified. For watersheds with highly permeable soils and little or no surface runoff, interflow will dominate the response from all storm events. In these cases the timing sometimes appears to vary with the magnitude of the event, i.e. a greater UZK is indicated for large events than for small rises. Since only a single value can be used, it is generally best to try to match the response of the larger events when this situation occurs, though sometimes ADIMP can be used to produce a faster response from the larger events without affecting the smaller events very much.

Figure 7-8-21 illustrates the effect of changing UZK on model response. Changing UZK primarily affects the smaller rises where interflow is basically the only source of storm runoff. When surface runoff is significant, modifying UZK doesn't have much affect on the response. It should be noted that there is a large difference in the two UZK values used in this figure. This indicates that UZK is not as sensitive as some of the other model parameters. The effect of small changes in the value of UZK may be difficult to see.

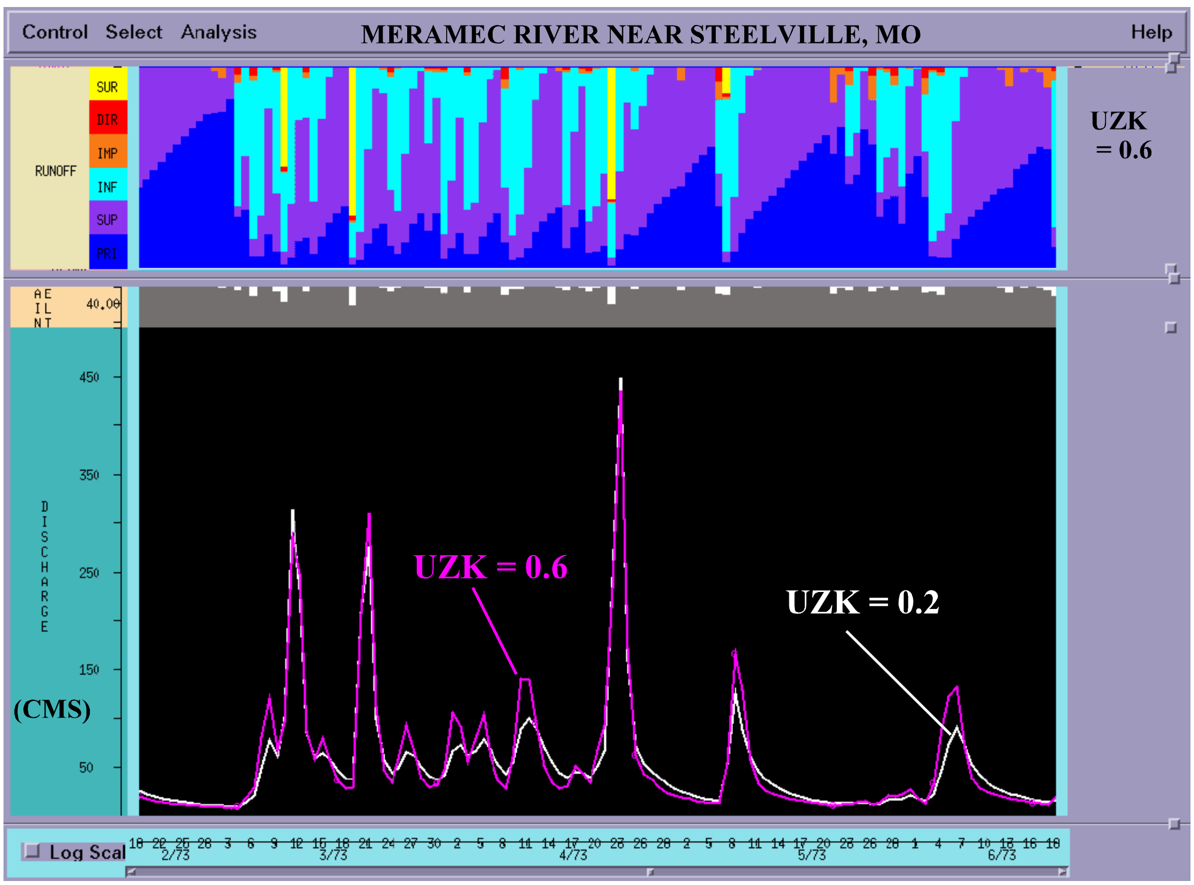
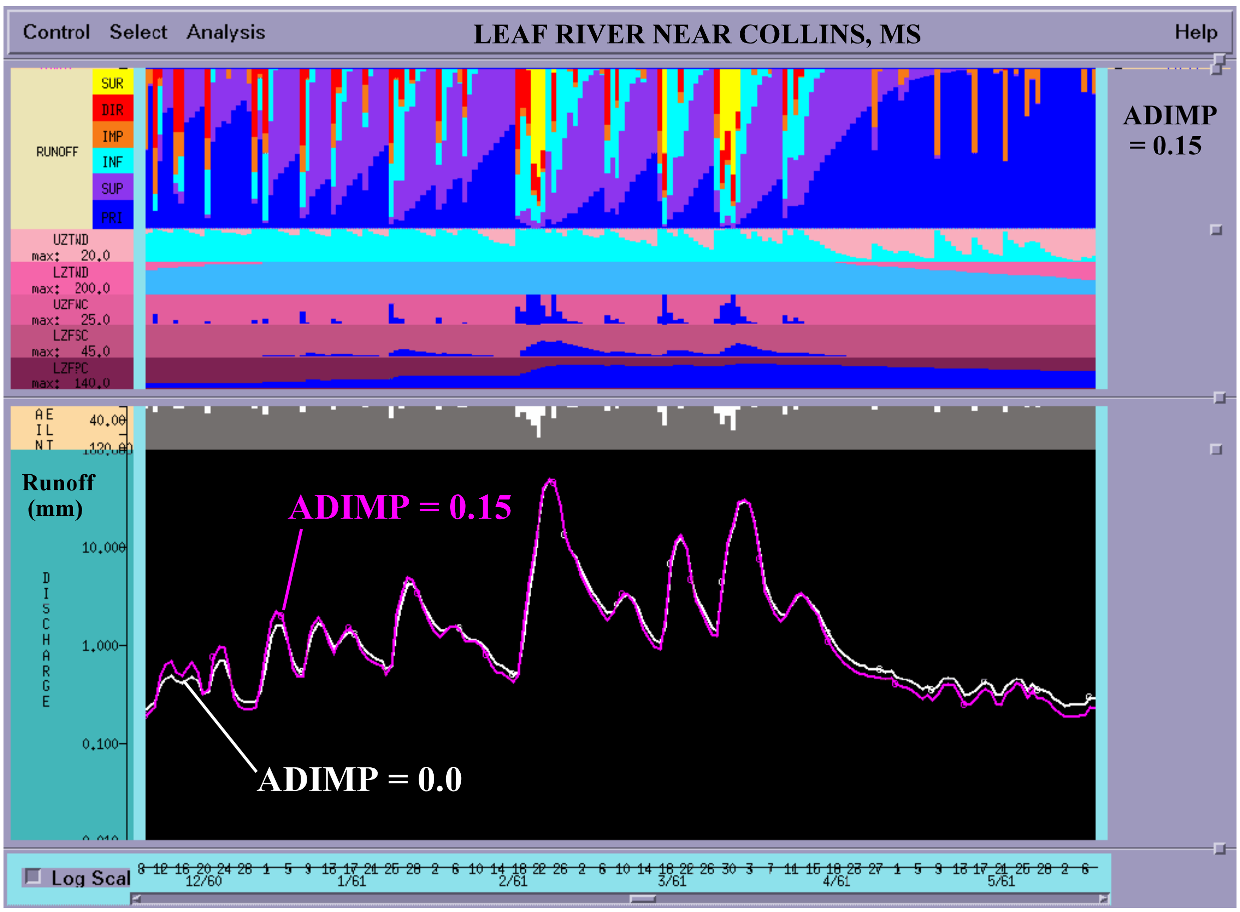


Figure 7-8-21. Effect of changing UZK on model response.**ADIMP**

The primary function of the ADIMP parameter is to produce some immediate response runoff (direct runoff) in cases when precipitation intensities are relatively low or the soils are very permeable. These are events when interflow dominates and there is little or no surface runoff. This suggests that for watersheds where surface runoff occurs frequently ADIMP may not be needed and that ADIMP will have the most noticeable effect on watersheds where surface runoff seldom or never occurs. It should be remembered that direct runoff can only occur when upper zone tension water is full, i.e. during events that produce some storm runoff.

Figure 7-8-22 illustrates the effect of ADIMP on a watershed that generates surface runoff from most large rain events. For the large events where surface runoff predominates, adding direct runoff by using some ADIMP produces little difference in model response. For smaller events where there is no surface runoff, the use of ADIMP generates a more rapid response though the semi-log scale masks some of the effect. Figure 7-8-23 illustrates the effect of ADIMP on a watershed that seldom produces any surface runoff. In this case adding some direct runoff produces a more rapid response from all the storm events.



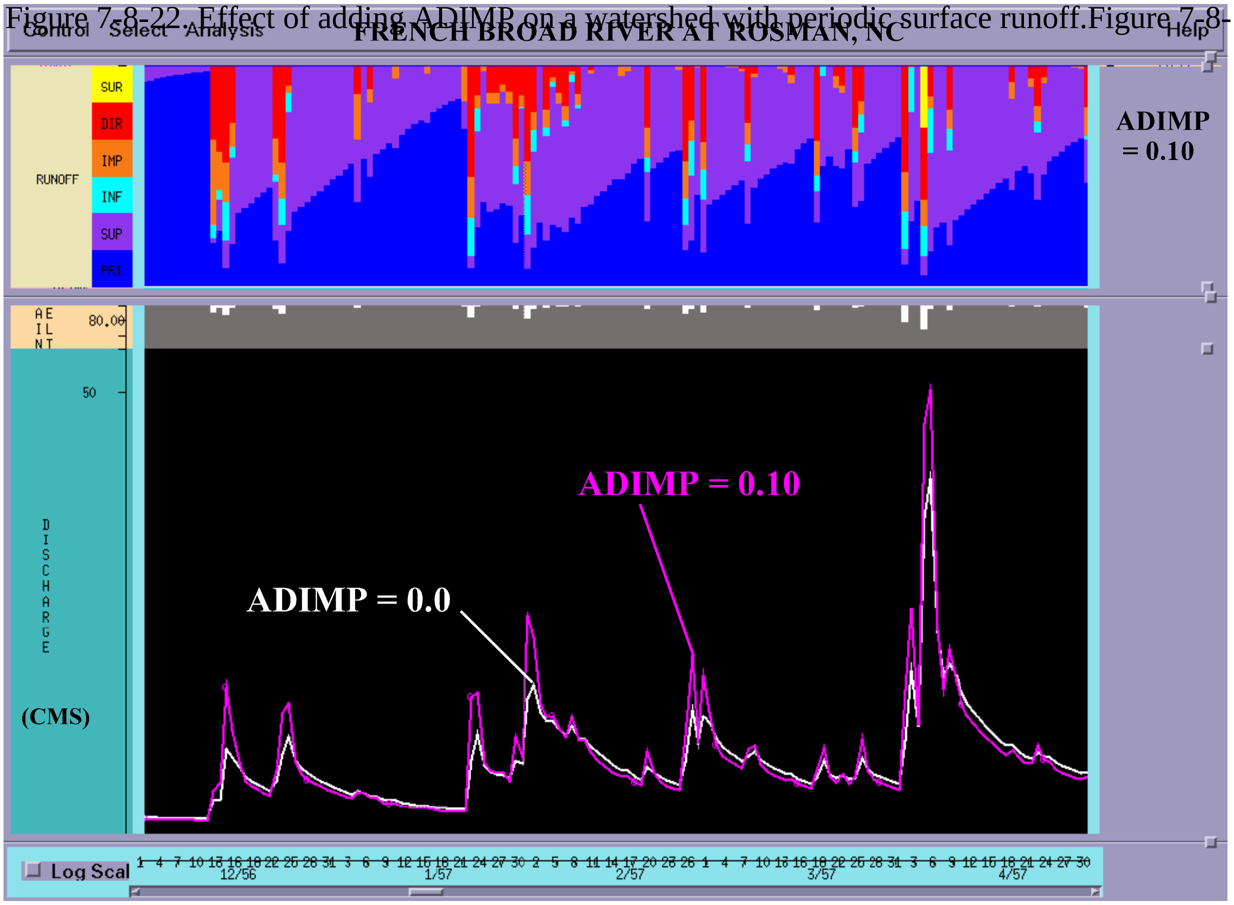


Figure 7-8-22. Effect of adding ADIMP on a watershed with periodic surface runoff.Figure 7-8-

23. Effect of adding ADIMP for a watershed with little surface runoff.

As indicated in Section 7-5 it is best to start with ADIMP set to zero unless a value can easily be derived from a hydrograph analysis. Then during the calibration decide whether ADIMP is needed. There is no reason to add complexity to the model if it is not clearly needed.

RIVA

The primary function of the RIVA parameter is to draw down the baseflow during very dry periods when ET-Demand rates are significant. These are the periods when riparian vegetation doesn't have adequate moisture near the surface to satisfy its needs so it withdraws water from groundwater before it reaches the channel system. Thus, the periods to examine to determine if the value of RIVA needs to be changed are those when there is a substantial upper and lower zone tension water deficit during a time of the year when significant evaporation is occurring. Typically the most likely time for riparian vegetation evaporation to occur is in the later part of the summer and early fall during a dry year. Figure 7-8-24 illustrates how adding RIVA will affect the model response during a dry period. In this case substantial tension water deficits exist from late May into October. The lower zone tension deficit doesn't fill until early January, but the riparian vegetation effect is over by mid November primarily because of the reduction in the evaporation rates and partly because of reduced upper zone tension water deficits.

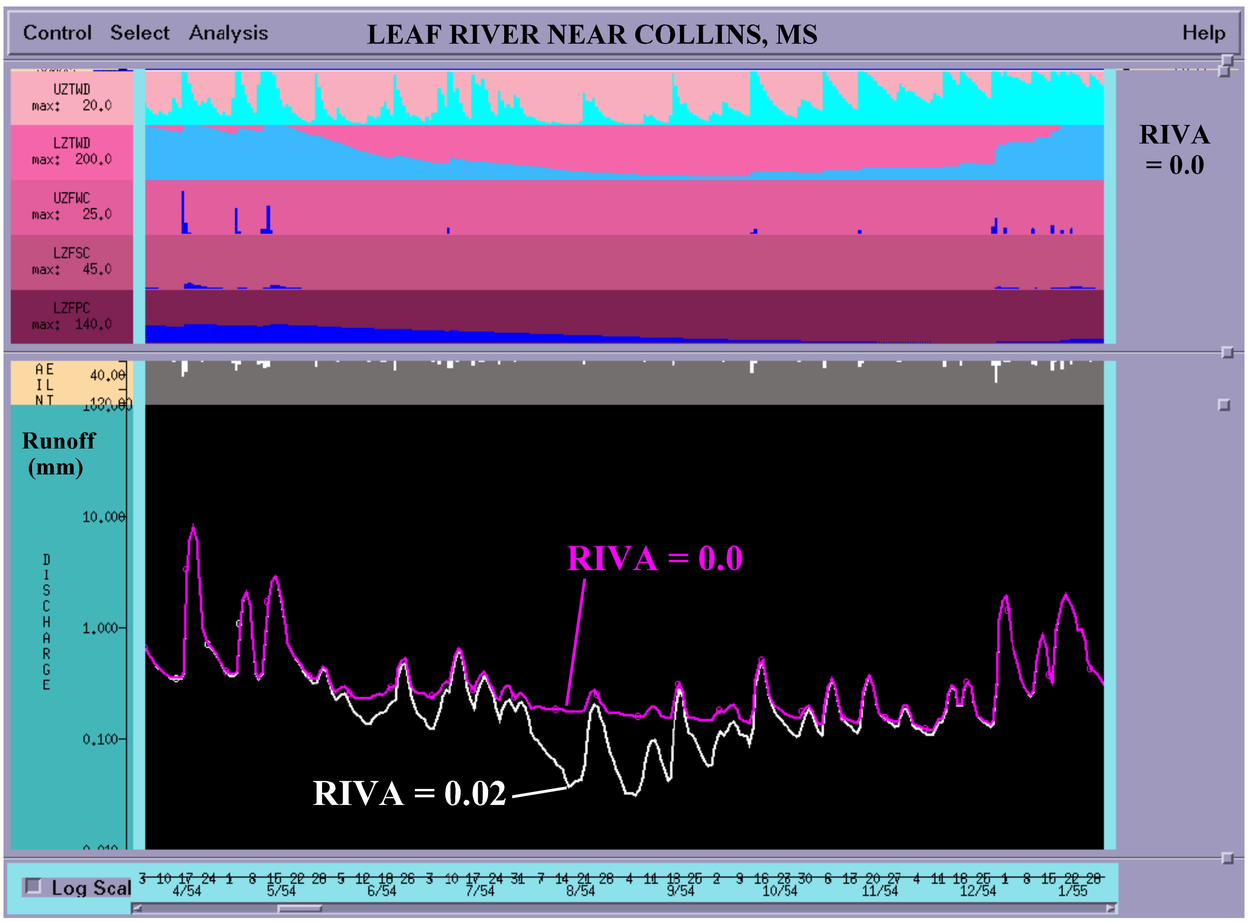


Figure 7-8-24. Effect of adding RIVA on model response.

PE Adjustment Curve

Changes to ET-Demand are indicated by a pattern in the seasonal, i.e. monthly, bias values on the statistical summary. Since other processes can affect the seasonal bias, such as the division between storm runoff and baseflow, baseflow withdrawal rates, and snowmelt timing, one shouldn't look at possibly changing the ET-Demand until problems with these other processes have been corrected. Errors in ET-Demand could be the result of improper estimates of PE, but are most likely due to an erroneous estimate of the seasonal PE adjustment curve. Thus, it is best to change the ET-Demand rate by modifying the PE adjustment curve. When using average monthly ET-Demand as input, the PE adjustment curve should be changed and then each months value multiplied by the average PE. This should insure that the shape of the PE adjustment curve remains physically realistic. Figure 7-8-25 illustrates how changes to the PE adjustment curve will affect the seasonal bias pattern. It should be noted that changes in the ET-Demand for a given month may affect the bias in subsequent months since tension water deficits produced by evaporation don't affect runoff until an event occurs.

