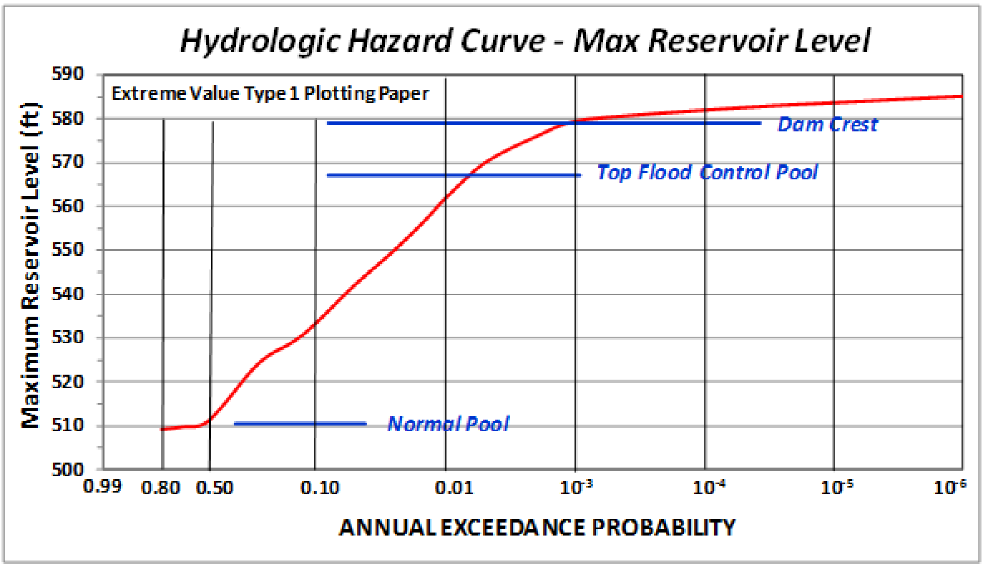
Stochastic Event Flood Model (SEFM)

Technical Support Manual



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October 1998
Updated March 2018

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OVERVIEW OF TECHNICAL SUPPORT MANUAL

This manual provides technical information about operation of the Stochastic Event Flood Model (SEFM). Development began in 1998 and SEFM was created to provide magnitude-frequency estimates for flood peak flow, runoff volume and maximum reservoir level resulting from long-duration general storms for use in hydrologic risk assessments at dams. It was originally developed for application in mountainous areas of the western United States where rain-on-snow flood events are common and snowmelt runoff is a contributor to flooding.

Numerous improvements and features have been added to SEFM over the years. SEFM is now configured for application on watersheds subjected to the full range of storm characteristics including long-duration synoptic-scale storms to intermediate-duration mesoscale storms with embedded high-intensity convective cells and short-duration small-scale local storms. This was accomplished by using gridded precipitation at a spatial and temporal resolution sufficient for depicting the temporal storm characteristics of importance for watersheds of various sizes. Features are also included for modeling of watersheds in cold environments with seasonal snowpack as well as climatic conditions ranging from arid through rainforest.

The manual is organized in five parts.

- Part I is intended to provide an overview of the operation of the computer model. It describes the basic concepts employed in operation of the computer model and identifies the various hydrometeorological components that are modeled in the computer simulations.

- Part II describes each of the hydrometeorological components in greater detail. This includes a discussion of the assumptions and model operation for each component and guidance and experience gained from conducting analyses for other regions and watersheds. It presents the computer screens that are used for data entry of the input parameters that are required for computer simulation of each hydrometeorological component. It also contains detailed descriptions of the analyses used to determine the probabilistic input parameters needed for computer simulation of the various hydrometeorological components.

- Part III describes the mechanics of executing the computer programs for pre-processing input data, executing the SEFM model, and post-processing output from the computer simulations.

- Part IV discusses a number of miscellaneous topics related to operation of the model.

It should be noted the SEFM model continues to evolve as experience is gained in applications to watersheds in a wide variety of climatic conditions and as more is learned about the probabilistic characteristics of the hydrometeorological processes. This manual will be periodically updated as the model evolves and improvements are made to the model.

PART I - DESCRIPTION OF THE STOCHASTIC EVENT FLOOD MODEL

1-1 BASIC CONCEPTS

The basic concept of the Stochastic Event Flood Model (SEFM) is to employ a deterministic watershed model for flood computations and to treat the hydrometeorological input parameters as variables instead of fixed values. Monte Carlo sampling procedures are used to allow the hydrometeorological input parameters to vary in accordance with that observed in nature while preserving the natural dependencies that exist between some climatic and hydrologic parameters.

Multi-thousand computer simulations are conducted where each simulation contains a set of input parameters that are selected based on historical data for each parameter while preserving any dependencies that may exist between parameters. The simulated floods represent an annual maxima flood series and the resultant flood magnitude-frequency estimates reflect the likelihood of occurrence of the various combinations of hydrometeorological factors that affect flood magnitude. The watershed model can be a continuous or single event. However, the watershed model is operated in event mode to reduce the computational time for the many thousands of computer simulations required to develop the hydrologic hazard curves (flood magnitude-frequency curves).

The use of the stochastic approach allows for the development of separate hydrologic hazard curves for flood peak flow (Figure 1-1a), maximum reservoir level (Figure 1-1b), flood runoff volume (Figure 1-1c) and any other flood characteristic that can be obtained from the outputs of a watershed model. In particular, frequency information about maximum reservoir levels is important for use in hydrologic risk assessments for dams because it accounts for flood peak flow, runoff volume, hydrograph shape, initial reservoir level, and reservoir operations.