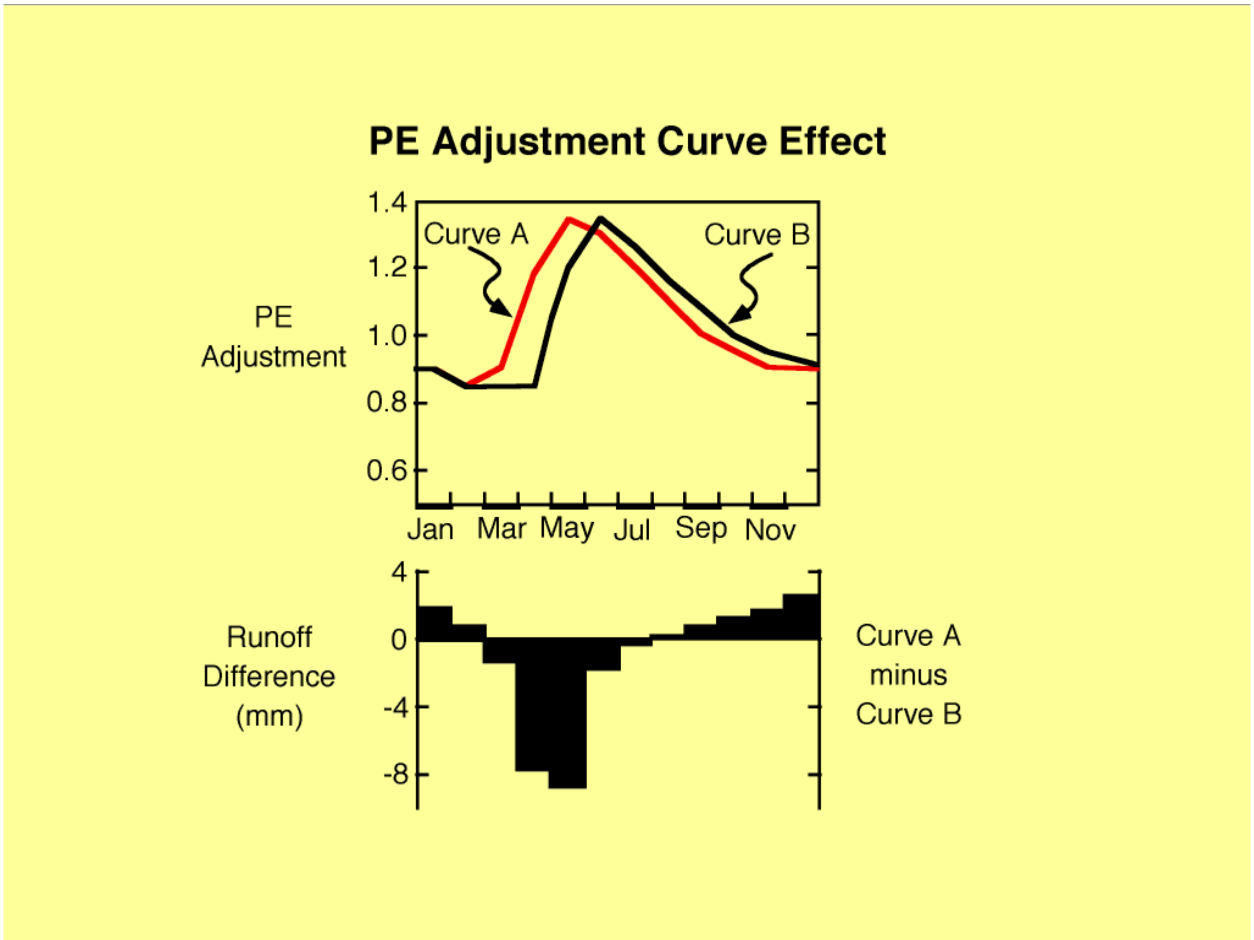


Figure 7-8-25. Effect of changing the PE adjustment curve on the seasonal bias pattern.

Parameter Effect Summary Table

Parameter	Primary Effect
LZPK	Controls slope of primary baseflow recession
LZSK	Controls timing of supplemental baseflow
LZFPM	Controls magnitude of primary baseflow
LZFSM	Controls magnitude of supplemental baseflow and percolation curve
PFREE	Controls baseflow recharge when lower zone tension deficit exists
SIDE	Determines if recharge to deep groundwater aquifers occurs
UZTWM	Controls maximum tension deficit that can occur in the upper zone (determines when storm and direct runoff and recharge will first occur after a dry period)
PCTIM	Controls the amount of fast response runoff when an upper zone tension deficit exists
LZTWM	Controls the maximum tension deficit that can occur in the lower zone
Percolation Curve	Controls the division between storm runoff and baseflow • ZPERC determines percolation rate when soil is completely dry • REXP determines the shape of the percolation curve • LZFSM controls the saturated percolation rate
UZFWM	Controls when surface runoff occurs
UZK	Controls the timing of interflow
ADIMP	Determines whether direct runoff occurs from low intensity events when the soil is wet
RIVA	Determines whether evaporation from riparian vegetation occurs when the soil is dry and evaporation is significant
PE Adjustment Curve	Controls the seasonal ET-Demand pattern along with PE - effect reflected in statistical seasonal bias pattern

Table 7-8-1. Summary of primary effect of each Sacramento model parameter.

Section 7-9

Evaluation of an *A Priori* Parameter Estimation Procedure

Introduction

This section illustrates how an *a priori* parameter estimation procedure can be evaluated for use in a given region. As mentioned in Section 7-5, is it important to evaluate the derived parameter values based on periods when the effects of each parameter on the hydrograph can be isolated rather than on overall 'goodness of fit' statistics. This is the only way to determine if the procedure is determining physically realistic values for the parameters. It is also helpful to determine if the *a priori* procedure can derive realistic spatial variations in parameter values over a river basin especially when some of the watersheds response quite differently than others or have significantly different values of key physiographic factors.

The Koren [2000] procedure is used in this section to illustrate the method for evaluating the derived parameter values. In this procedure total soil depth and porosity, field capacity, and wilting point information for 11 soil layers (from ground surface to 2.5 m beneath) derived from the STATSGO high resolution gridded soil data files are used to calculate estimates of 11 of the Sacramento model parameters. Tension water is determined as a function of the difference between the field capacity and wilting point and free water as the difference between porosity and field capacity, which is physically what these storages are intended to represent. The capacity of these storages are determined by dividing the soil profile depth into an upper and lower zone and further dividing the lower zone free water into primary and supplemental components. This assumes that the free water and tension water for each zone occupy the same space in the soil profile. This may not be the case. Certainly in most watersheds the primary baseflow, and probably the supplemental, aquifers are further down in the soil than the limits of the root zone which controls the lower limit of tension water storage. The free water withdrawal rates are calculated from empirical relationships. ZPERC is determined using the model percolation equation and assuming that the maximum daily percolation rate is equal to the contents of the all the lower zones, which may not be a correct assumption. The percolation curve shape parameter, REXP, is estimated using an empirical equation that produces low values, near 1.0, for sand and high values for clay soils, which are appropriate. The PFREE parameter is assumed to relate to water that follows paths through cracks, faults, etc. to escape the capillary demands of the soil and it is further assumed that clay type soils have more cracks. The PFREE parameter is actually more likely to be related to the distribution of lower zone tension water depths over the watershed and the fact that some portions of the area are saturated and thus recharging groundwater while other areas still have tension water deficits.

Evaluation

The suggested method of evaluating any *a priori* procedure for estimating model parameters is to compare the simulated hydrograph produced by the derived parameters to the observed streamflow for the watershed. The objective is then to examine the periods when the effects of each parameter can be isolated to determine if the derived values are reasonable. In the following illustration of this technique, the parameters derived using the Koren method are referred to as soil based parameters.

In order to generate a hydrograph other parametric information is required in addition to the 11 Sacramento model parameters produced from the soils information. For the examples in this section these other parameters were determined as follows:

- Sacramento model parameters PCTIM, ADIMP, and RIVA are set to 0.0. Also RSERV is set to 0.3, its recommended default which is typically satisfactory for most watersheds, and SIDE is set to 0.0, which is the case for most areas.

- The ET-Demand curve was either obtained from a calibration of the watershed or from CAP estimates of mean monthly PE and the seasonal PE adjustment curve. If the overall bias was greater than a few percent, the PEADJ factor in the SAC-SMA operation was used to get the water balance within this limit.

- The unit hydrograph was obtained from a calibration or by estimating the channel response and then making adjustments to obtain a reasonable fit of the timing for major runoff events.

- If snow was included in the simulation, the snow model parameters were obtained from a calibration of the watershed.

Generally when evaluating an *a priori* parameter estimation procedure for the Sacramento model, ET-Demand values would be estimated as described in Section 6-5, the initial unit hydrograph would be obtained as discussed in Section 7-6, and the initial snow model parameters would be based on the guidelines included in Section 7-4. In this case calibrated values were used whenever possible to remove any variability generated by improper values of these parameters.

The first basin examined is the Oostanaula River basin in Georgia. Figure 7-9-1 shows a semi-log plot comparison of the soil based parameter simulation to the observed flow for the Conasauga River near Tilton (TLNG1) for a portion of the period of record. Figure 7-9-2 is an arithmetic plot for the same period. These figures indicate that at least most of the soil based parameter estimates are quite realistic for this watershed. Some slight adjustments are probably needed to some of the baseflow parameters, but overall the method derives values that produce a very reasonable simulation. In Chapter 4 a spatial assessment of hydrologic variability within the Oostanaula basin, based on hydrograph plots as shown in Figure 4-1, indicated that there were significant differences in how the Ellijay, Hinton, and Tilton watersheds responded. This assessment indicated that the percolation rate for Elijay and Hinton should be greater than for Tilton as those watersheds generate much more baseflow and considerably less fast response storm runoff than the Tilton watershed. In order to see if the soil based parameter estimation

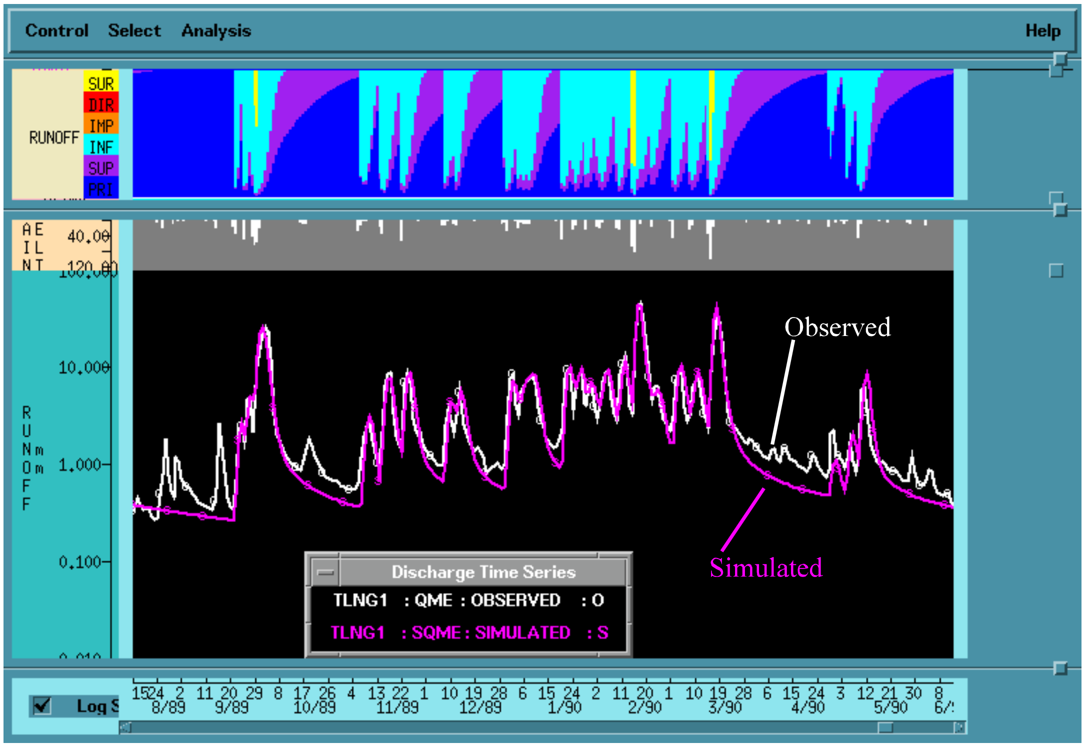


Figure 7-9-1. Soil Based Simulation for Tilton - semi-log plot.

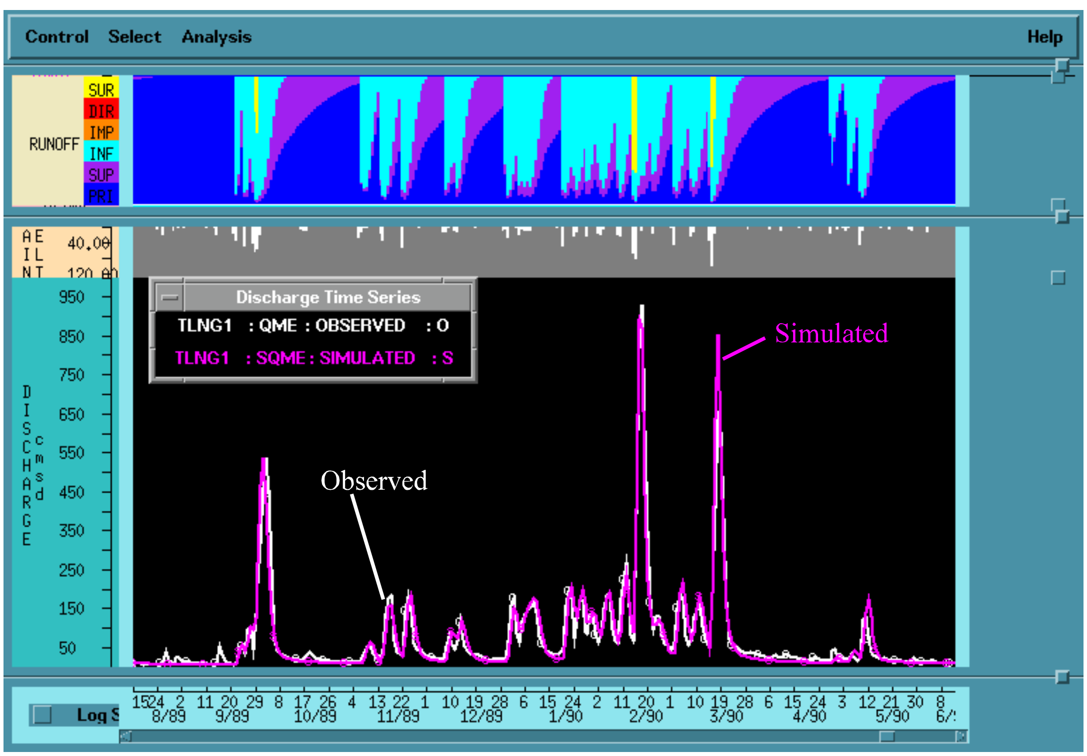


Figure 7-9-2. Soil Based Simulation for Tilton - arithmetic plot.

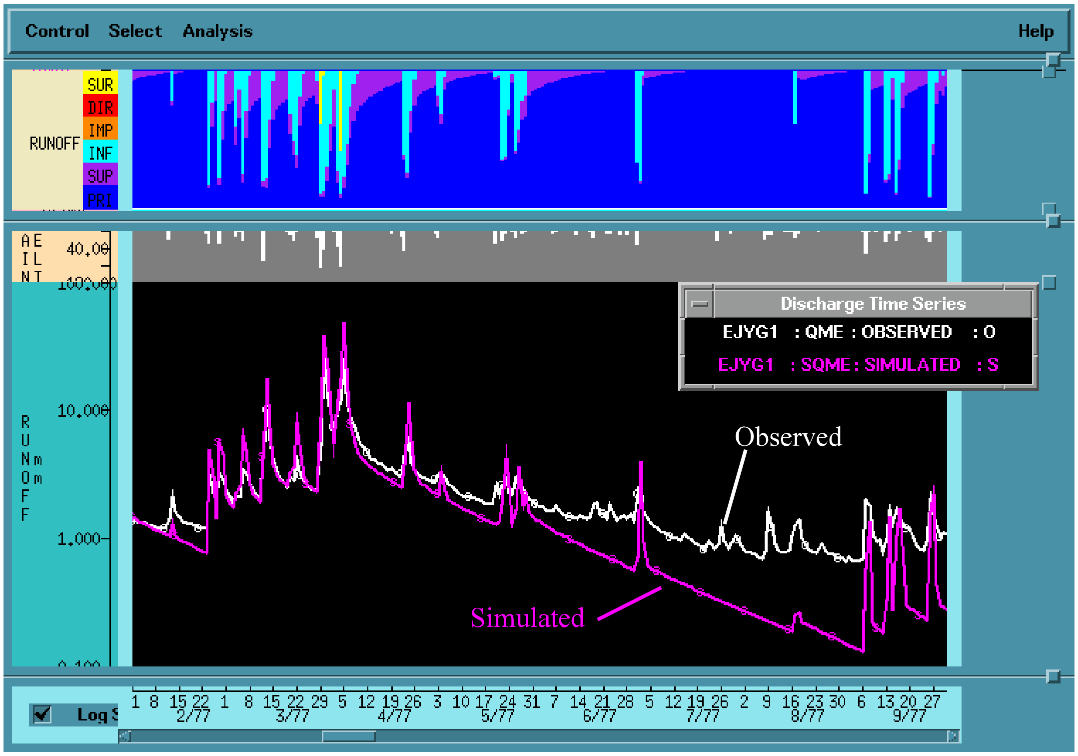


Figure 7-9-3. Soil Based Simulation for Elijay - semi-log plot.

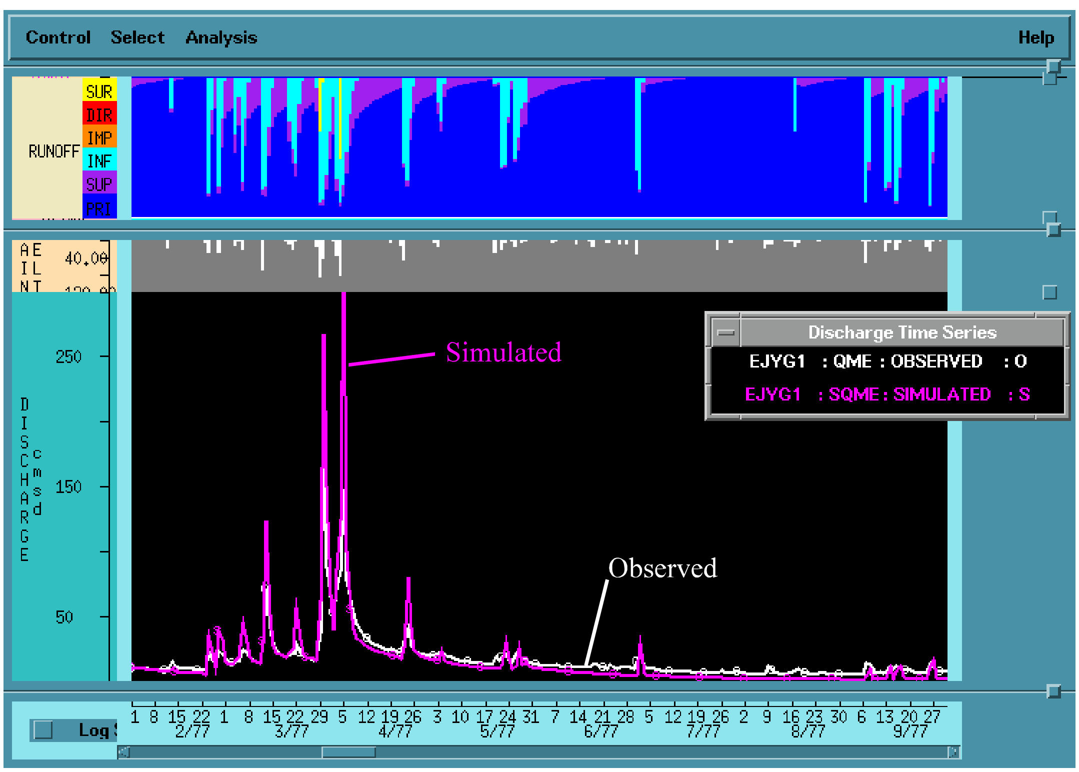
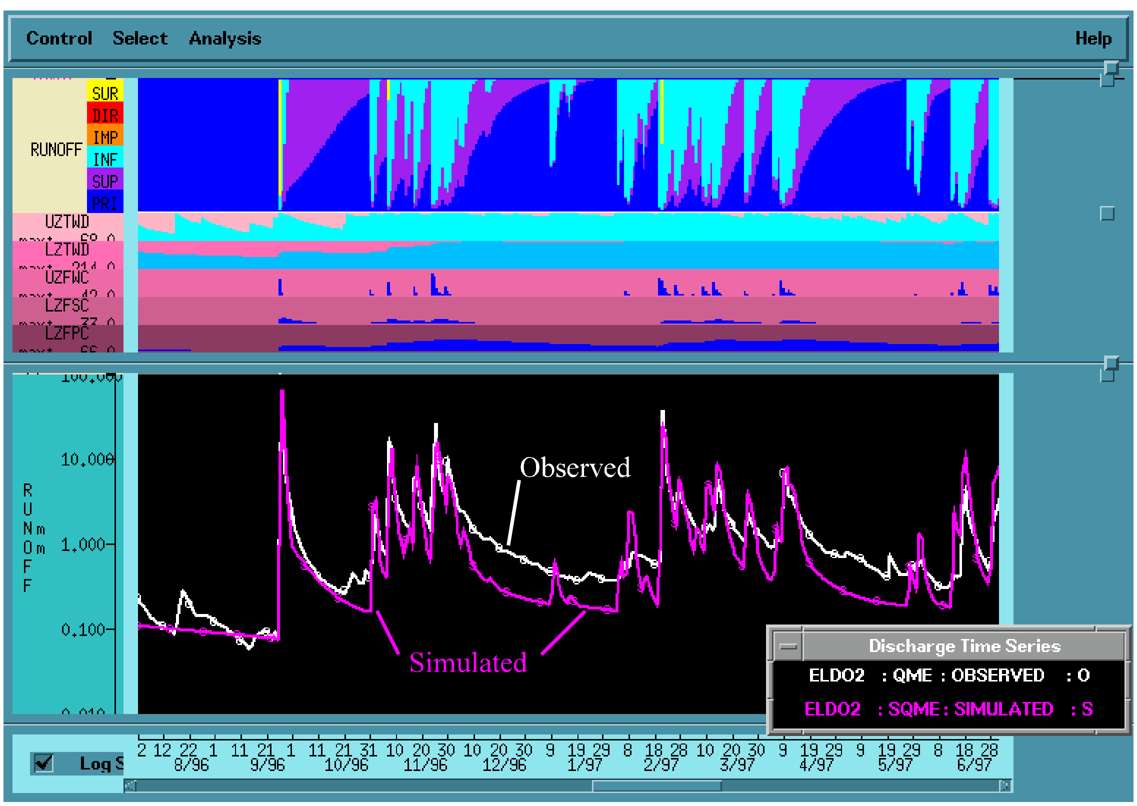


Figure 7-9-4. Soil Based Simulation for Elijay - arithmetic plot.

method could reproduce these differences, the method was applied to the Coosawattee River near Ellijay (EJYG1). Figures 7-9-3 and 7-9-4 show semi-log and arithmetic plots comparing the soil based simulation to the observed flows for this watershed. These plots indicate that the soil based procedure is not able to detect the variability in hydrologic conditions that exist between Tilton and Elijay. The soil based simulation for Elijay generates too much surface runoff and not nearly enough baseflow. The primary baseflow recession is much too fast and supplemental baseflow is practically non-existent.

The next basin examined is the Illinois River above Tenkiller Dam in Oklahoma. Figure 7-9-5 shows a semi-log plot of the soil based parameter simulation versus the observed flow for a portion of the period of record for the Barren Fork at Eldon (ELDO2). The figure shows that the soil based parameters are fairly reasonable and would at least be useful as initial estimates. Some adjustments are needed to the baseflow withdrawal rates and storage capacities. Also the interflow withdrawal rate appears to be too fast. Figure 7-9-6 shows a comparison of observed flows at Eldon and the Illinois River at Watts (WTTO2). This figure indicates that the response of these two watersheds is very similar. Figure 7-9-7 shows a comparison of the soil based parameter simulations for the same two watersheds. The parameters and the resulting hydrographs are basically the same. Thus, in this case where there is little difference in the response of two nearby watersheds, the soil based method correctly indicates that conditions are similar.



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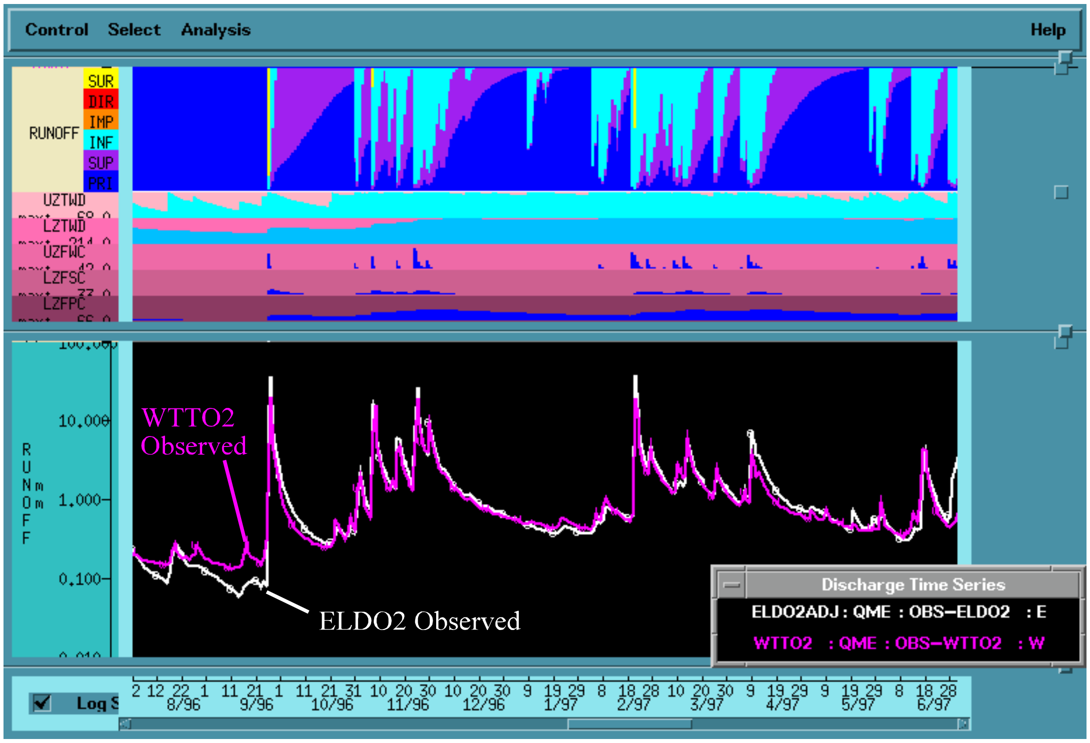
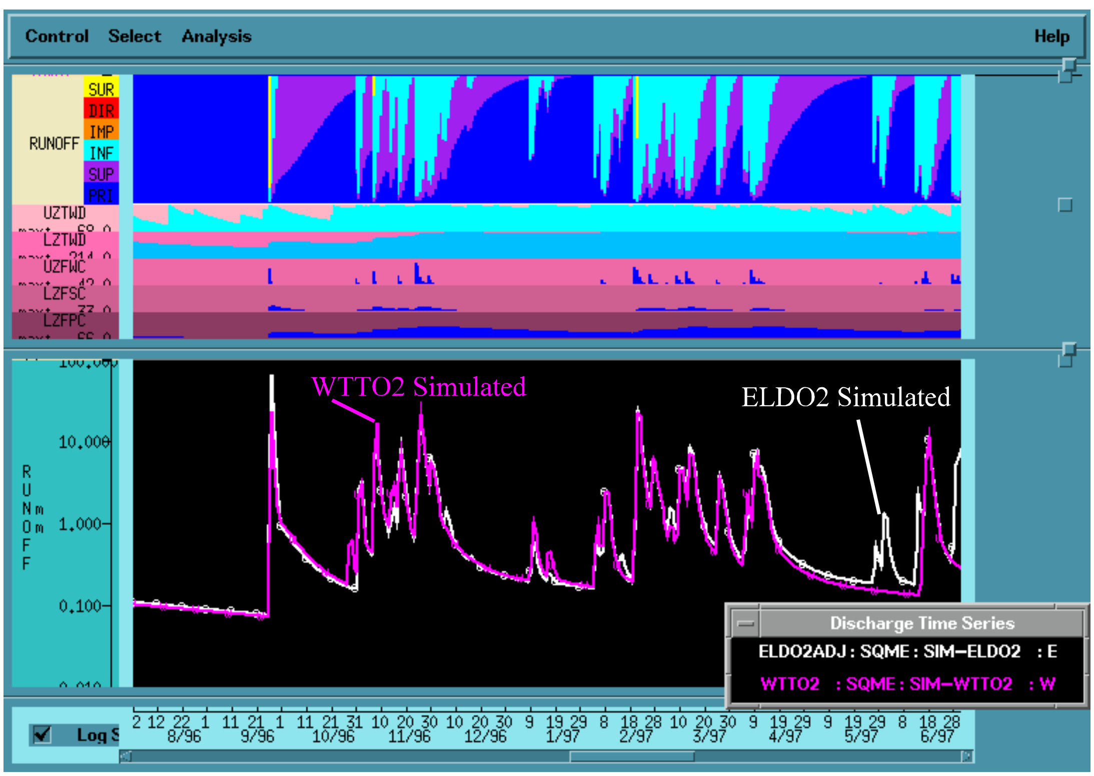


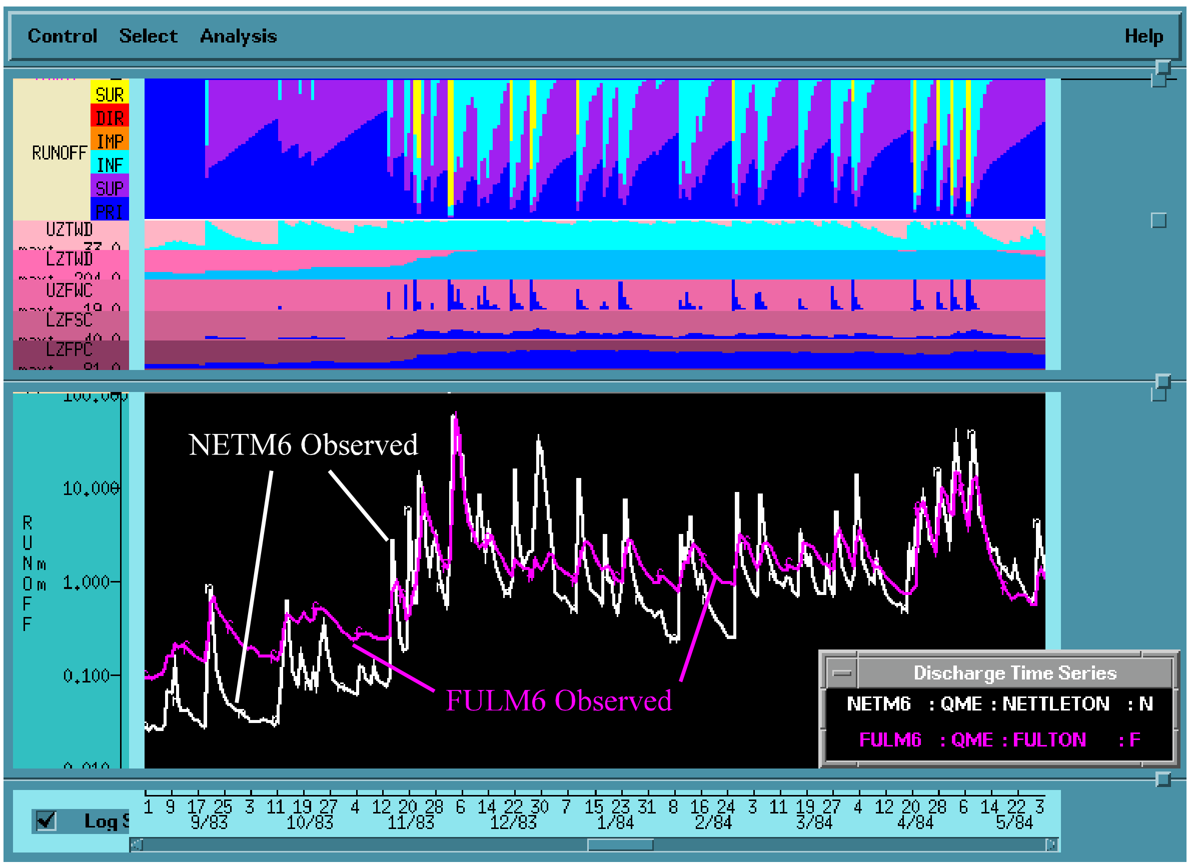
Figure 7-9-6. Comparison of Observed Flows for Eldon and Watts.



Figu re 7-

9-7. Comparison of Soil Based Simulations for Eldon and Watts.

The next basin evaluated was the Upper Tombigbee River in northeastern Mississippi. Figure 7-9-8 shows a comparison of the observed streamflows for Town Creek at Nettleton (NETM6) and the Tombigbee near Fulton (FULM6). The response of these two adjacent watersheds is fairly different. Town Creek is mostly within the region called the Black Belt that extends from central Alabama into northeastern Mississippi and contains very black, fertile soil. The Fulton drainage is just outside of this region. The soil based parameter estimation method recognizes that the soils are different between the two watersheds in terms of generating somewhat different values for a number of the parameters (e.g. UZTWM - 33 mm vs. 42 mm, UZFWM - 19 mm vs. 33 mm, UZK - .30 vs. .46, ZPERC - 93 vs. 66, LZFPM - 81 vs. 125, LZSK - .08 vs. .12, LZPK - .010 vs. .020, and PFREE - .37 vs. .26 – the value for Nettleton is listed first), however, as shown in Figure 7-9-9 the simulations using the soil based parameters are quite similar. The simulated hydrographs are much more like the response of the Fulton watershed than Town Creek. Thus,



even though individual parameter values vary from one watershed to the other, the resulting soil based simulations do not reflect the differences between the two drainages.

Figure 7-9-8. Comparison of Observed Flows for Nettleton and Fulton.

The next basin tested was the Merrimack River basin in New Hampshire and Massachusetts. Figure 7-9-10 shows a semi-log plot comparing soil based simulated flows versus observed values for the Smith River near Bristol, New Hampshire (BRSN3). Figure 7-9-11 shows an

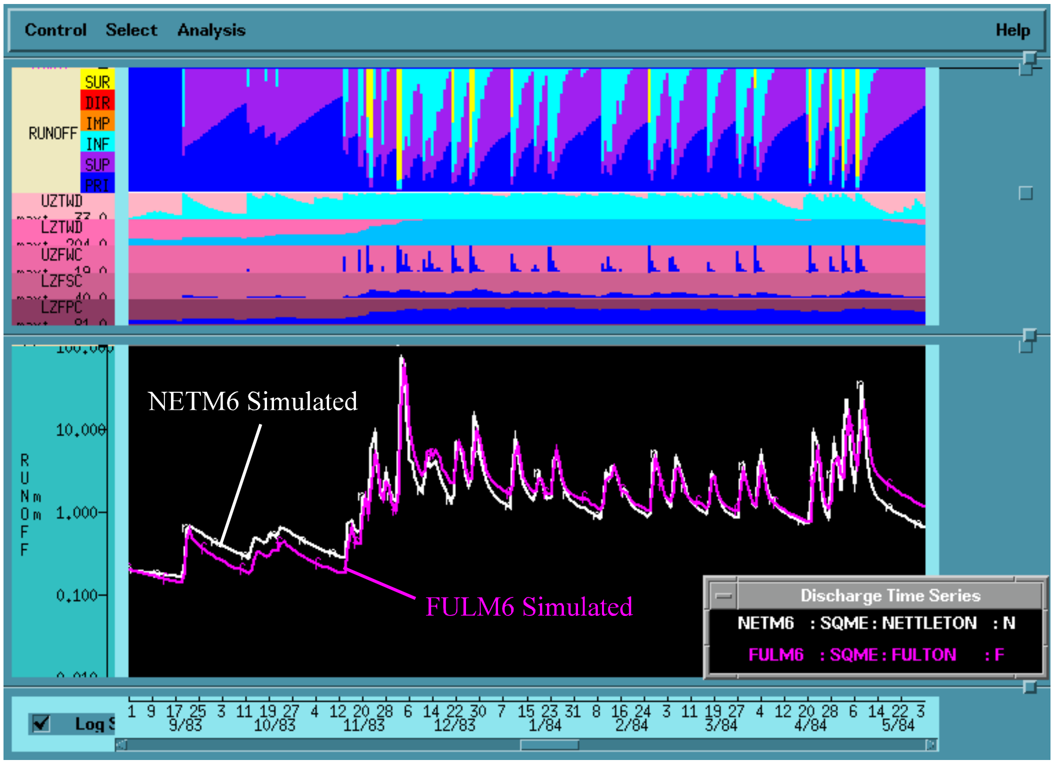


Figure 7-9-9. Comparison of Soil Based Simulations for Nettleton and Fulton.

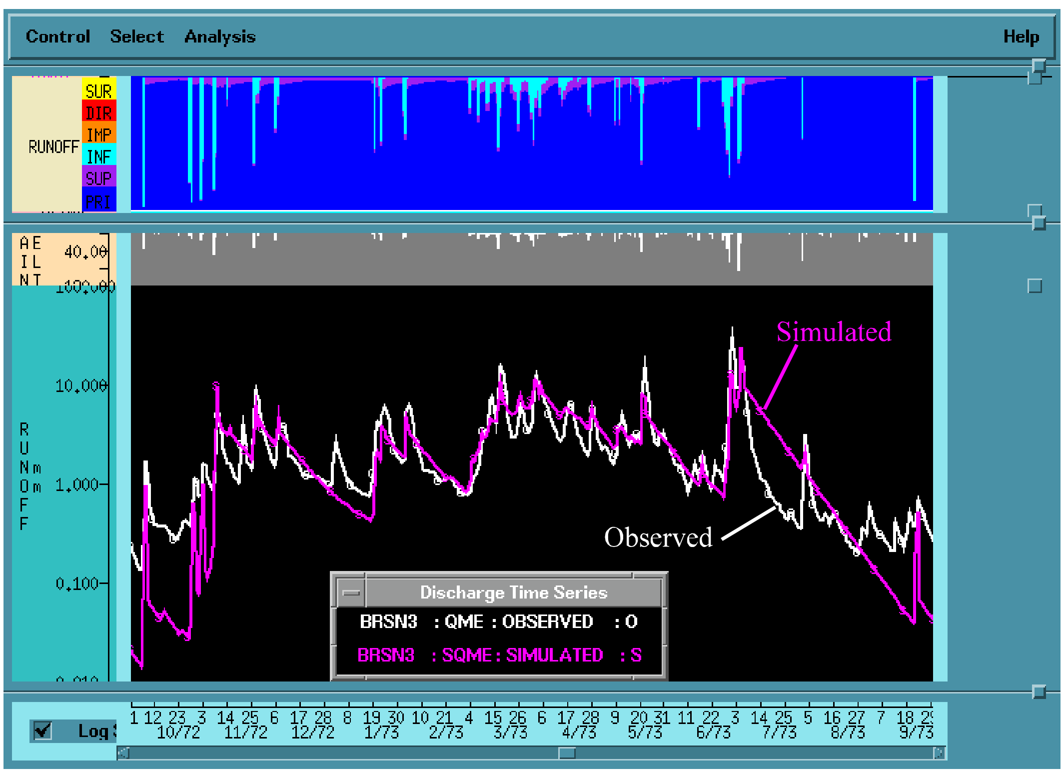


Figure 7-9-10. Soil Based Simulation for Bristol - semi-log plot.