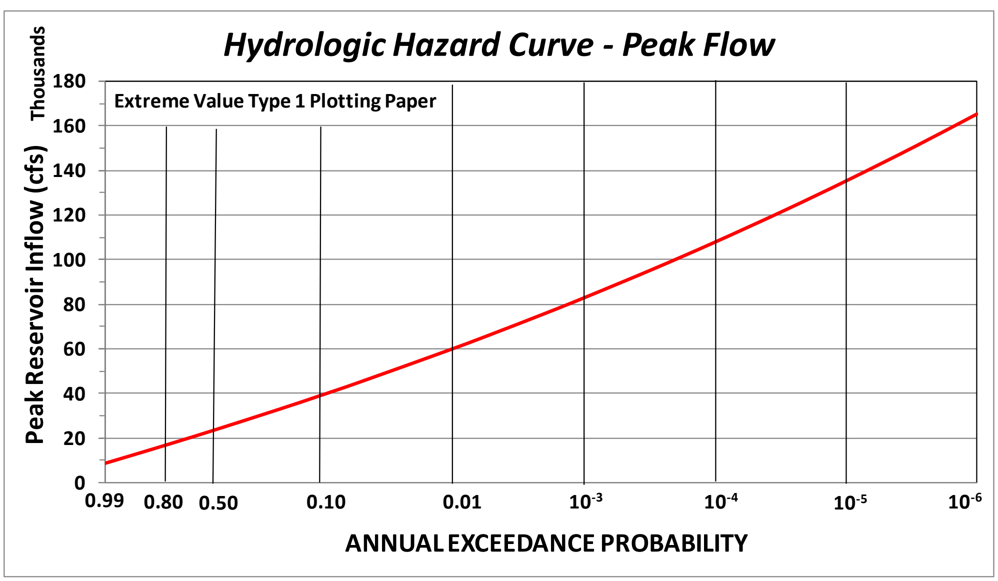


Figure 1-1a – Example Hydrologic Hazard Curve for Peak Reservoir Inflow

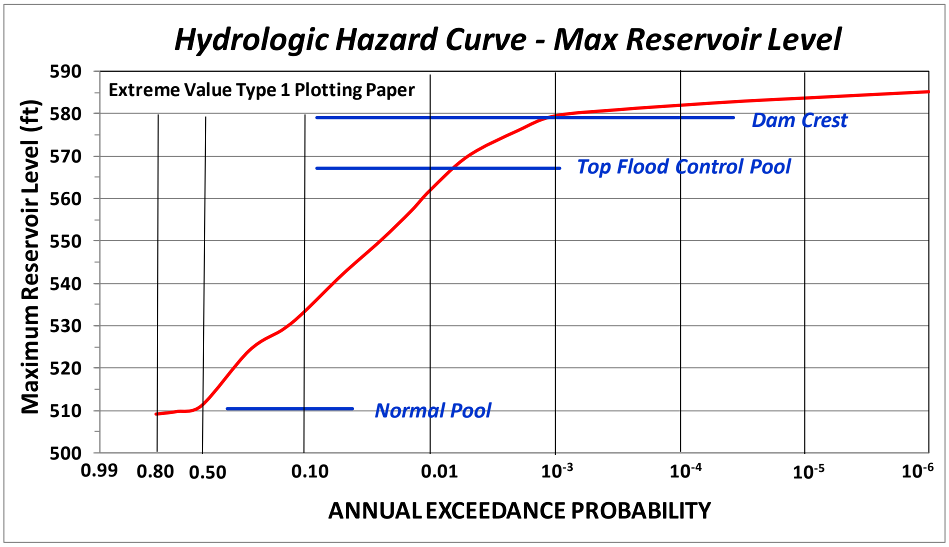


Figure 1-1b – Example Hydrologic Hazard Curve for Maximum Reservoir Level

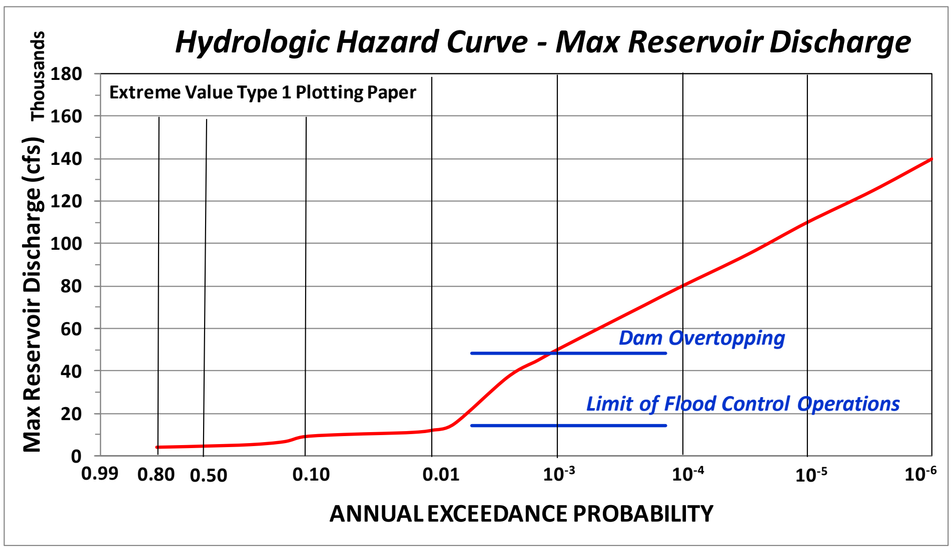


Figure 1-1c – Example Hydrologic Hazard Curve for Reservoir Outflow

1-2 SOFTWARE COMPONENTS OF SEFM

There are three components that control the operation of SEFM and include: the SEFM stochastic engine; a deterministic watershed model; and the SEFM post-processor (Figure 1-2). Each of the three components is briefly described below.

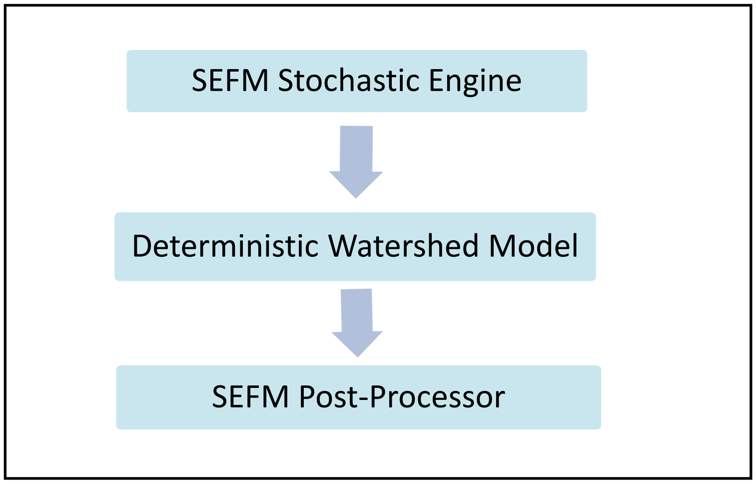


Figure 1-2 – Software Components of Stochastic Event Flood Model

1-2.1 SEFM Stochastic Engine

The SEFM engine is the software component for generating the stochastic hydrometeorological inputs for stochastic flood modeling. This component is independent of the choice of watershed model. The stochastic engine uses a combination of standard Monte Carlo sampling, Latin-hypercube sampling and resampling methods for generation of the hydrometeorological inputs. This module contains all of the data entry for probabilistic and deterministic hydrometeorological parameters and pathing to all necessary data files for stochastic inputs.

1-3.1 Deterministic Watershed Model

SEFM currently incorporates four deterministic watershed models. These include:

- SEFM watershed model
- HEC-1 watershed model
- HEC-HMS watershed model configured in sub-basin mode, backward compatible to HEC-1
- Sacramento Soil Moisture Accounting Model
- UBC watershed model

The SEFM *Watershed Model* utilizes a modified Holtan[19] infiltration equation and computes runoff as two components; surface (or quick) flow, and interflow. The SEFM watershed model includes a graphical interface for defining the watershed layout and can accommodate multiple subbasins and reservoirs.

SEFM is also configured to use the HEC-1[124] watershed model. This feature is useful for projects that have been analyzed using HEC-1 as part of a deterministic PMF study. The standard HEC-1 input file is modified to include SEFM inputs. These inputs are then replaced during the simulation by stochastically generated inputs. These inputs include surface and interflow computed using the SEFM watershed model and initial reservoir level. In this case, nearly all of the hydrologic computations are conducted within the SEFM and HEC-1 is used primarily as a stream network and routing model. In addition, watersheds that have been modeled in HEC-HMS [x] using a sub-basin configuration can be readily executed within the SEFM framework using the legacy HEC-1 watershed model.

In concept, any deterministic watershed model could be linked with the SEFM stochastic engine. The SEFM stochastic engine has been previously paired with the UBC Watershed Model[116] and WATFLOOD[105]. To use a different watershed model, an interface would need to be constructed for passing the stochastic hydrometeorological inputs to the chosen watershed model.

Deterministic Watershed Models in Future Versions of SEFM

Future versions of SEFM will be compatible with the following watershed models:

- UBC watershed model
- RORB watershed model
- Sacramento Soil Moisture Accounting Model

1-4.1 SEFM Post-Processor

The SEFM post-processor is used for a variety of purposes. The post-processor includes a database for storing the hydrometeorological inputs and flood outputs for each flood simulation. The post-processor performs analyses of the flood outputs and produces hydrologic hazard curves for flood characteristics of interest such as flood peak flow, maximum reservoir level, runoff volume, and spillway discharge. It organizes flood outputs into a probabilistic framework useful for conducting failure-mode and fragility analyses. This includes probabilistic information on depth and duration of dam overtopping and depth and duration of reservoir levels above a user-specified elevations, such as the invert elevation of an emergency spillway or the dam crest.

1-3 CAPABILITIES OF SEFM

SEFM has the capability to simulate a wide range of hydrometeorological and watershed conditions. Computer simulations can be conducted for floods resulting from a variety of storm types including long-duration storms such as synoptic scale mid-latitude cyclones and tropical storms, as well as shorter-duration mesoscale convective systems and local storms.

Runoff is computed on a distributed basis for polygons of land called Hydrologic Runoff Units (HRUs) that have common mean annual precipitation, elevation, and soil characteristics. Hydrometeorological parameters that vary seasonally with mean annual precipitation, elevation or soil type, such as antecedent precipitation, antecedent snowpack, and soil moisture, are allowed to vary spatially within the watershed via accounting through the HRUs. Runoff is computed separately for each HRU and then aggregated to the sub-basin level for use in the flood computations.

SEFM can be run in a completely stochastic mode where all hydrometeorological parameters are allowed to vary. It can be run in a completely deterministic mode with all parameters fixed, or it can be run in a mixed mode with some parameters treated as variables and other parameters fixed.

In most cases, the flood responses of a given watershed and reservoir are sensitive to only a few of the hydrometeorological parameters. Recognizing this situation, the data entry interface allows the user to specify how each of the hydrometeorological parameters is to be treated - variable or fixed value. This approach allows the user to provide a greater level of detail in the simulation of those hydrologic processes that have the greatest influence on the watershed/project under study. Hydrometeorological parameters that do not have a significant effect on the flood outcomes can be treated as fixed values.

Simulations are conducted based on mid-month and end-of-month conditions throughout the storm season for the various hydrometeorological input parameters. A twice-monthly time increment was chosen for two reasons. First, it provides reasonable efficiency in analysis of historical data because many hydrometeorological variables are reported on end-of-month intervals. Second, use of a twice-monthly time increment results in the dates of storm/flood occurrence that are on-average 4-days, and at-most 8-days, different from those obtained if the storm/flood date could occur on any day of the year. Thus, twenty-four time increments are deemed sufficient for sub-division of the water-year (October 1 to September 30) to depict the natural seasonal variability in hydrometeorological inputs such as soil moisture, snowpack, initial streamflow, reservoir level, etc.

SEFM has the standard hydrologic modeling capabilities of computing flood hydrographs and conducting reservoir routing, including reservoir operation by complex rule-curves. It also has the capabilities to:

- Generate storms with spatial and temporal patterns obtained from historical storms
- Generate synthetic storms with characteristics obtained from guidelines or policy directives
- Simulate surface runoff and interflow runoff
- Compute runoff on a distributed basis using conditions within each HRU
- Compute snowmelt runoff while accounting for the initial snow density condition
- Account for frozen ground conditions and set surface infiltration rates accordingly

The following hydrometeorological inputs and hydrologic model parameters can be treated as variables in operation of the SEFM model:

- Date of occurrence of storm
- Watershed-average precipitation magnitude
- Spatial distribution of precipitation throughout the watershed
- Temporal distribution of precipitation which varies spatially throughout the watershed
- Centering of storm over the watershed
- Seasonally and spatially varying antecedent precipitation
- Seasonally and spatially varying snowpack snow-water equivalent
- Seasonally and spatially varying initial snow density
- Seasonally varying freezing level for snowmelt computation
- Storm-specific temporal air temperature pattern for melting of snowpack
- Seasonally and spatially varying soil moisture conditions at onset of the storm
- Soil-specific surface infiltration rate as function of soil moisture condition
- Streamflow prior to extreme storm
- Reservoir level prior to extreme storm

SEFM has features which provide information on flood likelihoods for conducting fragility analyses to support hydrologic risk analyses. SEFM can also be executed in a less rigorous mode with regard to the depth of analysis for the various hydrometeorological inputs which can provide qualitative flood likelihood information for conducting failure-mode analyses. The following features are provided as part of the SEFM post-processor functions.