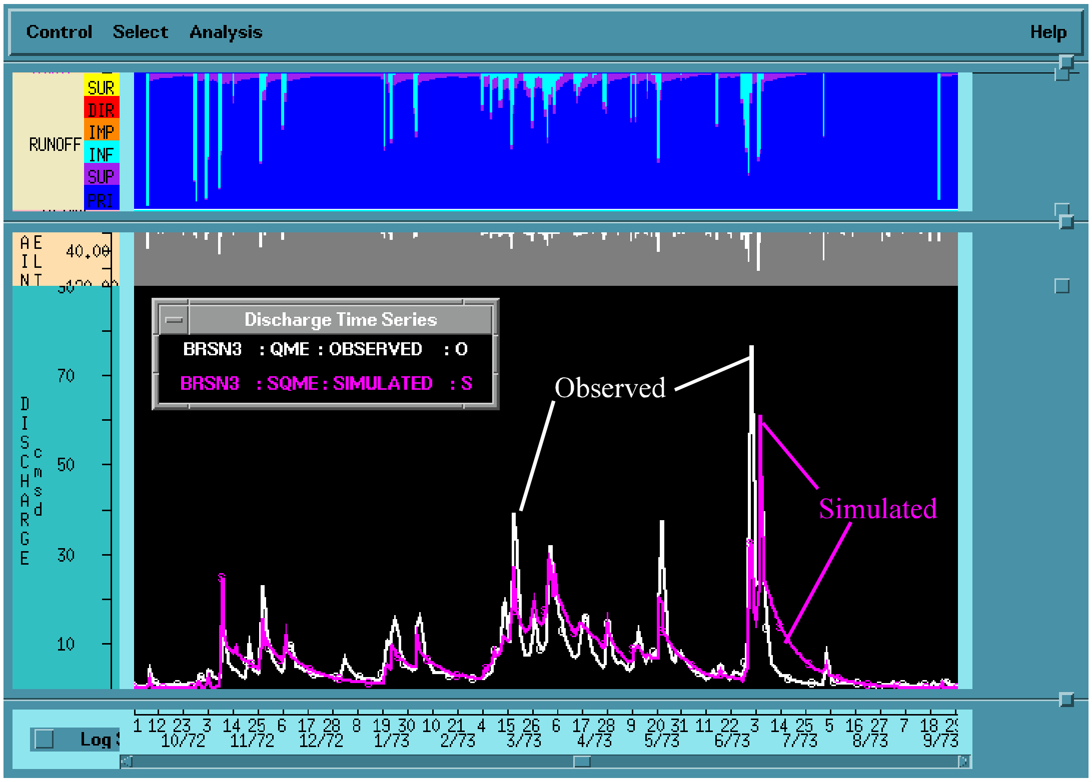


Figure 7-9-11. Soil Based Simulation for Bristol - arithmetic plot.

arithmetic plot for the same period. For this watershed the soil based parameter values are not physically realistic. Almost all of the flow is primary baseflow with some fast interflow during storm events. In reality the primary baseflow withdrawal rate should be much slower, the supplemental baseflow contribution should be considerable, there should be much more interflow, though at a slower withdrawal rate, and the largest events should produce surface runoff. Similar results were obtained when applying the soil based method to two other watersheds in the Merrimack drainage; the Pemigewasset River near Woodstock, NH and the Assabet River near Maynard, MA. Thus, the soil based method did produce similar parameter values throughout the Merrimack basin as would be expected based on Figure 4-2, however, the values were not reasonable.

The last watershed examined was the Gallatin River near Gallatin Gateway, Montana (GLGM8). Figure 7-9-12 shows a semi-log plot of the comparison between the soil based simulation and observed flows for this two elevation zone, western, snowmelt runoff dominated drainage. Figure 7-9-13 contains an arithmetic plot for the same period. As for the Merrimack basin, the soil based parameters for this watershed are not physically realistic. There is too much primary baseflow and the withdrawal rate is much too quick, there is not nearly enough supplemental baseflow, and the amount of interflow is too great and too fast.

For these five basins the results from the Koren soil based parameter estimation procedure are

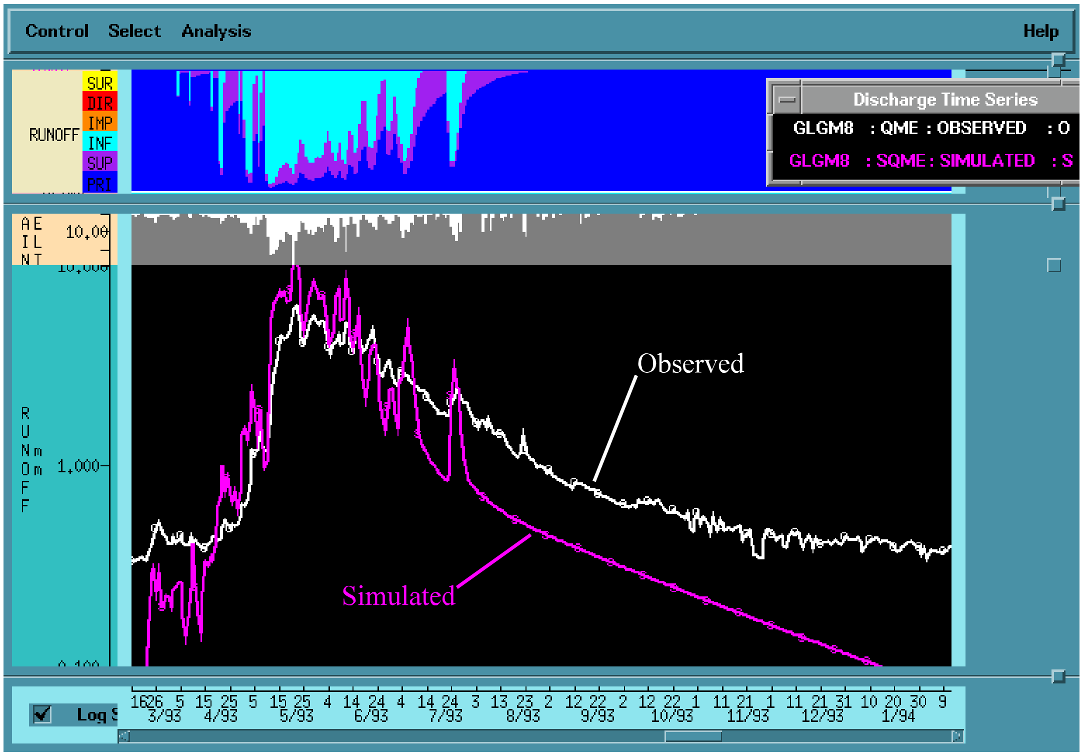


Figure 7-9-12. Soil Based Simulation for Gallatin Gateway - semi-log plot.

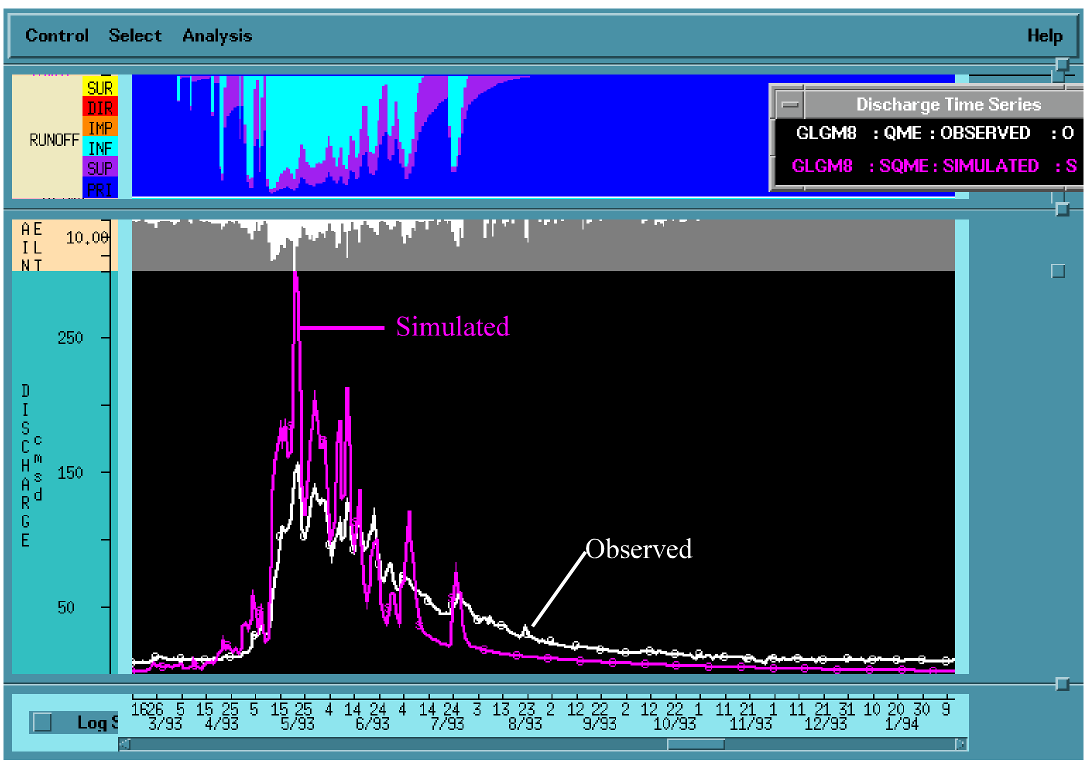


Figure 7-9-13. Soil Based Simulation for Gallatin Gateway - arithmetic plot.

mixed. In the three river basins scattered across the southern part of the country, the Oostanaula, the Illinois, and the Tombigbee, the soil based method generated values that at least for one watershed in each basin produced fairly realistic parameter values, however, in the two cases where there were differences between the response of adjacent watersheds, the simulations using the soil based parameters didn't reflect this variability. For the other two basins, the Merrimack and the Gallatin, the parameter estimates from the soil based method were not physically realistic and wouldn't be useful even as initial parameter values. It should be noted that, at least in this case, all of the watersheds that exhibited the worse results with the soil based parameters, the Gallatin, Merrimack, and Elijay, were in mountainous areas with considerable forest cover. This could just be coincidence. Overall, the greatest weakness of the soil based method seems to be in determining appropriate values for the free water storage parameters, both the upper and lower zone withdrawal rates and capacities. These are parameters for which reliable estimates can often be obtained by analyzing the observed hydrograph as described in Section 7-5.

<u>Summary</u>

It is critical to carefully evaluate any *a priori* parameter estimation procedure before using it in a given region. Such procedures may work well in some regions and not in others. It is also important to verify whether the procedure will serve the purpose for which it might be used. A given method might provide reasonable initial parameter values for a calibration for some watersheds, but not adequately reflect the variability in parameter values across the region. It is recommended that a given procedure be evaluated by comparing *a priori* parameter simulations to observed flows for several watersheds in the region. The emphasis of the comparisons should be to determine if the parameter values are realistic by looking at the portions of the hydrograph where each parameter can be isolated and not by comparing overall 'goodness of fit' statistics.

Chapter 8

Step 6 - Operational Implementation of Calibration Results

Introduction

A properly performed historical data analysis and model calibration should have significant benefits for the operational application of the models and procedures as mentioned in Chapter 1. To repeat, these 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.

However, these benefits can be substantially diminished if the operational system is applied in a manner that produces biased results compared to the calibration. There should be differences in the random variations between operational and calibration simulations (ideally the operational results will exhibit less random error), but there shouldn't be a bias.

The primary purpose of historical data analysis is to generate unbiased estimates of the model input data, as well as the output data that will be used to validate the simulations. The aim is also to have the minimal amount of random noise given the available historical data networks. These data are then used to calibrate the hydrologic models to simulate streamflow and other variables throughout a river basin. The primary purpose of calibration is to obtain the parameter values for each model that will generate the most unbiased simulation possible. Calibration also aims at producing parameter values that properly represent the physics that are occurring and are consistent from one watershed to another. The purpose of model calibration is not to produce the best possible value of some "goodness of fit" statistic, but instead to determine physically realistic and consistent parameter values that will allow the models to be used to generate the best possible results in an operational application.

The primary purpose of operational forecasting is to produce an unbiased forecast of what will occur in the future with minimal random variation. In order to use the calibration results to accomplish this goal, several things must occur.

- The operational data estimates must be unbiased compared to those used for calibration.

- The models are defined such that the basic simulation (i.e. the simulation produced using the same input data types and model configuration used for calibration with no alternative data analyses, modeling schemes, or real time adjustments included) will be unbiased compared to that obtained during calibration.

- Real time analysis procedures, that in many cases involve data not available or examined during the historical processing step, are applied in a way that reduces the random error in the data estimates, without producing a bias.

- Adjustments are applied to the models that reduce the random variations and unavoidable trends that were in the calibration simulations in a manner that doesn't produce bias in the forecasts.

This chapter describes how to use an operational forecast system so that the real time results will be unbiased compared to calibration simulations. There is some discussion of ways to reduce random error, but the emphasis is on minimizing bias. As with the rest of this manual, the concepts might apply to any forecast system that relies on conceptual hydrologic models, but the discussion is focused on the application of the NWSRFS Operational Forecast System (OFS). It should be clearly stated that this chapter is not intended as a complete guide on how to produce operational river forecasts, but only to describe what must be done to insure that the benefits of calibration are preserved.

The chapter will be divided into two main parts. The first part will indicate what needs to be done to define the basic operational system so that it will generate results that are unbiased compared to those produced during calibration. The amount of random variation will differ from that experienced during calibration primarily due to differences in the density and distribution of the data networks, primarily precipitation. The second part will discuss various procedures and techniques that can be used to reduce the random errors in the data input and model results. The focus will be on applying these procedures and techniques in a manner that will minimize adding any bias.

Operational Definition using Calibration Results

Introduction

In NWSRFS various information needs to be specified in order to use the Operational Forecast System (OFS). This includes the definition of :

- all stations with their available data types and related parametric information,

- all of the areas for which mean values of precipitation, temperature, and evaporation are to be computed along with their parametric information, and

- all segments with the sequence of operations (models and procedures needed to generate simulations of streamflow and other variables of interest) and the parametric information for each operation.

Most of the parametric information needed when defining the operational system are obtained directly from the calibration results or are based on values derived during the calibration. The material presented in this part of the chapter describes guidelines for defining the operational system so that it should very closely mimic the results obtained during calibration. In this definition no changes are made to the time and space scale that the data analysis procedures and hydrologic models are applied or to the types of data used during calibration. Recommendations for using different data types and analysis methods or varying the time and space scales will be mentioned in the second part of the chapter. These may involve making changes to the basic definition of the operational system described in this part. Except for variations caused by differences between the density and distribution of the real time and historical networks, the operational system as defined by following the guidelines in this part of the chapter should produce, with no run time modifications applied, essentially the same simulation results as the calibration system.

Operational Station Definitions

Station definitions can be one of the major reasons for operational results to be biased as compared to calibration simulations. This is primarily due to differences in the real time and historical data networks. It is common for stations to be available in real time that were not included in the historical records and vice versa. Bias can occur due to an improper specification of parametric information for stations that are only available operationally, equipment at sites with only operational data being incompatible with the gages used for calibration, inconsistencies that occurred after the historical data period, and differences in the reporting characteristics of the networks. The best case scenario would be for the operational and historical networks to be comprised of exactly the same stations with no changes in location, equipment, or reporting characteristics, however, this is seldom the case. Thus, it is critical to make sure that all the real time data are compatible with the station data used for calibration.

When data for which monthly mean values must be provided operationally (mountainous area precipitation stations and all temperature stations) are checked for compatibility, the checks are always made based on the full period of record of the historical data, i.e. the period for which the data were analyzed and processed, not the period used to calibrate models at any specific location. This can present a dilemma when different historical periods of record are used for different portions of an RFC area. Generally the same historical data period is used for an entire river basin. Ideally all the river basins that utilize the mountainous area precipitation analysis procedure or use temperature data within the RFC area of responsibility would have the same historical data period. However, this is likely not the case due to such factors as differences in networks over time (e.g. the SNOTEL network record length might only impact a portion of the RFC area - see Chapter 5) and the length of time involved in calibrating an entire RFC area (i.e. last basin calibrated would have more historical data available than the first basin). Stations that are used only for computing mountainous area MAP and any MAT time series within a single river basin are not affected. The dilemma occurs for those stations that are near the divide between two or more basins that have different historical data periods. Mean monthly values for these stations can vary from one historical period to another. Hopefully the differences are not too great. This will likely be the case if the historical data periods are quite long. The best that probably can be done when operationally defining these stations is to use the average, or a weighted average of the mean monthly values for each historical period depending on which basin the station has the most influence.

Though there are similarities in the methods of checking for compatibility from one data type to another, there are also differences, thus each major data type will be discussed separately.

Precipitation Data

Precipitation is the single most important input to the snow and soil moisture accounting models. As shown in Chapter 6 any bias in precipitation will be magnified in the runoff computations. Thus, it is critical that the precipitation observations used operationally be as unbiased as possible when compared to that used in calibration. In order to avoid such bias, all station precipitation data used operationally must be compatible with the historical station data. The methods for doing this depend on whether a given station is part of a mountainous or non-mountainous area procedure for computing MAP. Stations that can be used in both types of procedures should be checked using each method.

Some RFCs use either non-mountainous or mountainous area procedures over their entire area, however, in some cases the procedure used to process precipitation data varies from one part of an RFC area to another. This is especially true when there is a clear demarcation between the relatively flat terrain and mountains. During calibration either one procedure or the other is used for any group of stations in a precipitation analysis (i.e. either monthly means are defined for all stations or they are not). However, during operations, stations in the transition zone from flat to mountainous terrain could be used for areas that use both types of procedures. For operational precipitation station definitions, any station that can be assigned weight, or used to estimate missing data for a station that can be assigned weight, for an MAP area that uses the mountainous area procedure should have mean monthly precipitation amounts (often referred to as characteristics) included in its definition. Typically this means that all stations in the mountains will have mean monthly values defined, as well as any stations in the adjacent flat lands that can be used to estimate missing data at a mountain station. The mean monthly amounts should be those that are appropriate for the historical period of record used for the mountainous areas. If there is not a clear demarcation between the flat terrain and the mountains, it is usually easier to include mean monthly values for all stations.