- Develop hydrologic hazard curves for flood peak flow, maximum reservoir level, reservoir discharge and a variety of flood characteristics
- Provide probabilistic information on the depth and duration of dam overtopping

- Provide probabilistic information on the depth and duration of reservoir levels above user specified elevations
- Provide probabilistic information on the duration of spillway discharges above a user-specified magnitude

1-4 APPLICABILITY OF THE STOCHASTIC FLOOD MODEL

Conceptually, there is no computational limit to the size of the watershed to which a stochastic flood model can be applied. However, the complexity in simulation of hydrometeorological inputs and flood responses generally increases with watershed size. Simulation of very large watersheds for large river basins would require that additional measures be taken to properly account for the spatial variability of many of the hydrometeorological inputs including the possibility of storms with partial areal coverage of the watershed. In very large river basins, there is also the issue of extreme floods being generated by a sequence of storms occurring over several weeks where runoff volumes and river levels may be augmented by snowmelt in the spring of the year. These conditions are outside the scope envisioned for development of SEFM.

SEFM, in its current configuration, is applicable to watersheds up to a nominal size of about 10,000-mi^2 for synoptic-scale mid-latitude cyclones and precipitation associated with tropical storms. Similarly, SEFM is applicable to watersheds up to a nominal size of about 2,000-mi^2 for modeling of mesoscale storms with embedded convective cells capable of generating flash-flooding such as Mesoscale Convective Systems (MCSs).

The following conditions and assumptions have been incorporated in development of SEFM. The simulated floods from SEFM will be more representative of the flood responses from a watershed the more closely the following conditions are satisfied.

- Each SEFM model is intended for simulation of floods produced by one storm type. Separate SEFM models will be needed for each storm type where there is a mixed population of storm types that produce floods. In the case of mixed populations of storm types and floods, the final hydrologic hazard curves would be developed based on combining of the hydrologic hazard curves for the various storm types/floods.
- Floods are generated by a single storm event occurring over a timeframe of up to several days. The storm event is preceded and followed by climatic conditions and possibly other storms which are representative of the seasonality of occurrence of the storm event.
- The watershed size is such that a common non-exceedance probability is representative of antecedent precipitation and antecedent snowpack throughout the watershed. In simple terms, it is a dry, typical or wet year everywhere in the watershed as opposed to very large watersheds where antecedent climatic conditions can be quite different in distant parts of the watershed.
- The chosen watershed model has appropriate hydrological computation algorithms for the dominant hydrological processes that produce floods in the watershed. Specifically, the computational algorithms for quickflow runoff, interflow runoff and very-delayed runoff are representative of the flood-generating mechanisms in the watershed.
- The watershed model has been calibrated by replication of historical storms/floods. The combined SEFM engine and watershed model has also been calibrated to replicate the historical flood-frequency relationships for various durations of interest (instantaneous peak flow, 6-hour peak flow/volume, 24-hour peak flow/volume, etc.).

1-5 DISTRIBUTED RAINFALL-RUNOFF WATERSHED MODELING

A key element in the stochastic approach is the selection of realistic initial conditions in the watershed at the onset of the extreme storm. The hydrologic models currently includes in SEFM support the distributed hydrologic approach. This requires that a distributed approach be used in modeling the rainfall-runoff process so that the spatial variability of soil moisture, soil moisture storage characteristics, soil infiltration rate, snowpack can be properly considered in computing runoff.

1-5.1 Hydrologic Runoff Units

To accommodate the distributed approach, the watershed is divided into numerous sub-areas. These sub-areas are comprised of irregularly shaped land areas (polygons) having common mean annual precipitation, elevation, and soil infiltration characteristics and are termed Hydrologic Runoff Units (HRUs). Runoff is computed separately for each HRU and then combined to obtain the response of each sub-basin. Additional information about the process for delineation of the sub-areas that comprise an HRU is described in section 2-1, *Watershed Layout*.

1-5.2 Mean Annual Precipitation Zones

Mean Annual Precipitation (MAP) often varies widely across mountainous watersheds in the arid, semi-arid, and sub-humid western US. This spatial variability requires that a watershed be sub-divided into zones of similar mean annual precipitation to facilitate the allocation of antecedent precipitation, allocation of winter snowpacks, and computation of soil moisture budgets. Sufficient zones should be employed to adequately describe the variability of monthly antecedent precipitation, snowpack, and soil moisture that occurs due to differences in the magnitude of monthly and annual precipitation.

1-5.3 Elevation Zones

Elevation information is used in SEFM for several tasks. Elevation zones are used in setting seasonal evapotranspiration for use in soil moisture accounting prior to occurrence of a storm. Elevation zones are also used in allocating snowpack and to account for temperature changes that occur with elevation during storms. Air temperature varies with elevation and is used for snowmelt computations and for checking for frozen ground conditions. Selection of upper and lower bounds for the elevation zones should be based on the relationship between elevation and area within the watershed to ensure proper apportioning of areas.

1-5.4 Soil Zones

Soil zones are used to delineate contiguous areas with similar soil characteristics. Each soil zone represents a unique combination of hydrologic soil characteristics where the specific soil parameters are dependent upon the rainfall-runoff computation algorithms in the chosen watershed model. For the case of the SEFM watershed model and HEC-1, a modified Holtan equation is used for rainfall-runoff modeling (Section 2.13-1, *Soil Characteristics/Infiltration*). The hydrologic soil parameters for the modified Holtan approach include: surface depression storage; maximum and minimum surface infiltration rate; deep percolation rate; soil moisture storage capacity; and sub-surface storage capacity. These values are subsequently refined through calibration of the hydrologic model using observed climate and streamflow data. Other hydrologic models in SEFM, such as the UBC or Sacramento models, utilize the infiltration/runoff equations native to those models.

1-6 HYDROMETEOROLOGICAL COMPONENTS

A number of hydrometeorological inputs are determined through Monte-Carlo sampling procedures. The hydrometeorological inputs sampled by SEFM depends on the chosen hydrologic model. Continuous hydrologic models such as Continuous Holtan and the UBC models utilize a parameter resampling approach to define antecedent precipitation, temperature, soil moisture, and snowpack. The resampling approach is described in detail in Section 208. Antecedent conditions for single-event hydrologic models (SEFM and HEC-1) are defined using Monte-Carlo sampling procedures. The hydrometeorological inputs are listed in the following sections and Table 1-1 identifies the dependencies that are preserved between hydrometeorological parameters. More detailed information about each of the hydrometeorological inputs is contained in Part II of the Manual.

Table 1-1 – Dependencies of Hydrometeorological Parameters

NO.	PARAMETER DETERMINED FROM MONTE-CARLO SAMPLING	DEPENDENCY	APPLICABLE HYDROLOGIC MODELS	VARIES BY ZONE
1	Date of Storm Occurrence	Independent	All	
2	Antecedent Precipitation	1	SEFM, HEC-1	Mean Annual Precipitation
3	Antecedent Temperature	1	SEFM, HEC-1	Elevation
4	Antecedent Snowpack	1 and 2	SEFM, HEC-1	Mean Annual Precipitation, Elevation
5	October 1st Soil Moisture	Independent	SEFM, HEC-1	Mean Annual Precipitation, Soils
6	Antecedent Soil Moisture	1, 2, 4 and 5	SEFM, HEC-1	Mean Annual Precipitation, Elevation, Soils
7	Initial Streamflow	1 and 2	All	
8	Initial Reservoir Level	1 and 2	All	
9	Precipitation Magnitude-Frequency	Independent	All	
10	Storm Temporal Characteristics	Independent	All	
11	Storm Spatial Characteristics	Independent	All	
12	Storm Centering	Independent	All	
13	1000-mb Air Temperature During Storm	1	All	
14	Freezing-Level During Storm	1 and 9	All	
15	Air Temperature During Storm	1, 9, 13 and 14	All	Elevation

1.6-1 Probabilistic Inputs for Initial Watershed Conditions

Date of Occurrence of Extreme Storms – is the mid-month or end-of-month date for the occurrence of the extreme storm. It is based on the seasonality of extreme storms as depicted by the distribution of the historical occurrences of the storm type being simulated.

Antecedent Precipitation – is the total precipitation from the start of the water-year (October 1st) until the given date of storm occurrence for locations within a specified zone of mean annual precipitation. It is used in computing soil moisture budgets and can be used as an explanatory variable in correlation relationships with other hydrometeorological parameters.

Antecedent Snowpack – is the snow-water equivalent for specified zones of mean annual precipitation and elevation for a given date of storm occurrence.

Soil Moisture at Start of Water-Year – is the soil moisture for the start of the water-year (October 1st) for a specified HRU. It is used for computing soil moisture budgets throughout the watershed.

Antecedent Soil Moisture – is the soil moisture at the onset of the extreme storm for a specified HRU. It is obtained through soil moisture accounting that addresses antecedent precipitation, evaporation, moisture held in the snowpack, and moisture losses due to runoff based on the soil moisture storage capacity for the specified HRU.

Antecedent Temperature – is the average temperature in the two-week period prior to the selected date of storm occurrence. It is used for checking for frozen ground conditions in each HRU.

Antecedent Streamflow – is the streamflow at the onset of the storm proportioned to sub-basins throughout the watershed.

Initial Reservoir Level – is the reservoir level at the onset of the storm.

1-5.2 Probabilistic Inputs Related to the Occurrence of the Extreme Storm

Stochastic simulation of the temporal and spatial distribution of extreme storms is the most complex component of the Stochastic Event Flood Model. Storms are simulated using the conventional practice of scaling a storm shape pattern (precipitation time-series) by a precipitation magnitude for a duration that is compatible with the hydrologic response time for the watershed and reservoir.

The following general descriptions of the stochastic storm elements provide an overview of the stochastic storm generation process. More detailed descriptions and discussions are presented in Part II of this manual.

Precipitation Magnitude-Frequency – The precipitation magnitude-frequency relationship used for scaling of storm temporal and spatial patterns is developed based on regional analyses of precipitation annual maxima for precipitation gages within the project watershed and in climatologically similar areas. The findings of spatial analyses of historical storms are used to develop a relationship between point precipitation and watershed-average precipitation for use in developing the watershed-average precipitation-frequency relationship. An example watershed precipitation-frequency relationship is shown in Figure 1-3.

The duration of precipitation is chosen based on the hydrologic response time of the watershed and reservoir. This may result in storm events ranging from several hours to several days. Precipitation durations of 48-hours and 72-hours have commonly been used in prior applications of SEFM for scaling of synoptic-scale storm temporal and spatial patterns. A duration of 6-hours is commonly used for mesoscale storm events with embedded convective cells such as MCCs and a 2-hour duration is commonly used for small-scale local storms on small watersheds.