- Non-Mountainous Areas - As defined in Chapter 6, a non-mountainous area is an area where the long term average values of the variable being analyzed are essentially the same at all locations. The compatibility checks to be performed for stations in non-mountainous areas depend on whether the station was part of the historical analysis. For real time stations that were part of the historical analysis, the user needs to verify that there have been no station moves or equipment changes since the end of the historical analysis period. Equipment changes would involve substituting a different type of precipitation gage or adding or removing a wind shield. If this is so, then it is reasonable to assume that the real time data should be compatible with that used for calibration. If the station was moved or the equipment altered, then the consistency of the record should be checked by doing a double mass analysis against a group of other precipitation stations in the vicinity. If an inconsistency is found, the appropriate consistency correction should be applied in the operational station definition (i.e. a correction that will make the real time data consistent with the historical period - e.g. if the gage now catches more than during the historical period, the operational consistency correction would be less than 1.0). In the OFS real time precipitation corrections can be applied on an annual or seasonal basis.

For real time stations that were not part of the historical analysis, a check should be made that the long term average precipitation for those stations is essentially the same as the stations that were available historically. It might be assumed that since long term average precipitation is the same, or a general trend of slowly increasing or decreasing values exists, over the region, that any new station will have a catch that is consistent with the gages used in the historical analysis. This may not be true due to site exposure or the type of equipment used. Windy, open sites or locations with nearby obstructions might under or over catch precipitation. Especially in regions where snow is important, windy, open sites should be avoided unless the gage is properly shielded. In addition, various studies have shown that the catch from certain types of gages are not compatible with the catch from standard climatological stations. For example, it is recognized that heated tipping bucket gages catch less precipitation, especially snowfall, than a universal weighing gage. Different types of gages can also catch varying amounts of rain. A study by the USGS west of Chicago [*Straub and Parmar*, 1998] compared the catch from 5 NOAA climatological gages (8 inch nonrecording and universal weighing gages) and 10 USGS tipping bucket gages. Using only periods when rain occurred, the USGS gages caught only 86% of the amount recorded by the NOAA gages (the tipping bucket gages were adjusted during periods of intense rain as per manufacturer's specifications). When one gage of each type was installed at the same location for a short period, the USGS gage recorded 91% of the catch of the NOAA gage. The inclusion of a number of such gages in the operational network could result in long term MAP values being biased by 5-10%, depending on the weights assigned to each station, as compared to those used for calibration. This could result in a 10-25% bias in runoff computations.

Before using any stations operationally that were not part of the historical network, it should be verified that the catch from these stations is compatible with the historical data. The method used to do this is to compute the ratio of the catch at the new station to one or more nearby stations that were part of the historical network which haven't had any relocations or equipment changes. This should be done over some period of time in order to remove the effect of spatial variations within individual storms. Typically the ratios are computed using monthly totals from the gages. Generally in a non-mountainous area one or two years of data should be sufficient to obtain reasonably stable values of the ratios. The ratios should be very close to 1.0. If not, either the new station shouldn't be used as part of the operational network or it should be corrected so that its precipitation measurements are compatible to the historical data. Hopefully a couple of years of past data can be obtained from the new station in order to do the comparison. If not, sufficient data should ideally be collected so that the data can be checked before defining the station as part of the operational network. In many regions there is a real deficiency of real time precipitation reports. In these cases, it may be judged that any new gages should immediately be used to compute areal values even if their use may create a bias. This may be a reasonable decision, but at least the data should be analyzed after a couple of years to determine if an adjustment is needed.

In the western parts of the United States the RFCs have always recognized that there are tremendous variations in amount of precipitation from one location to another in the mountains and have thus always taken this into account when generating model input. In the east, however, there has been a tendency in the past to ignore the effect of the mountains. Station weights were computed for both calibration and operations using weighting schemes such as the Thiessen method that only considers the station location. In many cases the historical and operational networks were somewhat different, though for many years most of the gages were in the mountain valleys and thus the overall effect on MAP computations wasn't too great. In addition, empirical rainfall-runoff models, such as API type models, used in the past were not as sensitive to precipitation bias as conceptual soil moisture accounting models such as the Sacramento model. With the switch to conceptual moisture accounting models and the advent of the IFLOWS network that covers much of Appalachia with gages on the mountain ridges, the continued use of the non-mountainous area procedure for mountain areas will likely cause a considerable bias between the operational and historical MAP values and result in over forecasting most flood events. The mountainous area procedure should be used in all such regions, both for historical and operational precipitation processing.

• <u>Mountainous Areas</u> - In a mountainous area mean monthly precipitation amounts must be defined for all stations. <u>The monthly means used in the operational definition should be those that correspond to the period of record used for the historical data analysis</u>. <u>For real time stations that were part of the historical analysis, the mean monthly values determined using the PXPP program during the historical analysis should be used when the station is defined in the operational system</u>. As with non-mountainous areas, these stations should be checked for consistency if any moves or equipment changes have occurred in the years since the historical analysis period ended. If there are any inconsistencies, corrections should be applied in the operational system so that the real time reports are adjusted to be consistent with the historical analysis period.

<u>For operational stations that were not part of the historical network, mean monthly values must be determined prior to the stations being defined as part of the operational network</u>.

The procedure for estimating mean monthly values for each of these new stations for the historical period of record is as follows:

- compute the ratio of precipitation at the new station for each month to that at one or more nearby stations that were used in the historical analysis and have well defined monthly means (i.e. the monthly means are based on a long period of observed data), and then

- multiply these monthly ratios by the mean monthly amounts for each of the nearby stations used in the historical analysis to obtain estimates of the mean monthly amount for the new station -- then average or weight the estimates if more than one nearby station was used.

Typically monthly totals are used to compute the ratios rather than daily or storm totals. The length of the period needed to get a stable estimate of the ratio for each month varies somewhat with the spatial variability of the precipitation in the region. In regions with strong orographic patterns during most events, such as the Pacific Coast, 3 years of data should be sufficient to obtain a good estimate of the ratios. In regions with considerable convective activity at times during the year, such as the intermountain west, experience with the PXPP program has shown that around 5 years of data are needed before a reasonably stable estimate of the mean monthly values are obtained. The data needed to compute the monthly means might already be archived or it may be that such data will need to be collected before the station can be defined and used in the operational system. If the user wanted to start using the new station immediately, estimates of the mean monthly precipitation could be obtained from the isohyetal analysis after it is adjusted to the historical period of record (see Section 6-3). This should only be done if the user has considerable confidence in the isohyetal analysis. Even then local exposure and equipment peculiarities could cause the isohyetal estimate to deviate from the actual value enough to cause a significant bias in the resulting MAP values. Operationally it is best to only use stations that were not part of the historical analysis after sufficient data are available to get a good estimate of the mean monthly precipitation at these sites.

For all types of areas, differences in how historical and real time precipitation data are reported can also produce a bias between the resulting MAP time series. In the past many non automated stations in the real time network used a 0.5 inch reporting criterion, i.e. the observer only was to begin reports after more than that amount of precipitation occurred during a storm. Especially during days with spotty convective activity, there was a definite tendency to significantly overestimate the missing amounts at those stations that didn't report using the few stations that did receive more than 0.5 inches of rain. Undocumented studies at the Southeast RFC and HRL showed that the average bias during summer months in regions with a lot of this type of convective activity and many criterion reporting stations could reach nearly 100%. It could not even be assumed that when a station didn't report that it must have had less than 0.5 inches of precipitation as surveys at two RFCs indicated that such stations only reported about half the time when they should.

The 0.5 inch reporting criterion is no longer used, however, there still are differences, some perhaps very subtle, in how historical and real time data are reported that could produce biased operational precipitation estimates. A Forecast Systems Laboratory (FSL) study [*Tollerud*, 2001] and conversations with personnel from some RFCs indicate that there can be substantial differences in the number of reports from observers on days with light or scattered amounts as opposed to days when most stations receive some precipitation. It appears that many manual observing sites only report on days when precipitation occurs. The FSL study showed that there were dramatically different frequency distributions of the percent of rain days between daily reporting stations and automated sites. There were even some differences between automated real time sites and stations in the hourly climatological network. The study also showed that a sizable number of the automated stations have 1-4 missing hourly observations per day. Such real time reporting characteristics, especially having many stations not reporting on days with scattered convective activity, could easily result in biased estimates of station precipitation amounts. This is clearly something that needs to be carefully monitored and evaluated as a significant bias could be produced in many cases when there are substantial differences in how real time and historical precipitation data are reported.

Temperature Data

Biased temperature estimates will have a significant effect on the timing of snowmelt runoff as shown in Chapter 6. They will also have a negative effect on the determination of the form of precipitation. Since for all temperature stations the mean monthly maximum (max) and minimum (min) values must be defined in the operational system, the key, as far as the station definitions, is to make sure that the mean monthly values provided are compatible with the period used to perform the historical data analysis. It doesn't matter whether a given station is to be used for a mountainous or non-mountainous area or both.

For operational stations that were included in the historical analysis, the mean monthly max and min temperatures provided for the operational definition should be exactly the same as those used in the final MAT run for the historical period of record. If any of these stations have been relocated since the end of the historical data period, then the consistency of the record should be checked and if necessary, corrections applied in the operational definition to adjust the current data so that it is compatible with the data for the historical period.

For operational stations that were not part of the historical network, mean monthly max and min temperatures for the historical period need to be computed. The procedure for estimating these values for each new station is as follows:

- compute the difference in max and min temperature for each month between the new station and one or more nearby stations that were used in the historical analysis and have well defined monthly means (i.e. the monthly means are based on a long period of observed data), and then

- add these differences to the mean monthly max and min temperatures for each of the nearby stations used in the historical analysis to obtain estimates of the mean monthly max and min temperatures for the new station -- then average or weight the estimates if more than one nearby station was used.

The differences should be computed using monthly average max and min temperatures to avoid the effects of different observation times and frontal passages. Only months with complete records should be used. Monthly differences, rather than long term, should be used because the relationship between stations can vary seasonally, even in non-mountainous areas. Typically a couple of years of data should be sufficient to determine stable temperature differences since temperature can be observed every day as opposed to precipitation which occurs only periodically and because temperature is not as spatially variable as precipitation.

Evaporation Data

Evaporation data only need to be defined in the operational system for stations where Potential Evaporation (PE) is computed on a daily basis from meteorological factors. If the models only use climatological estimates of mean evaporation rates, these values are supplied with the other model parameters in the segment definition. The primary cause for daily operational PE estimates to be biased compared to the values used in the historical analysis are differences in how solar radiation data are obtained. In addition, an incorrect specification of the anemometer height in the operational definition will also produce a bias. The user needs to make sure that the correct anemometer height is provided as part of the operational station definition and that this value is updated whenever the height is changed.

The only currently available historical daily PE estimates from NHDS are based on solar radiation being derived from manual observations of sky cover. Historical daily PE estimates can be obtained for a selected group of synoptic stations scattered across the country up until the time that each station's ASOS system was commissioned. Once ASOS is commissioned at a station, manual sky cover observations are no longer available. Some automated sky cover values are included in the variables observed by ASOS, but these are not compatible with the method used to estimate solar radiation from manually observed sky cover. In order to estimate solar radiation from manual sky cover observations a parameter, referred to as the B3 parameter, must be supplied. Also a correction factor is needed that adjusts the computed PE values so that they give the same annual lake evaporation as shown in NOAA Technical Report 33 for the location of the station (see section on "Determination of PE" in Section 6-5). These values are automatically provided when historical estimates of PE are produced using the NHDS. If manual sky cover observations were still available at a synoptic station, both the B3 parameter and the appropriate correction factor should be supplied in the PE section of the OFS station definition.

There are other ways of obtaining daily solar radiation data to use for operational daily PE computations. As mentioned in Section 6-5, percent sunshine observations have been shown to produce estimates of solar radiation that will generate unbiased estimates of PE as compared to the Technical Report 33 annual lake evaporation. Thus, operational estimates of PE using percent sunshine to estimate solar radiation should be unbiased as compared to historical estimates of PE available from NHDS. Solar radiation can also be measured directly. Such data are not readily available at many locations. There is also a method of obtaining daily solar radiation from satellite data. Whatever data are used operationally to obtain solar radiation estimates for use in computing daily PE, the user needs to make sure that over the long term the resulting annual PE values are essentially the same as those shown in Technical Report 33. If not, the PE values being used operationally are likely biased compared to those that were used for calibration. As discussed in Chapter 6, biased PE values will result in a bias in runoff computations. Such a bias will especially have a significant effect on the soil moisture deficits that are produced after a dry period and thus, can have a major effect on the runoff produced by a subsequent storm event.

Operational Area Definitions

Generally bias in the operational estimates of areal inputs for the models is the result of problems with station data or incorrect information supplied when defining the stations. However, bias can also be produced if the areas are not defined properly. As with station definitions, each data type will be discussed separately.

Mean Areal Precipitation (MAP)

For non mountainous areas the operational MAP time series should be generally unbiased as compared to the historical values as long as the stations involved are checked for consistency and compatibility and the reporting characteristics of the network don't result in biased station estimates, especially on days with spotty convective activity. A slight bias is difficult to completely avoid when there are differences in the composition of the two networks. However, if the station data are properly selected and corrections applied when needed, the resulting bias in the MAP values should be no more than a couple percent as long as the reporting characteristics of the network don't cause a more serious problem.

For mountainous areas, the operational MAP values shouldn't be biased if the appropriate mean monthly precipitation is determined for the stations that were not part of the historical analysis, the stations are checked for consistency when moves or equipment changes occur, network reporting characteristics don't result in biased station estimates on days when precipitation is not occurring over most of the area, and the areas are properly defined. For each MAP area that uses the mountainous area procedure, the exact same average mean areal precipitation that was used for computing historical station weights with Eq. 6-3-4 should be used to compute operational station weights. This can be a seasonal or annual average depending on what was used during the historical analysis. Just as for the historical analysis, Eq. 6-3-4 is used to compute the operational station weights. If the operational network differs from the historical network, the relative weight assigned to each station may be different, but this will not cause a bias. The guidelines for selecting relative weights mentioned in Section 6-3 should also be used when determining relative weights for the operational system.

The amount of random error in the areal precipitation estimates will vary based on differences in the density and distribution of stations in the historical and operational networks. However, if the stations and areas are properly defined and the network reporting characteristics don't create a problem, this shouldn't result in a bias between operational and historical MAP values. As mentioned earlier, if either estimate is only based on a single station, the noise will typically be so great that proper application of the models is not possible. Also, in mountainous areas if there are great discrepancies in the distribution of the gages, especially in terms of elevation, from one network to the other, there may not be a long term bias, but the likely statistical differences in the variability of the estimates will cause problems.

Comparisons should be periodically made between the operational MAP values and what would be obtained using the historical network due to the importance of precipitation estimates and because of all the factors that could cause deviations between operational and historical MAP amounts. This requires that the operational MAP values be archived. Such a comparison can be done anytime that there is a sufficient overlap between the archived operational MAP estimates and the available climatological data needed to compute historical MAP values. An ideal time to perform an MAP comparison is when extending the historical data record (record extension discussed at the end of Chapter 6). If archived operational MAP data are available for the extension period, it would be very easy to compare the values. Besides bias comparisons, both annual and seasonal, other statistics could be computed (e.g. based on precipitation amount, frequency, and variability) to determine what differences exist between the operational and historical estimates. Each time series could also be used to produce simulations of streamflow and other variables to assess how any differences affect model performance. Unfortunately such comparisons have seldom been done in the past.

Mean Areal Temperature (MAT)

For non mountainous areas grid point weights are typically used for both historical and operational MAT computations. For any MAT areas where the station weights differ from the operational to the historical network, areal mean monthly temperatures should be computed and compared. This is done by multiplying the weight for each station by its mean monthly max and min temperature to get the weighted mean monthly max and min temperature for the area. This should be done for all months that the MAT values impact model computations, typically months that can have snow. The weighted mean monthly temperatures should be essentially the same for both networks. If not, either the weights could be modified by using predetermined weights operationally or stations whose mean values deviate significantly from the other stations could be removed from the computations. It is essential that the weighted areal mean temperatures are basically the same for both networks to avoid biased temperature data used in the model computations.

For mountainous areas, the typical procedure is to define a synthetic or "dummy" station that represents the average temperature over the area or the portion of the area that is generally affected by snow. The synthetic station is then assigned a weight of 1.0. When defining mountainous MAT areas in the operational system, it is critical to use the exact same mean monthly temperatures for the synthetic station as were used in the historical analysis. The location of the synthetic station can vary from the historical to the operational system, but not the mean max and min temperatures assigned to the synthetic station. The location of the synthetic station in the operational system should be based on obtaining the best possible estimate of the areal value based on the available real time temperature data. That is, the same logic is used for locating the synthetic station operationally that was used for the historical analysis (see Chapter 6-4).

The historical MAT time series are generated by using only max and min temperature data. As shown on Figures 6-4-1 and 6-4-2 in Section 6-4 the use of just max/min data can produce erroneous MAT estimates not only on days when the diurnal variation differs from the assumed pattern, but also on other days based on when the max and min values are observed. Even though the problem only occurs on certain days, it can cause the historical MAT data to have an overall bias as compared to what would be computed using both instantaneous and max/min values. The NWSRFS operational system uses both types of temperature data. For stations with an a.m. observation time, this causes the historical estimates to be somewhat greater than the operational values on the affected days. For stations with a p.m. observation time, the result is just the reverse. The overall difference for any area will depend on whether a.m. or p.m. observation times prevail in the historical network. In addition, as mentioned in Section 6-4 the diurnal variation used to obtain 6 hour means from max and min values when computing historical MAT is based on sites in northern Vermont and the central Sierras of California. This assumed typical daily temperature pattern might not be representative of all regions, especially Alaska where the daylight period can be quite a bit longer during melt periods than in the lower 48. It would be very difficult to operationally correct for the bias caused by using only max/min data historically. The real solution to this problem is to modify the historical MAT preprocessor so that it uses the same data, i.e. both instantaneous and max/min, as the operational MAT preprocessor.

Just as with precipitation, comparisons should periodically be made between the operational MAT estimates and those that would be generated from the climatological network to insure that there is minimal bias. Again the ideal time to make such comparisons is when the historical data record is being extended.

Mean Areal Potential Evaporation (MAPE)

The operational MAPE definition should use exactly the same synoptic stations and weights as used for the historical estimates. The average monthly PE values required for the operational definition should be those that were computed by the calibration MAPE program for the historical data period (table of monthly averages displayed at the end of the calibration MAPE program output). Though the calibration MAPE program allows for the use of daily pan data to be used for MAPE computations, this is seldom done. The NWSRFS OFS doesn't include the option of using daily pan observations. If pan data were used historically, any bias between the operational and historical estimates should be minimal if all the computed station PE values are adjusted to conform to the lake evaporation given in NOAA Technical Report 33 (see Section 6-5).

While it would be good to compare archived operational MAPE estimates to values computed from climatological data, this is currently not an option since the data used historically are no longer available with the advent of ASOS. The best that can be done is to verify that the operational estimates of PE at each station are compatible to the annual lake evaporation from report 33.

Forecast Data

Estimates of precipitation, temperature, and evaporation out into the future are clearly important for river forecasting. Any bias in future data will not have a cumulative effect, but it will decrease forecast accuracy. Bias in observed data estimates affect the model state variables (in NWS terminology carryover) that are saved in order to initiate subsequent forecast runs, thus not only affecting the current period, but also later events.

- Future Precipitation - Future estimates of MAP are input directly into OFS and are not computed based on any defined information. In the past Quantitative Precipitation Forecasts (QPF) that were used to determine areal estimates of future precipitation for the next few days were generally biased on the high side, especially during convective storm periods. Much work has been done over the past decade to reduce this bias. QPF is now routinely used at most RFCs for short term forecasting. It is still important to verify that the future MAP values being used are unbiased compared to the data used for calibration. In order to properly do this, future MAP should be compared to MAP values generated from climatological data, i.e. the same data used for calibration. Comparisons between future MAP and operational MAP values don't prove that the QPF estimates are unbiased since, as discussed earlier, the operational MAP estimates can be biased.

- Future Temperature - Future estimates of MAT are generated in OFS using the station and area definitions that are used for the observed data period. The major difference is that for the future period the computations are based only on forecast max and min temperatures, typically for only a subset of the observational network. Even though this appears to be the same procedure that is used to generate historical MAT estimates, there are some differences which could result in a bias. First, the equations used to compute 6 hour means from max and min values, i.e. represent the typical diurnal temperature pattern, are somewhat different than those used in the historical MAT program. The future MAT equations are also based on Z time rather than local time, thus they produce a slightly different diurnal pattern for each time zone. Second, at least some of the forecast temperatures used by the RFCs are the mid-day and early morning predictions. Thus, the "max" could be lower than the "min" if the temperature was forecast to drop throughout the day. Also, the problem described in Section 6-4 of the wrong max or min being used on days when temperatures are generally increasing or decreasing should not occur with forecast values. Third, the meteorological forecasts may not result in the same long averages used in the historical analysis since they are produced using a different procedure. For all these reasons it is important to compare the future and historical MAT values periodically. It would also be more consistent if all the MAT computations in NWSRFS used the same method. The most accurate estimates should come from a procedure involving the use of both max/min and instantaneous temperature values.

• Future Evaporation - Future MAPE values are calculated in OFS from the average monthly values defined for each area. The last computed value for the observed data period is blended over a specified number of days to the average curve. The average curve is determined by linear interpolation between the average monthly values. Thus, if the average monthly values are properly defined, the future MAPE values shouldn't create a simulation bias.

• Data for Extended Predictions - The historical time series of precipitation, temperature, and evaporation are currently used as the input for extended predictions. Near future estimates, as just described in the preceding paragraphs, are typically used for the first few days and then blended into the historical data in an attempt to minimize the effect of events in the historical record that are very unlikely to occur based on the current weather forecast. Since the same input is being used for extended predictions as was used for calibration, there shouldn't be a bias introduced other than that contained in the model states for the start of the run and in the forecast data for the first few days. However, given the meteorological outlook, it could be that the data traces for each of the historical years are not equally likely to occur this year. Methods to include long range weather outlooks in ESP runs have been subjective in the past.

Operational Segment Definitions

All parametric information contained in the active part of the basic segment definitions (i.e. the operations that perform the actual simulation computations as opposed to operations that convert or display data) should be exactly the same in both the operational and calibration systems. This includes the areas that are being modeled and the time interval of all data and model computations. Changes may need to be made to some of this parametric information if the space and time scales used operationally are modified in an attempt to improve forecasts by using new data types and processing methods that were not available historically. Such changes will be discussed in the second part of this chapter. This section will concentrate on the proper definition of the segments to reproduce the results obtained during calibration utilizing similar data with no real time modifications to input values or model states.

Operational segment definitions need to reflect the different data types that are typically used for real time computations, such as river stage observations that need to be converted to discharge with the STAGE-Q operation as opposed to historical streamflow data that has been already converted by the agency responsible for collecting the data. Operational segments will contain direct input of reservoir and diversion data, that were used historically to compute natural flow conditions, when operational forecasts need to reflect what is actually occurring within a river basin. In other cases, especially in the west where water supply is the major concern, the operational segments will continue to generate natural flow as during calibration. The operational segments will also include different operations to produce and display the output needed for forecasting instead of the WY-PLOT and PLOT-TS displays used to verify simulation results during calibration. However, the bottom line is that the basic segment definitions should conform to the same areas and time intervals that were used for calibration and all the parameters for the models that are performing the basic hydrologic computations should be exactly the same as those determined during the calibration.

When first defining a segment, initial values of the state variables need to be provided for many of the models. In many cases, such as for channel response, routing, and reservoir models, these values can easily be estimated from current river and pool levels or default values can be used for operations where the values will only affect the computations for a short period. For the snow model, the initial values of the model states can be defaulted to zero when no snow cover exists. If a significant amount of snow is present when the model is initiated, then it is critical to input a realistic estimate of the current mean areal water equivalent. If a greater amount of snow existed earlier in the season, then the maximum water equivalent since snow began to accumulate also needs to be provided. Both of these values can be obtained from available snow measurements as described under the .WECHNG MOD in Section 8-1. The heat deficit, antecedent temperature index, and liquid water content are estimated based on the temperature pattern in the recent past. For the Sacramento model, estimates of the lower zone free water contents should be able to be derived from the hydrograph by determining the current supplemental and primary flow contributions. These runoff amounts are then divided by the appropriate withdrawal rates to get the current contents. Upper zone free water contents are typically set to zero since the effect of this variable will only last for a few days. Tension water contents can be reasonably estimated by comparing the general precipitation pattern over the last few months with a similar period from the calibration simulation. The initial value of ADIMC is set to the sum of the upper and lower zone tension water contents.

Introduction

The major objective during forecasting is to utilize all available information so that simulations closely mimic observations and forecasts have maximum lead time with minimal uncertainty. Random fluctuations that were tolerable during calibration, in that they didn't drastically interfere with the determination of the proper values of the model parameters, now need to be reduced to a minimum to provide the best possible operational forecasts. There are several methods for improving real time forecasts over what would be obtained by just using the simulated results generated from the basic OFS station, area, and segment definitions (i.e. the definitions just described in this chapter utilizing the same types of station data and modeling schemes used for the historical analysis and calibration).

- Use data analysis procedures that incorporate the dynamics of what is occurring, both by new measuring techniques and physical modeling, to improve the input to the hydrologic models over that provided by the historical techniques which often rely on climatological patterns. Such procedures are capable of providing better spatial and temporal resolution as well as improved areal estimates.

- Apply the models in a distributed manner at a finer spatial and temporal resolution than was possible during calibration by utilizing the output from the new data analysis procedures.

- Adjust the model states and computations, either automatically or manually, based on real time observations or the output from external modeling systems.

Besides these methods for improving river forecasts which will be discussed in more detail in this chapter, forecasts can also be improved for many users by quantifying the uncertainty in the predicted values. This has been done in the past for extended predictions. In the future probabilistic forecasts will be possible for all lead times. In order to make accurate probability statements for short term forecasts, the uncertainty in the models themselves and the model states must be taken into account, in addition to the uncertainty in future precipitation, temperature, and evaporation. The ensembles used to generate probabilistic predictions will need to incorporate the trends and uncertainty in meteorological forecasts from short term QPF to long range outlooks. Whatever is done in terms of producing the ensembles, it is important that the statistical properties of the historical data and the historical model simulations based on the calibrations be preserved, including subtle features like the amount of snow verus rain and the frequency of surface runoff.

Before discussing each of the listed methods for improving forecasts a couple of general items should be noted . First, in most cases there is not a one-to-one relationship between new data estimates and the historical values used for calibration or between observations or values computed by external modeling systems and values produced by conceptual models. Thus in order to avoid any bias being introduced, the relationship between the estimates must be determined and corrections applied when necessary. Second, most new data analysis or hydrologic modeling systems evolve over some period of time. Even though a new method is tested thoroughly during the development phase, further modifications to the algorithms and data processing techniques are frequently needed when the procedure is put into operational use. Thus, the relationship between values produced by the new method and the historical calibration may change for some period of time before becoming stable.

The intention of the following discussion of each of the methods for improving forecasts is to indicate how such methods can be applied in a manner that preserves the benefits of calibration. The emphasis is on how to use such procedures without creating a bias compared to the calibration simulations. It is not the intention of this manual to describe these methods in any detail or to offer guidelines for their use other than how they can be applied in an unbiased manner.

Improved Data Analysis Procedures

The only procedure that is currently available operationally for improving model input utilizes radar, raingage, satellite, and other data to produce hourly estimates of precipitation on a 4x4 km grid. This procedure is currently referred to as the Multisensor Precipitation Estimator (MPE) [*Seo et al.*, 2000]. Since the MPE procedure generates estimates with a finer spatial and temporal resolution than generally can be obtained from just raingage data, it opens up the possibility of not only providing improved precipitation values for use by lumped applications of hydrologic models, but of allowing for the real time use of distributed models for river forecasting.

Other possible real time data analysis procedures that might be developed in the future to improve operational input include:

- mountainous area precipitation analyses that utilize some combination of orographic modeling, gage reports, radar information, and other data to account for the storm dynamics,

- mountainous area temperature analyses that utilize a combination of meteorological modeling, temperature observations, upper air soundings, and other data to account for the dynamics of how temperature varies with elevation, and

- direct estimates of ET-Demand that account for vegetation dynamics on evaporation rates.

Experience with radar-based estimates of precipitation have indicated that in many cases the estimates are biased and not consistent over time [*Jonhson et al.*, 1999]. This is partly due to changes that have been made to the algorithms and data processing techniques. There have especially been difficulties with obtaining reasonable precipitation estimates from radar-based methods in mountainous areas and when snow is occurring. Thus, before using these data as either lumped or distributed input to the hydrologic models for real time applications, it is essential that the estimates are carefully evaluated in a systematic manner. This evaluation should determine whether radar-based precipitation estimates can be used to produce unbiased simulation results and if so, how they can be applied in order to improve operational forecasts. The application could be to provide lumped 6 hour values or lumped hourly estimates of precipitation. Beyond that radar-based precipitation estimates could allow the models to be applied in a distributed manner.

One possible procedure of evaluating whether improvements are possible by using radar-based precipitation estimates is described in this subsection. In the discussion of the procedure 3 types of mean areal precipitation time series are utilized. These are referred to as:

- MAPX - areal mean precipitation produced from the radar-based estimates by averaging the grid points that fall within the area being modeled.

- MAPH - areal values produced from climatological data, i.e. values generated using the same precipitation gage data and methods as used for the historical analysis.

- MAPO - areal values produced using real time precipitation reports with the OFS MAP preprocessor function based on the station and area definitions discussed previously in this chapter.

The steps in the procedure for a given watershed are as follows.

1. Calibrate the watershed following the methods described in this manual. This will insure that a sufficiently long record is used so that a stable set of parameter values can be obtained considering the noise in the input data.

2. Evaluate the archived radar-based estimates of precipitation for consistency and potential bias. There probably needs to be in the order of 5 years of reasonably stable radar based estimates to obtain a good evaluation. One way to do this is to compare the monthly MAPX values to overlapping MAPH estimates. The pattern of the ratio of MAPX to MAPH values should be consistent over time. There will be scatter since each method will compute different values for each storm. Trends in the ratio with time generally would indicate changes in how the radar based values were processed. Ideally the average ratio should be reasonably close to 1.0. For a non mountainous area this would indicate that the radar based procedure is producing values over the long term at each point that are the same as would be measured by a raingage. However, it is more critical that the ratio is reasonably consistent over time than being equal to 1.0, though typically if there is a significant bias, there may also be a lot of variability associated with the radar-based estimates.

   This would also be a good time to compare archived MAPO values with overlapping MAPH estimates. If the station and area definitions for OFS are compatible with those used for the historical analysis, the monthly and annual ratios of these time series should be very close to 1.0. If not, it indicates that either the OFS station or area information is not correct or something else, such as different reporting characteristics, causes these time series to differ.

3. If the evaluation in step 2 looks reasonable, then generate 6 hour MAPX time series (assuming that was the time interval used for calibration) for the watershed and use these as input to the hydrologic models. Compare the results to those obtained using the MAPH estimates as model input. If the long term ratio of MAPX to MAPH is 1.0, the overall simulation bias should be similar from both time series. If the ratio is not 1.0, then the MAPX values need to be adjusted, typically by a multiplying factor (PXADJ in either the SNOW-17 or SAC-SMA operation). It is preferable at this point to use PXADJ to correct for any bias as opposed to modifying model parameter values because the simulation bias is caused by differences in the MAPX and MAPH amounts. If the MAPX estimates are not consistent over time, this will result in the model simulations using those data to have more of a time trend than those produced by the MAPH time series.

Once the MAPX values are adjusted so that the overall bias is the same for both precipitation time series, an evaluation can be made of the results. Ideally the MAPX values will contain less random error and thus provide an improved simulation capability. If so, it indicates that at least the radar based precipitation can be used to provide a lumped 6 hour input for operational forecasting that should improve results. If the comparison of the simulation results indicates that there is a pattern, perhaps seasonal, in terms of which MAP produces the best results, then rules can be devised for when to use the radar based values operationally and when to use MAPO estimates (assumes that the MAPO values are compatible with the MAPH estimates). Such a situation will likely exist in regions where snow predominates during the winter months. In this case the MAPX values may provided improved input during warm months, but the MAPO estimates would produce better results during the cold season (the MERGE-TS operation is used in OFS to switch between alternative time series). The MAPX and MAPH time series for the test period could be merged based on the proposed rules to determine how this should affect the operational simulation results.

4. If the use of MAPX time series indicates an improvement in step 3, then generate 1 hour MAPX time series, adjust model parameters for the change in the time scale if necessary, and evaluate the results. Models that are non linear, such as the Sacramento model, are scale dependent, i.e. the results can vary depending on the spatial and temporal scale that the model is applied [*Finnerty et al.*, 1997]. Thus, in order to get similar results at different scales, some of the parameter values will likely need to be altered.

Hourly data should have the most chance of improving simulation results for fairly fast responding watersheds that have significant amounts of surface runoff and variations in rainfall intensity during storm events. For these watersheds instantaneous streamflow data, preferably hourly, is needed in order to make the parameter adjustments and to properly evaluate the results. The PXADJ value determined in step 3 should continue to be used to correct for the overall bias in the MAPX time series. The most likely Sacramento model parameter modifications are to the percolation rate and UZFWM. The percolation curve would typically need to be adjusted slightly upwards. This should be done by changing the LZFSM and LZFPM parameters by the same percentage. This will change the PBASE value, but retain the shape of the curve and not alter baseflow recession rates. UZFWM should need to be increased somewhat. The unit hydrograph would also need to be converted to a one hour runoff duration. It is also likely that there would be a need to modify the shape of the unit hydrograph somewhat based on the finer temporal resolution of the computations and the observed flow data.

If doing the model computations on a hourly basis improves the simulation results, it should primarily be noticeable in the simulation of storm peaks. This would especially be the case for major surface runoff events when high intensity rainfall occurs for just a few hours within the 6 hour intervals. Watersheds that don't generate much or any surface runoff or have fairly uniform rainfall rates during major storms, shouldn't show any real improvement in simulation results by using hourly precipitation input. During seasons when snowmelt runoff predominates, it is unlikely that using hourly precipitation input will improve the results. The melt rates, especially when using a temperature index model, will not vary significantly from hour to hour and the snow cover will have a damping effect during rain-on-snow periods.

By going through such an evaluation for several watersheds scattered throughout an RFC area, it could be determine whether the radar-based estimates would provide unbiased values of precipitation for use with the calibrated conceptual models. A determination could be made of whether radar-based estimates could be used all the time or only for certain seasons or types of storms. It could also be determined whether adjustments were needed to the model parameters in order to avoid a simulation bias, especially when a change is made to the temporal scale of the model computations. Radar-based estimates of precipitation clearly have the potential of improving this critical model input, at least in non mountainous areas. However, before they are used operationally it should be verified that a simulation bias is not be introduced.

Distributed Modeling

The Hydrology Laboratory of NWS has had a major research effort for a number of years involving the use of distributed models for river forecasting [*Smith et al.*, 1999]. This effort is aimed at evaluating the data needed for such an application, examining various options for how models can be applied in a distributed manner, investigating the appropriate models to use, and ultimately to come up with a set of guidelines for how to use distributed models and under what circumstances they are needed and should produce improved forecast products.

The use of hydrologic models in a distributed mode offers the potential for improvements in simulating the response from basins with spatially varying precipitation patterns and allows for creating forecast products at a finer spatial resolution. Forecasts could not only be generated at the watershed outlet, but possibly also at interior points. This would allow for significant improvements in specifying the locations of possible flash flooding. The greatest potential for benefits from distributed modeling is in basins where runoff typically only occurs over a portion of the drainage area and in areas where the location of intense rainfall and thus fast response runoff varies from event to event. In such watersheds the magnitude and timing of the hydrograph response is highly dependent on where the runoff is being produced. Distributed modeling should allow for the successful simulation of streamflow in regions where lumped applications provide unsatisfactory or marginal results (see Figure 1-1). Even in regions where lumped applications generally provide reasonable results, distributed models could improve the forecasts for certain events. The most improvement should be noticed for events with considerable surface runoff concentrated over only a portion of the drainage. Elongated watersheds are more likely to have a different hydrograph response in such cases than a more oval basin. The more dampening of the response either due to infiltration and percolation, snow cover, or the channel system, the less likely that a distributed application of the models will result in improved simulation results.

In order to apply models in a distributed mode it is essential that quality precipitation estimates are available at the appropriate spatial and temporal scale. This is why the validity of gridded precipitation estimates, such as those from radar-based procedures, must first be verified before attempting to use the models in a distributed manner. In addition to gridded estimates of precipitation, some of the rainfall-runoff model parameters will have to be modified when going to a finer spatial resolution. This is because of the scale dependency of many such models, including the Sacramento model [*Finnerty et al.*, 1997]. These factors imply that some period of stable gridded precipitation estimates need to be available for testing the distributed application of the model and to determine what parameter changes are needed to insure that the results are unbiased compared to the lumped calibration. This could be done by applying the model in a distributed mode for a period with stable precipitation estimates and comparing the simulation to the lumped calibration results for the same period (calibration simulation would most likely use the areal average of the gridded precipitation, but could use MAP computed from historical gage data). Parameters should be adjusted so that the overall bias of both simulations are the same. Also such a comparison would allow for an evaluation of the potential benefits of distributed modeling.

For watersheds in regions where the lumped application of conceptual models generally yields unsatisfactory results (see Figure 1-1), the comparison and parameter adjustment procedure just described is not really relevant. In such regions it is impossible to obtain appropriate model parameter values by applying the models in a lumped mode and the climatological records do not contain a sufficient gage density to attempt a distributed calibration. In such regions reasonably reliable calibrations and operational application are only possible after a sufficiently long record of stable radar-based precipitation values have been archived. These data would then be used in an attempt to calibrate the models in a distributed mode.

Distributed modeling could also be attempted for snow accumulation and ablation. Most likely this would be done by using an energy budget approach for computing the snow cover energy exchange rather than by trying to figure out how to realistically vary melt factors from one subarea to another. There are potential difficulties in determining how precipitation and the energy balance input vary in mountainous areas as a function of elevation, aspect, slope, and vegetation cover. Even though a energy budget based distributed snow model will hopefully remove the trend of under simulating major melt events, a comparison of distributed model simulation results with a lumped application of a temperature index model should be able to determine if the distributed results are reasonably unbiased and provide an overall improvement compared to the historical calibration.