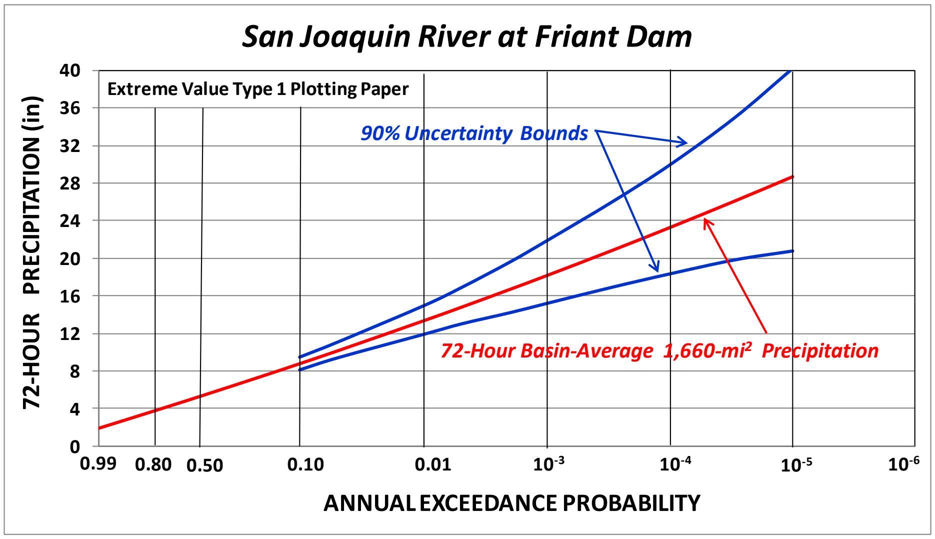


Figure 1-3 – Example Watershed Precipitation-Frequency Relationship for Friant Dam on the San Joaquin River in Southern California

Precipitation Temporal and Spatial Characteristics – A resampling approach is used for simulating the spatial characteristics of storms. In the resampling approach, a storm temporal pattern is selected from a catalog of storms (typically 10 to 20) using Monte-Carlo sampling procedures. The selected storm is then scaled to the desired magnitude using the storm magnitude sampled from the precipitation-frequency distribution. This approach maintains the same relative spatial distribution of precipitation across the watershed as occurred in the observed historical storm. An example of a spatial pattern for a historical storm is shown in Figure 1-4 and a basin-average temporal pattern is shown in Figure 1-5.

Storm Centering – The historical storm center is preserved as part of the scaling process for the spatial distribution of precipitation in the storm resampling approach.

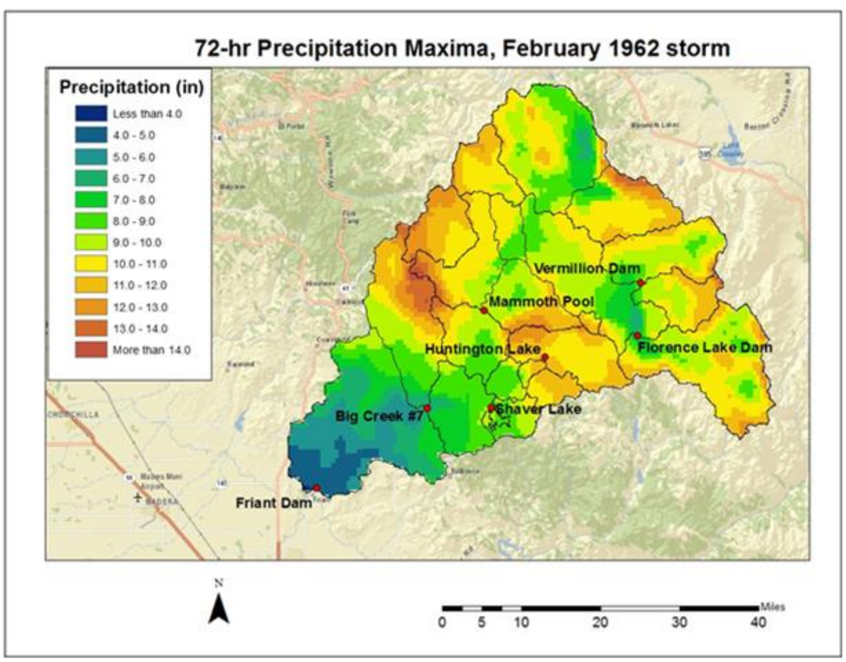


Figure 1-4 – Example Spatial Pattern of 72-Hour Precipitation Storm of February 9-11, 1962 on the Friant Watershed

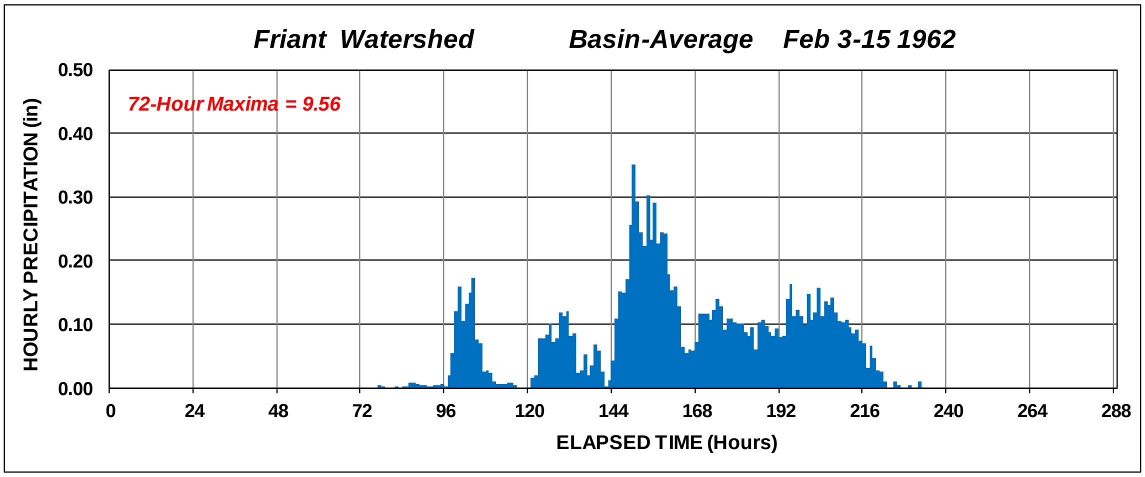


Figure 1-5 – Example Basin-Average Temporal Precipitation Pattern
for the Storm of February 9-11, 1962 on the Friant Watershed

1-5.3 Inputs Related to Rainfall-Runoff Modeling

A modified Holtan[19] infiltration equation is used in the SEFM watershed model and in the legacy HEC-1 watershed model. Rainfall-runoff computations are accomplished in two stages. First, surface runoff is computed based on a surface infiltration rate using an exponential type decay function where the surface infiltration rate is dependent on the magnitude of soil moisture. Next, interflow runoff is computed based on a deep percolation rate. Separate rainfall-runoff computations are conducted for each HRU to reflect the site-specific climatic and soil conditions. The runoff from each HRU is aggregated to the sub-basin level and surface and interflow unit hydrographs are used to compute the surface and interflow flood hydrographs. Inputs for rainfall-runoff modeling are described below.