It also should be noted that changes to the spatial and temporal scales that the models are applied operationally has an impact on ensemble streamflow prediction (ESP) techniques used to generate probabilistic forecasts. Short term ESP applications will most likely use ensembles that are generated based on uncertainties in QPF and other meteorological forecasts. These ensembles should be able to be generated for the same spatial and temporal scale as the models are being applied operationally. However, for extended ESP applications the ensembles have been the historical precipitation, temperature, and evaporation time series that were produced during the historical data analysis step of the calibration process. These time series are at the spatial and temporal scale that was used for model calibration. Thus, in order to make extended ESP runs, the models must, at least currently, be defined operationally at these same scales. It would be quite difficult for an RFC to maintain multiple sets of compatible operational segment definitions at different spatial and temporal scales for short term forecasting and extended predictions. Thus, until some solution to this dilemma is developed, basins for which extended ESP applications are important will need to be defined operationally at the same spatial and temporal scale as used during calibration.

Adjustment Procedures

One of the most common methods for reducing the variability of the operational simulations is to adjust the input data, model computations, or model state variables based on a variety of observations or the output from an external modeling system. Adjustments can be made manually by the forecaster, generated by an external analysis of relevant data, or through the use of an automated procedure. The aim in all cases is to reduce variability and remove trends so that the models can be used to generate an unbiased forecast with minimal uncertainty. It is important when applying such adjustments that a bias is not introduced as compared to the simulation that would result if no adjustments were applied, other than the removal of some of the modeling deficiencies mentioned in Chapter 7.

Automated updating procedures include Kalman filter based procedures such as that utilized by the SS-SAC operation in the OFS [*Georgakakos et al.*, 1988] and a variational assimilation approach [*Seo et al.*, 2002]. The application of these automated procedures have thus far been limited to non-snow, lumped, single area headwater basins. The procedures use streamflow observations to adjust precipitation and evaporation inputs to the Sacramento model and state variables for the Sacramento and channel response models. The procedures are primarily intended to make adjustments during runoff events. The SS-SAC updating procedure uses a state-space version of the Sacramento model. Since this version doesn't exactly duplicate the regular Sacramento model computations, there is some potential for bias to be introduced. Both of these procedures have primarily been tested by comparing short lead time forecasts using the updating procedure to forecasts produce using a simple blending or persistence technique. In evaluating such procedures it would be important to determine which variables are being altered and by how much. It is possible that state variables could be changed to physically unrealistic values based on current streamflow observations that would not impact a short lead time forecast, but could produce a substantial bias for a longer lead time or especially for an extended prediction.

The primary method for making real time adjustments for all types of watersheds and modeling configurations with the OFS has been the use of run time modifications (MODs). The MODs in the OFS allow the user to modify time series values, model state variables, model parameters, and rating curves. Input data can be changed, as well as time series generated by any of the operations in the segment definitions. The user can specify where in the operations table the change is made and which values are modified. Model state variables can be altered at the beginning of a run or at a specified time within the run. MODs that alter model parameters are primarily used to adjust the computations on a temporary basis for such things as abnormal snowmelt rates or particular precipitation patterns that affect the channel response. Rating curve modifications are intended for locations with constantly changing ratings.

MODs can be specified by the forecaster via the Interactive Forecast Program (IFP) in NWSRFS at run time or they can be generated externally. When making MODs with IFP, the forecaster should not only rely on deviations between observed and simulated streamflow, but on a variety of other information such as: radar data, meteorological data and analyses including forecasts, observer reports, snow cover information, recent climatic trends (above or below normal conditions), satellite measurements, and river ice reports. MOD images are generated externally when an objective analysis procedure is used to compute the adjustments (e.g. procedures are available to compute snow water equivalent estimates based on snow course or areal gamma flight line measurements).

The main concern from the point of view of this manual is that MODs are not applied in a manner that will result in a biased forecast compared to what would be generated without any modifications. For example, it is difficult to determine the cause of any deviation between simulated and observed values and the magnitude of any needed adjustments early in a storm event. After the event is over, it is much easier to decide the cause (e.g. a volume problem can clearly be distinguished from a timing error after the event, however, early in the event the hydrograph response may look the same in both cases). The sooner the proper adjustment can be made, the longer the forecast lead time. However, if the wrong adjustment is made, it will typically result in the need to make further modifications which will alter the forecast and decrease the time available for action. In addition, the wrong adjustment might cause the state variables to take on values that could result is a considerable bias during the subsequent recession period or the next event and could especially impact extended predictions.

The chance of making a modification that could bias subsequent forecasts is even greater when there are several sources of error. For example, during the widespread flooding in the northeastern United States in late January 1996 [*Office of Hydrology*, 1998], the meteorological situation clearly indicated extreme snowmelt conditions, but there was also evidence of an underestimation of precipitation due to pronounced orographic effects. In addition, there was uncertainty in the initial snow cover and soil moisture conditions. If all the error was attributed to a single factor, it would be quite likely that some of the model states would not be correct and would result in subsequent forecasts being biased. In such cases it would be extremely valuable for the forecaster to have access to tools that would provide insight into potential errors and estimate a reasonable magnitude for each likely problem.

Besides storm events, there are other times when MODs are used to modify model states. During low flow conditions adjustments can be made to baseflow storages based on recent deviations between simulated and observed streamflow. Prior to the snowmelt season, model estimates of areal water equivalent are modified based on measurements of the snow cover. Soil moisture tension water deficits could be altered based on soil moisture measurements or model response after a dry period. Such updates can not only have an effect on the next significant runoff event, but more importantly they will alter the results of any extended predictions and can produce a substantial bias if not applied properly.

If the models being used for forecasting are well calibrated and properly applied operationally, two things should occur in regard to real time adjustments. First, there should be less need to make updates as the model simulations should more closely track observed conditions. Except for trends caused by model limitations or the spatial scale of the application (see Chapter 7), the errors from a well calibrated and properly applied model should be random. Models that are poorly calibrated or improperly applied will produce biased results and thus will need to be adjusted more frequently. Second, the proper adjustment to make and its magnitude should be able to be based on a logical assessment of potential sources of error. For example, a scientific evaluation of rainfall volume or snowmelt rates should be able to be used directly to determine if adjustments to these values are needed and the appropriate magnitude. Whereas, with a poorly calibrated or improperly applied model, there may be no logical explanation for the adjustments needed to cause the simulated conditions to reasonably match observations.

Section 8-1 provides some guidance for using the MODs directly associated with the SNOW-17 and SAC-SMA operations in a manner that reduces the chance of generating biased forecasts. General recommendations for using MODs are more in line with an operational forecasting, rather than a calibration manual, and are thus not included.

Operational Implementation Summary

If the objectives are met, i.e. unbiased simulation with minimal random error, parameters that properly reflect the function of each component of the models, and spatially consistent parameter values, then calibration results should significantly improve operational forecasts. The models should more closely track observations, fewer real time adjustments should be needed, and the choice of which modifications to apply and their magnitude can be based on logical decisions using all available information. In addition, besides producing unbiased short term forecasts with minimal uncertainty, the models can be used to generate accurate extended probabilistic predictions. However, all of these benefits are only possible if the calibration results are properly implemented in the operational environment. This requires that the results produced with the operational parametric definitions must be unbiased compared to the calibration results. It also requires that alternative sources of model input, changes to the spatial and temporal scales that the models are applied, and real time adjustments be applied in a manner that while reducing random error and model deficiencies doesn’t generate biased results.

While the guidelines and recommendations offered in this chapter should produce forecasts that contain the benefits of a proper calibration, the user needs to periodically verify the results and carefully evaluate alternative inputs and methods of applying the models. Comparisons and consistency checks should be made every few years to verify that real time data are indeed generating operational input and simulation results that are unbiased compared to the historical input and calibration output. New data analysis procedures, changes in the spatial and temporal scale that the models are applied, and real time adjustments need to be carefully evaluated to make sure that their use results in not only unbiased simulations, but produce real forecast improvements.

Section 8-1

Guidance for Using MODs with the SNOW-17 and SAC-SMA Operations

Introduction

This section provides some guidance for using the main MODs that are directly associated with the SNOW-17 and SAC-SMA operations in a manner that reduces the chance of adding a bias to future forecasts and thus preserving the benefits of calibration. For the SNOW-17 operation the MODs discussed are:

- .MFC (used to change the melt rate under non-rain situations)
- .UADJ (used to change the melt computations during rain-on-snow periods)
- .WECHNG (used to change the mean areal water equivalent)
- .AESCCHNG (used to change the areal extent of snow cover)

For the Sacramento model the MODs included are:

- .SACBASEF (used to change the amount of water in lower zone free water storages)
- .SACCO (used to change any of the Sacramento model state variables)

Though this discussion provides a brief description of exactly what happens when each MOD is applied and provides recommendations for their use, the focus, as mentioned, is on using these MODs in a manner that doesn't bias the state variables and thus cause problems during subsequent forecasts, including extended predictions.

.MFC MOD

The Melt Factor Correction (.MFC) MOD is used to multiply the non-rain melt factor by a constant for the period specified. This MOD can be used to change the melt rate for computational intervals within both the observed data period and out into the future. The primary reason for the .MFC MOD is that the relationship between air temperature and surface energy exchange varies depending on meteorological conditions. The normal seasonal variation in this relationship is specified when the SNOW-17 model is calibrated. However, the scatter about the seasonal melt factor curve is ignored during calibration as only the average relationship is being established. Operationally there is a need to remove this variability in order to improve forecast accuracy. During most periods the calibrated melt factor provides a very reasonable estimate of snowmelt, however, under certain situations the actual melt rate can be substantially different than the normal rate. Comparisons between energy balance melt computations and the SNOW-17 model have identified those meteorological conditions that produce the largest errors in temperature index based melt calculations [*Anderson*, 1976]. These include:

- Periods with high dew-points and high wind speeds - During such periods the turbulent transfer terms in the energy balance, i.e. the latent and sensible heat terms, transfer more energy than under normal conditions causing the melt rate to increase. In this case a .MFC value greater than 1.0 would be needed.

- Periods with much above normal temperatures and calm winds - Under these conditions the turbulent transfer terms are negligible, but the calibrated melt factor is computing more melt than would normally be expected at that time of year. This results in too much melt and thus the need for a .MFC value of less than 1.0.

- Periods with clear skies, but much below normal temperatures during the height of the melt season - Under these conditions there is a significant amount of solar radiation and the snow surface has aged so that the albedo is low enough for much of the radiation to be absorbed, however, the air temperature is indicating that not much melt should be occurring. In this case the .MFC value would need to be greater than 1.0.

Even though the forecaster can recognize these situations and realize that the melt rate needs to be modified, the problem is to determine the magnitude of the adjustment. If an error in the melt rate is the only cause for the simulated hydrograph to differ from the observed, the forecaster can interactively determine a correction that will bring the two hydrographs into line. However, even in this case there may be difficulties as the meteorological conditions could be changing from one time interval to the next. Thus, it may be possible to determine the average correction over several intervals, but the variation from one interval to another would be difficult to assess. The problem is compounded when there are multiple causes for the simulation errors or when trying to decide the correction to use when abnormal melt conditions are forecast for the next few days. This all indicates that a tool is needed to provide the forecaster with guidance as to when the .MFC MOD is needed and what is a physically realistic value for any corrections.

While it is difficult to obtain the data necessary to calibrate and apply an energy balance model on a routine basis, especially for complex forested areas in the mountains, it is likely that energy balance computations could be used to provide guidance for using the .MFC MOD. One possible procedure for doing this can be demonstrated using the January 1996 flood event in the northeastern United States [*Office of Hydrology*, 1998]. This event was characterized by extreme melt rates caused by high dew-points and winds and significant orographic precipitation. For this event energy budget melt values were computed for selected synoptic stations in the northeast. Dividing the melt computed from the energy balance by the air temperature minus MBASE gives the melt factor needed for each interval to reproduce the energy balance melt amount. The normal melt factor could be determined by calibrating the SNOW-17 model for each of these stations using observed temperatures and water equivalents. Then the ratio of the energy balance melt factor to the normal melt factor, which is the .MFC value, could be computed. Figure 8-1-1 shows how the ratio of the actual (energy balance) melt factor over the typical (calibrated) melt factor, i.e. the .MFC MOD, would have varied throughout this event for several synoptic stations in the northeast (in this case the normal melt rate was assumed to be 0.7 mm/°C/6 hr rather than based on a calibration of the sites - a typical melt rate for an open site in this part of the country for mid January).

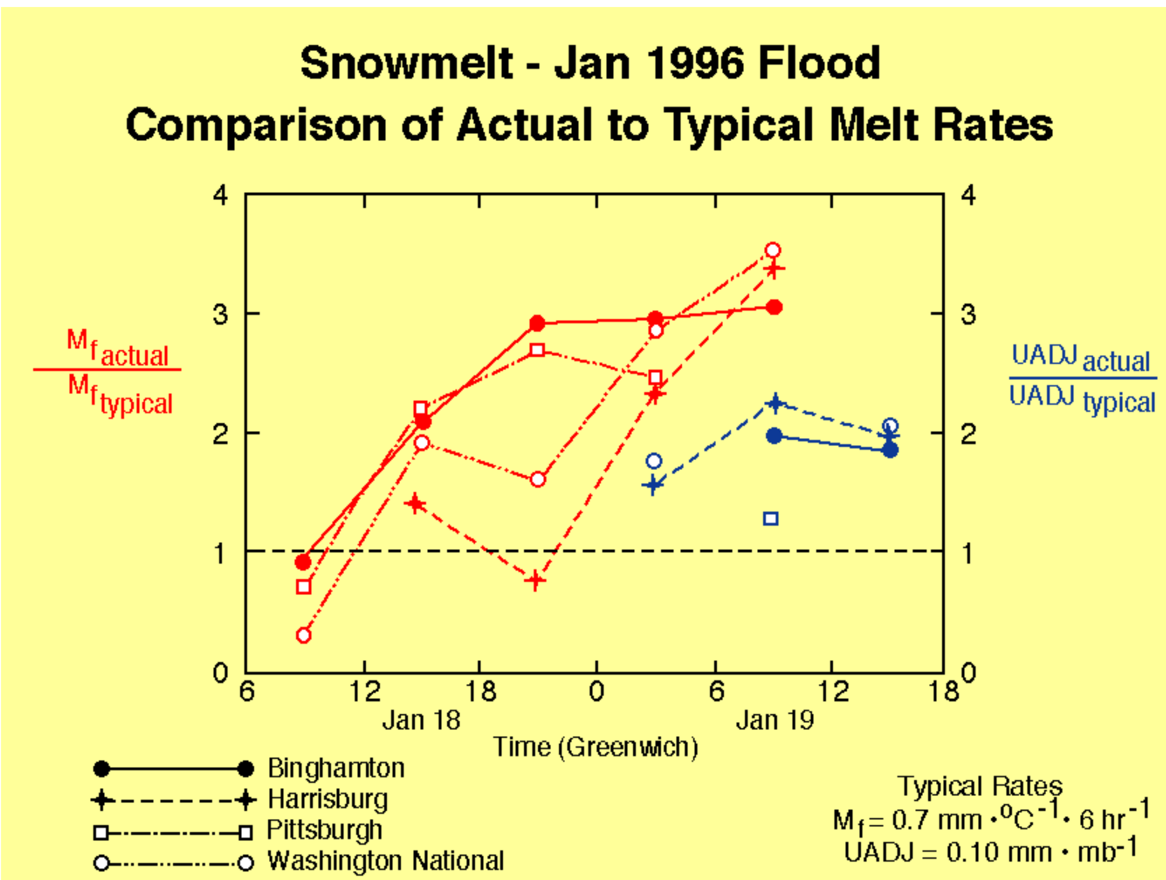


Figure 8-1-1. Variation of .MFC and .UADJ MODs for the January 1996 flood.

The next step in the procedure would be to map the .MFC values computed for each synoptic station (any station with the data needed for energy balance computations and observed water equivalent data could be used). This should give an indication of how the correction varies spatially. Isocorrection lines could be then drawn using meteorological observations or predictions as a guide. This is illustrated in Figures 8-1-2 and 8-1-3 for two successive 6 hour periods during the 1996 event. By 0Z high winds and dew-points existed in West Virginia,

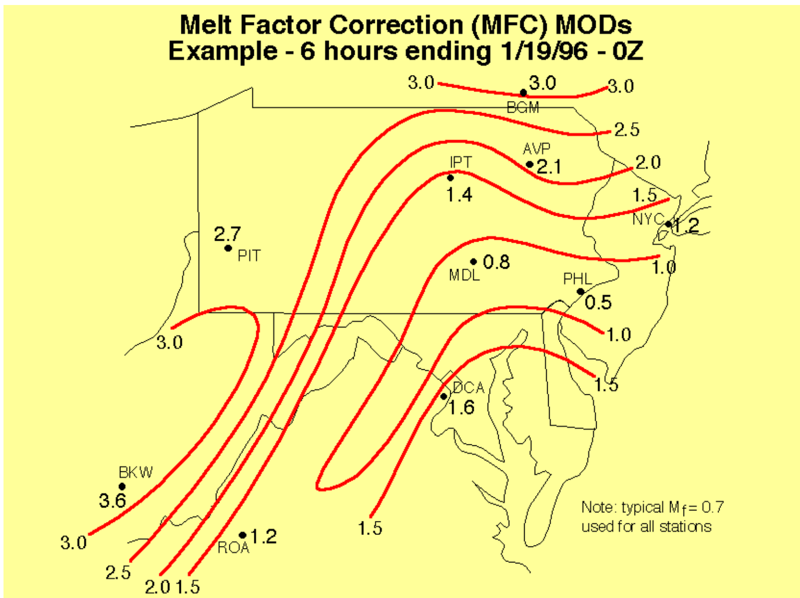


Figure 8-1-2. Variation in .MFC values for period ending at 0Z on Jan. 19,1996.

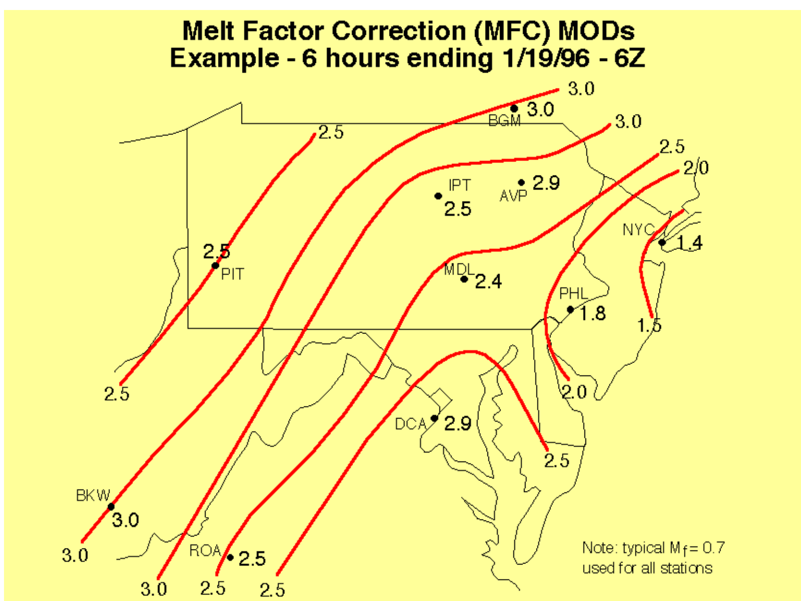


Figure 8-1-3. Variation in .MFC values for period ending at 6Z on Jan. 19,1996.

western Pennsylvania, and New York resulting in much above normal melt rates for these areas. Just east of the mountains conditions were very stagnant, though quite warm and humid, producing below normal melt conditions. By 6Z the high winds covered most of the region. The last step in the procedure would be to extract .MFC values for any particular watershed. This assumes that the .MFC values computed for an open site are appropriate to use for an entire watershed with mixed cover. This seems like a fairly reasonable assumption.