Interception **–** is the depth of precipitation which is retained by vegetation on plants and trees.

Surface Depression Storage **–** is the depth of precipitation which is held in surface depressions. This element is commonly used in high-elevation alpine areas of mountains where pot-holes and small lakes occur as closed depressions without an outlet.

Maximum Surface Infiltration Rate **–** is the maximum rate at which the soil can accept water at the soil surface for a specified soils zone. This occurs when the soil is at the wilting point having been desiccated by evapotranspiration.

Minimum Surface Infiltration Rate **–** is the limiting rate at which the soil can accept water at the soil surface for a specified soils zone. This occurs when the soil is fully wetted and soil moisture is at field capacity or higher.

Deep Percolation Rate **–** is the limiting rate that a soil layer, hardpan within the soil column, or underlying bedrock can accept water that has infiltrated the surface of the soil for a specified soils zone. Water that passes through this limiting soil layer, hardpan, or bedrock contributes to groundwater and does not return to the stream during the time interval for modeling of the extreme flood.
Soil Moisture Storage Capacity **–** is the moisture holding capacity of the soil column to the depth that can be affected by evapotranspiration.

***Sub-Surface Storage Capacity* –** is the moisture holding capacity of depressions and hollows in the sub-surface bedrock including soil-filled fractures in the sub-surface bedrock. This situation is common in mountainous areas in the western U.S. and is evidenced by little to no runoff being generated by storms at the start of the fall storm season. This type of sub-surface depression storage is filled by precipitation from storms following the warm growing season where evapotranspiration from deep-rooted trees and plants have removed the moisture from the sub-surface depressions.

***Evapotranspiration* –** is the average monthly potential evapotranspiration amount for a specified zone of mean annual precipitation.

Temperatures during Extreme Storms used for Snowmelt Computations – is the temporal time-series of temperatures during the occurrence of the storm for a specified elevation zone that is used for computing snowmelt runoff.

***Surface Runoff* –** Unit hydrographs are used to convert the computed surface runoff volume from each sub-basin into a flood hydrograph. Surface runoff unit hydrographs are determined based on calibration to observed floods.

***Interflow Runoff* –** Linear reservoir routing methods are used to convert the computed interflow runoff volume from each sub-basin into a flood hydrograph. Interflow runoff hydrographs are generated with a two-stage linear reservoir model that is calibration to observed floods.

***Reservoir Routing and Dam Operations* –** reservoir operations are simulated consistent with standard operating procedures for the project under study. The computer program is currently set up to use the reservoir routing features of the HEC-1 model or to use the USBR computer program FLDRT. Each month may have a separate reservoir operation rule curve and stage-storage-discharge relationship. Project-specific modules can also be developed to simulate more complicated operational procedures.

1-6 SIMULATION PROCEDURE

One of the key features of the stochastic model is the use of Monte Carlo simulation methods (Jain[26], Salas et al[47]) for selecting the magnitude and combination of hydrometeorological input parameters for computation of floods. While the individual elements of the model can be complex, the basic concepts used in the simulation are straightforward. A flowchart for the stochastic simulation procedure is depicted in Figure 1-2 and the basic concepts of the simulation procedure are described below.

1-6.1 Construction of Flood Magnitude-Frequency Curves using Probability-Plot Methods

A comparison with traditional flood-frequency analysis can be used to obtain a perspective on the approach used with the stochastic model for constructing flood hydrologic hazard curves. The primary focus in traditional flood-frequency analysis is flood peak flow. In conducting an at-site frequency analysis for peak flow, the basic steps are to: collect an annual maxima series dataset for the period of record; view the magnitude-frequency characteristics of the data by constructing a probability-plot using a standard plotting position formula to estimate annual exceedance probabilities; and fit a probability distribution to the annual maxima data in attempting to capture the statistical information contained in the dataset. Flood peak flow magnitude-frequency estimates are then made using the estimated distribution parameters for the fitted probability model.

If an extremely long period of flood record were available (multi-thousand years of flood peak flow annual maxima in a stationary environment), then a plotting position formula and probability-plot would be sufficient for capturing the frequency characteristics for all but the rarest flood events within the dataset. The computer simulation of multi-thousand years of flood annual maxima provides a flood record analogous to the latter case described above. With that in mind, the basic construct for the Monte Carlo simulations are listed in Figure 1-6 and can be described as follows.

An extremely long record of basin-average precipitation annual maxima is generated for a user-specified duration using Monte Carlo sampling procedures (assuming stationary climate). A storm is stochastically generated for each of the precipitation annual maxima with the spatial characteristics scaled to yield the basin-average precipitation and with storm temporal patterns scaled to yield the sub-basin precipitation amounts. A storm date (month and day) is selected for the date of storm occurrence. Hydrometeorological parameters (inputs) are then selected to accompany each storm based on the historical record in a manner that preserves the seasonal characteristics and dependencies between parameters. The storms and all other hydrometeorological parameters associated with the storm events are then used to generate an annual maxima series of floods using rainfall-runoff modeling. Characteristics of the simulated floods such as peak flow, runoff volume, maximum reservoir level and reservoir discharge are ranked in order of magnitude and a non-parametric plotting position formula and probability-plots are used to describe the hydrologic hazard curves as illustrated in Figures 1-1a,b,c.