In the future estimates of the appropriate melt factor corrections could possibly be obtained from the Snow Data Assimilation System (SNODAS) being developed by NOHRSC [*Carroll et al.*, 2001]. SNODAS utilizes downscaled fields of meteorological data from numerical weather models and gridded precipitation estimates to drive a distributed energy and mass balance snow model. The resulting snow model states can be updated using satellite, airborne, and ground-based snow observations. The procedure was first run for the central and eastern U.S. in the spring of 2001 and continuously for the conterminous U.S. for the winter of 2110-2002. SNODAS is still in the evolutionary stage. Adjustments are being made to many of the algorithms and data fields. It will probably take a few more years for the system to reach a stable configuration. A period would then be needed to develop the relationships between melt factors derived from the SNODAS energy budget calculations and those from the SNOW-17 model. These relationships could then be applied to SNODAS derived melt factors to identify when abnormal melt rates are likely to occur and to obtain realistic estimates of the magnitude of any corrections. Alternatively, the relationships might be used to adjust SNODAS energy exchange estimates prior to directly overriding the SNOW-17 computed values.

If some method is not used to determine a physically realistic estimate for melt factor corrections, there is good chance that the correction applied will be too large or too small. In either case, the resulting water equivalent at the end of the correction period will be off (assuming it was correct to begin with) and subsequent forecasts will contain too little or too much snow, thus producing a bias.

.UADJ MOD

The wind function correction (.UADJ) MOD is used to multiply the UADJ parameter (wind function term) in the rain-on-snow melt equation by a constant for the period specified. This MOD can also be applied to future intervals as well as the observed data period. It should be noted that the .UADJ value only affects the turbulent transfer terms in the rain-on-snow melt equation. The longwave radiation and heat of rainwater terms are not altered.

The primary reason to use the .UADJ MOD is to account for variations in wind speed during rain-on-snow periods when the temperature is enough above freezing so that significant melt occurs. Since .UADJ is only used when rain is occurring, there is always the question as to whether simulation errors are due to melt computations or whether the estimate of the amount of rain is in error. As with the .MFC MOD, energy budget computations could be used to determine a reasonable value for the wind function correction. Figure 8-1-1 shows .UADJ values derive by comparing the wind function derived from the energy budget to a typical value for an open site for several synoptic stations when rain was occurring during the 1996 northeastern U.S. flood event. Computations of .UADJ values at synoptic stations, or other sites with the data needed for energy balance calculations, could be used as a guide for determining watershed corrections. However, wind adjustments might be more difficult to extrapolate in regions with substantial terrain and forest cover than melt factor corrections. As with the .MFC MOD, improper wind function adjustments will affect the resulting water equivalent and cause some bias in subsequent forecasts. In the future relationships could be derived to possibly adjust SNODAS computations of melt during rain-on-snow periods for use within the SNOW-17 model.

.WECHNG MOD

The Water Equivalent Change (.WECHNG) MOD is used to change the mean areal water equivalent at a specified time during the period of observed data. When the water equivalent is modified with this MOD, the areal extent of snow cover is assumed to remain the same. This results in the areal depletion curve being shifted when the change is made when some bare ground exists. This is illustrated in Figure 8-1-4. In order to change both the water equivalent and the fraction of the area cover by snow, both the .WECHNG and .AESCCHNG MODs must be used. In this figure TWE is the total water equivalent, i.e. the sum of ice and liquid water in the snow cover, and A_s is the areal extent of the snow cover.

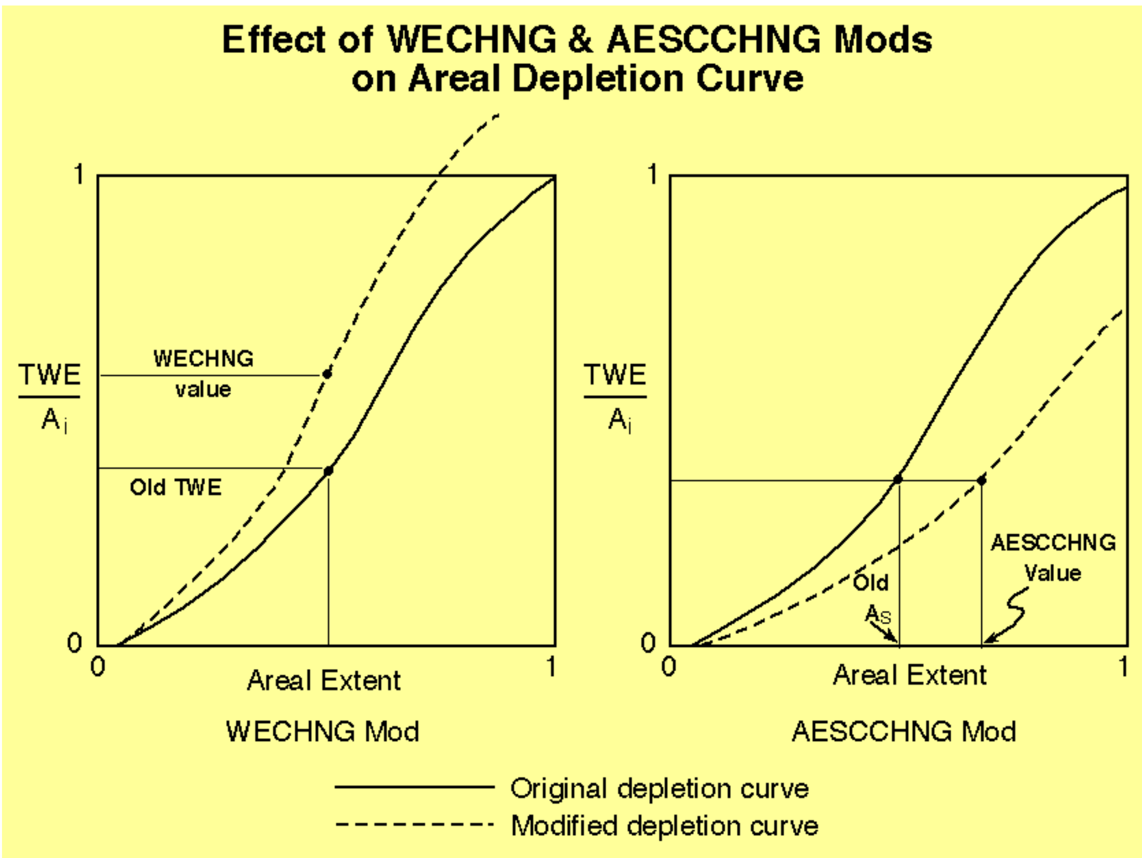


Figure 8-1-4. Effect of .WECHNG and .AESCCHNG MODs on the areal depletion curve.

The water equivalent typically needs to be modified because the snow cover accumulated by the model can be in error due to inaccurate precipitation input. This is caused by variations in catch deficiencies from normal and by storm dynamics that produce a different areal distribution than the typical pattern indicated by the isohyetal analysis. Also snowmelt computations may have been in error due to abnormal lapse or melt rates. The updated value of the water equivalent is normally based on water equivalent observations from snow courses, airborne gamma flight lines, or special surveys. The updated areal water equivalent derived from the observations can be directly substituted for the model value or each estimate can be given some weight. This depends on the relative uncertainty of each value. In many cases this is a subjective decision.

In flat terrain it may be okay to assume that there is a one-to-one relationship between the observations and the model's areal estimate. This is more likely if there are sufficient observations scattered over the area. The problem that can occur in very flat areas, like portions of the upper midwest, is that during the melt period significant water can pond in fields before ice at the outlet melts and allows the water to drain. In this case airborne gamma observations may include both snow and ponded water. If such observations are used directly, it could resulted in a biased estimate of areal water equivalent.

In mountainous terrain it is highly unlikely that even a weighted average of the observations can be used directly without first determining the relationship between the weighted average and model estimates. Generally the relationship between available observations and model values will vary from one time of the year to another. Thus, separate relationships need to be derived for each date that observations are typically available. In order to determine the relationship between the observations and the water equivalent generated by the model, first a reasonably long, stable historical record of observations must exist. Second, there needs to be a model simulation using historical gage data for an overlapping period.

The simplest updating procedure would be derived by plotting the observed water equivalent from a single site or a weighted average of several sites in and near the area against the model estimate for the same historical date. The average relationship derived from this plot could then be used to update the model whenever real time observations are available from those sites. The procedure can be evaluated by using the relationship to update the water equivalent during the historical period and then determine whether the resulting snowmelt runoff volume is an improvement over the simulation with no updates.

A more complex procedure is the Snow Estimation and Updating System (SEUS) based on the methodology proposed by Day [1990]. This system was in use by the western RFCs for awhile, but is no longer supported by the NWS. A replacement for SEUS was develop for use in the Pacific Northwest [*RTi*, 2000]. This procedure develops regression equations between fraction of normal values of observed and simulated water equivalents for various times during the snow season. The procedure is based on fraction of normal values to make it independent of the network of observations. This avoids having to recalculate regression equations every time a new station is added or deleted from the network. In addition, the procedure avoids having to estimate missing data since the estimated fraction of normal is based only on the stations which actually report. Based on tests on selected basins to evaluate the effect of this updating procedure on hydrograph simulations, it was decided to weight the estimate derived from the observations and the model simulated value equally.

In the future output from SNODAS may be used for determining water equivalent updates for SNOW-17. SNODAS could prove to be especially beneficial in the central and east regions of the country where the historical water equivalent network is quite sparse. SNODAS has the capability to use snow depth values, as well as water equivalent, to update model states. As with most updating procedures, relationships will need to be established between the SNODAS mean areal water equivalents and those produced by the SNOW-17 model in order to make sure that a bias is not introduced when the water equivalent is modified.

The key is to carefully evaluate any procedure for updating water equivalent as improper changes can have a large effect on the volume of snowmelt runoff and thus result in a significant bias. At least for mountainous areas, an objective procedure must be based on derived relationships between historical observations and model estimates.

.AESCCHNG MOD

The Areal Extent of Snow Cover Change (.AESCCHNG) MOD is used to change the areal extent of snow cover at a specified time during the period of observed data. When the areal extent of the snow cover is modified with this MOD, the mean areal water equivalent is assumed to remain the same. This results in the areal depletion curve being shifted. This is illustrated in Figure 8-1-4. In order to change both the water equivalent and the fraction of the area cover by snow, both the .WECHNG and .AESCCHNG MODs must be used.

The areal extent of snow cover may need to be changed because of variations in accumulation and melt patterns from normal or due to errors in the model simulation of water equivalent or melt. The most routine observations of the areal extent of snow cover are those obtained from satellite data by NOHRSC. At least in the past, aircraft were used in some regions to observe the snow line in the mountains and thus derive an estimate of the areal cover. Again, as with most observations, areal extent of the snow cover observations generally can't be used directly to update the snow model. It could be that in open, flat terrain the observed and simulated values of snow cover have a one-to-one relationship, however, this is certainly not the case in the mountains and even in watersheds with reasonably level terrain, but varying vegetation patterns. The main reason is that the snow model implicitly uses the areal depletion curve to account for variations in melt rates and other factors in addition to areal cover as discussed in Chapter 7-4 and illustrated on Figure 7-4-3. Thus, in most areas a relationship between the areal extent observations and the model computed values would have to be derived before the satellite estimates could be used to update the snow model. This hasn't been done to this author's knowledge. Such a relationship may not be linear as suggested by Figure 7-4-3. In order to derive the relationship an overlapping period with stable satellite observations and historical model simulated values must be available. In mountainous areas with multiple zones, the satellite estimates must correspond to the elevations used to divide the watersheds. If satellite observations are used to update the areal extent in the snow model without first defining the relationship with the simulated snow cover values, it is very likely that a bias will result, especially in mountainous regions.

.SACBASEF MOD

The Sacramento Baseflow (.SACBASEF) MOD is used to multiply the contents of both lower zone free water storages, i.e. LZFSC and LZFPC, by the same constant. This MOD allows the user to increase or decrease baseflow and maintain the relative division of water between the two storages. Generally this is the preferred method of modifying the amount of baseflow. A proper calibration should provide for a reasonable allocation of baseflow between supplemental and primary components. When there are low flow errors in a historical simulation, it is typically because baseflow is too high or too low, not the relative magnitudes of the two components.

When the .SACBASEF MOD is applied, it will take some period of time before the baseflow reaches the desired level, i.e. the change in the amount of baseflow doesn't appear instantaneously, but gradually over a number of time intervals. This is because baseflow, like all runoff generated by the Sacramento model, must pass through the channel response function, typically a unit hydrograph, before reaching the drainage outlet. Thus, the transition time is dependent on the number of ordinates in the unit hydrograph.

The decision as to whether baseflow needs to modified is generally based on comparing the simulated and observed hydrographs during a low flow period. When applying the .SACBASEF MOD there are several things to watch out for and situations to avoid. These include:

- The only flow components making up the simulated hydrograph should be primary and supplemental baseflow (supplemental flow can be zero if this storage is completely drained). There should be no other sources of runoff prior to when the hydrograph is being analyzed for a period equal to the length of the unit hydrograph. Currently there is not a graphical display of runoff components in IFP analogous to the ICP display shown in Figure 7-8-1, though this information can be obtained in a tabular form (PRINTSMA technique). In many cases during a recession it is assumed that the simulated hydrograph can be brought in line with the observed by changing baseflow, when in reality, other runoff components are still contributing to runoff. This can especially be the case near the end of a long snowmelt season. It appears that the hydrograph is in a baseflow recession, when snowmelt from a small portion of the area is still producing interflow and possibly impervious runoff.

- Baseflow modifications shouldn't be made during periods when there is evaporation from riparian vegetation. Such evaporation occurs when the RIVA parameter is greater than zero, there is a reasonable level of ET-Demand, and tension water deficits exist. The algorithms in the Sacramento model for handling riparian evaporation are quite simple, thus the simulation errors during such periods are much more likely to be the result of problems with computing the loss due to riparian vegetation than the amount of water in the lower zone free water storages. You probably just need to live with the simulation errors that exist under these conditions.

- It is probably unwise to modify baseflow at locations where problems can exist with the ratings, especially at low flows. This is certainly the case during the winter in northern regions. River ice can significantly affect the rating curves in these area, thus it may be very likely that the observed flow values are in error. Observed flows are also likely to be in error at other locations where the channel is not well defined at low water levels.

If care is taken when using the .SACBASEF MOD, this should be the best way to correct for simulation errors during baseflow periods. This MOD takes advantage of the calibrated relationship between supplemental and primary baseflow and thus, in general, is less likely to result in biased values of the related storages than if the lower zone free water contents were modified independently.

.SACCO MOD

The Sacramento Carryover (.SACCO) MOD is used to change the value of any of the Sacramento model state variables at a specified point in time. The contents of any of the 6 moisture storages, UZTWC, UZFWC, LZTWC, LZFSC, LZFPC, and ADIMC, can be modified. Tension water can be changed by either specifying a new content or deficit. The MOD also allows for modifying the value of the frost index used in the frozen ground algorithm associated with the Sacramento model.

One tool that can be helpful when using the .SACCO MOD is the tabulation summary of moisture contents that can be generated by the WATERBAL operation after a calibration is complete. This table shows the average, high, and low values for each of the 6 moisture storages for each month and thus can be used to avoid making changes to the contents that are outside of the range experience during the historical simulation.

Following are some guidelines for using the .SACCO MOD in a manner that will avoid generating biased values.

- LZFSC and LZFPC - The preferrable method for making changes to these contents is to use the .SACBASEF MOD. If only primary baseflow exists and the situations mention under the .SACBASEF discussion are not present, then the effect of using the .SACCO MOD to change the baseflow would be the same as using the .SACBASEF MOD, however, it is much easier to compute a multiplying factor than to calculate the content that would be needed to produce the desired amount of baseflow. When both supplemental and primary components are contributing to the baseflow, it very difficult to assess how to change the contents of each storage based on the short period of time that is typically displayed operationally (normally less than a week of observed data are being processed). This makes it is very difficult to change these two storages independently. It is much preferred to use the relationship between these two runoff components that was established during the calibration and rely on the .SACBASEF MOD to make run time modifications to the contents. On most watersheds the contents of the supplemental, and especially the primary, storage will affect the amount of low flow that is produced for a considerable time in the future.

- UZFWC - It is not recommended that the forecaster attempt to modify this value. The contents of the upper zone typically change quite rapidly, especially when water is entering the model. The UZFWC value could possibly be changed to increase or decrease the amount of interflow during the first few days of a recession, but even then it is difficult to determine a new value since the upper zone free water storage is losing water both as interflow and percolation. The only saving feature if UZFWC is modified, is that the effect will only last for a short time since this zone typically drains within a few days though the effect of altering the percolation amount would persist much longer.

- UZTWC, LZTWC, and ADIMC - Tension water deficits develop over some period of time during periods of dry weather and substantial evaporation. Potential errors in the size of these deficits are caused, in part, by biased evapotranspiration estimates due to abnormal weather conditions or vegetation activity. The errors can also be due to biased estimates of precipitation for the events, frequently convective, that occur during the period that the deficits develop.

Streamflow observations can't be used to determine if a problem exists in the size of the tension water deficits until a substantial runoff event occurs. This could be a rain storm after a dry period or the beginning of snowmelt for a year when the summer moisture deficiency wasn't satisfied by fall rains. In both of these cases the tension water deficits may only be a portion of the reason why the streamflow response is not simulated correctly. In the case of the rain event, the amount of rainfall for the storm could be incorrect. In the case of the snowmelt situation a number of factors can affect the simulation at the beginning of the melt season as discussed at the end of Section 7-7. These factors need to be taken into account when making modifications to the conditions prior to such events.

Tension water deficits could also possibly be adjusted based on soil moisture observations. There have been studies that showed favorable comparisons between the Sacramento model tension water deficits and soil moisture measurements. In order to properly use the soil moisture data to update the tension water contents, relationships would have to be established using an overlapping period of stable soil observations and historical model simulations. The problem in many cases would be in finding a sufficient record of moisture observations to develop the relationships. The soil moisture data would not have to be available in real time in order to be used for updating as tension water deficits develop slowly. It would be sufficient if the data were available within a day or two after the observations were made.

If the tension water contents are suspected to be in error prior to any runoff events and there is not an objective procedure for updating the values, extreme care is advised when making any changes. This is because these deficits, especially the lower zone deficit, can affect the amount of runoff produced over a considerable time into the future. Thus, any change can have a significant impact on an extended flow prediction, especially in times of drought. The range in the contents during the historical simulation should certainly be used to avoid a completely unreasonable modification.

Typically if the upper or lower zone deficits are altered and the ADIMP parameter is being used to produce direct runoff, the value of ADIMC should also be adjusted.

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