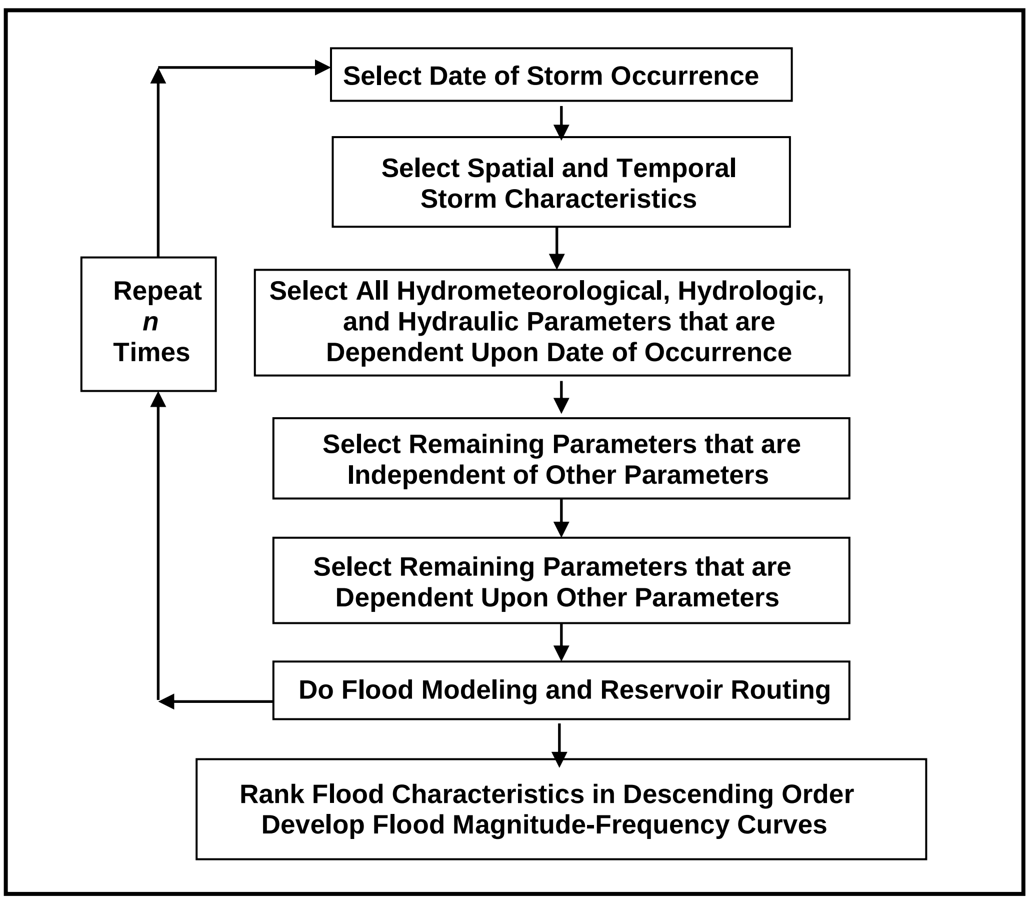


Figure 1-5 – Flow Chart for Stochastic Simulation Approach

1-6.2 Simulation Run Lengths and Simulation Options

Two options for conducting simulations are provided in SEFM. The first option is used when rare floods are of interest but extreme floods with very low annual exceedance probabilities are not needed. The second option utilizes the total probability theorem for development of hydrologic hazard curves for flood characteristics of interest.

All hydrometeorological inputs generated by Monte Carlo procedures are stored in a *Microsoft Access* database[34]. Likewise, all of the flood outputs generated by the watershed model are stored in the database. The model outputs are retrieved from the database by the SEFM post-processor as part of the standard process for analyzing the outputs for flood peak flow, runoff volume, maximum reservoir level, reservoir outflow, etc. Thus, the only constraint on the number of simulations is the practical limitation of the amount of time required to conduct the simulations.

<u>Record Length Simulation Approach</u>

In the *Record Length Simulation Approach*, the number of simulations is selected sufficient to provide reasonable reliability in assessing the flood characteristics for the target Annual Exceedance Probability (AEP). For example, if the interest is in flood characteristics for an (AEP) of 1:1,000, then a simulation of say 5,000 annual maxima could be used. The sample size of 5,000 would reduce the effects of sampling variability and increase the reliability of the estimate of the 1:1,000 AEP. Multiple simulations with a record length of 5,000 could be conducted to provide an improved estimate of the mean frequency curve at the target AEP of 1:1,000.

This option provides flood outputs for development of standard probability-plots of flood characteristics and also provides complete sample sets of flood annual maxima that can be used in a standard flood-frequency analysis. In particular, this type of approach is used in calibration of the SEFM model to the historical flood-frequency curve. Calibration will be discussed in detail in a later section. A flowchart describing this procedure is shown in Figure 1-5 and the procedures for conducting simulations using this approach are explained in detail in section 2-21, *Flood Simulations*.

<u>Total Probability Simulation Approach</u>

The *Total Probability Simulation Approach* is provided to reduce the number of simulations and associated computation time when the interest is in floods with very low annual exceedance probabilities. This second option uses the total probability theorem (Nathan et al[x]) wherein the [0-1] probability space for watershed precipitation-frequency relationship is sub-divided into intervals and numerous flood simulations are generated within each probability interval. The total probability theorem is then used to compute the hydrologic hazard curve which is depicted as a probability-plot for each flood characteristic of interest. This approach uses the upper loop in the simulation procedures (Figure 1-5) for storm/flood simulations within each of the precipitation intervals.

This second option does not produce an annual maxima data series suitable for conventional flood-frequency analysis. However, the SEFM post-processor module provides flood characteristics for selected AEPs that can be used in failure mode analyses and in fragility analyses for risk analyses. The procedures for conducting simulations using this approach are explained in detail in section 2-21, *Flood Simulations*.

PART II - HYDROMETEOROLOGICAL INPUTS AND DATA ENTRY

The following sections in Part II describe the hydrometeorological inputs in greater detail. Information is provided about the assumptions, expectations, and operation of the SEFM in utilizing the hydrometeorological inputs. Guidance and experience information is also provided to assist the user in selecting the manner in which the probabilistic analyses of the various hydrometeorological components are to be conducted. Example data entry screens are presented to assist in input of the parameters needed for operation of the computer model.

Underlying Assumptions/Expectations and Considerations – Probabilistic analyses are required to determine the parameters needed for describing many of the hydrometeorological components. A number of assumptions/expectations are inherent in the application of those analyses in the SEFM computer simulations. Several of the assumptions/expectations and considerations that are common to all analyses and computer simulations are listed below:

- It is expected that the statistical characteristics of hydrometeorological variables for conditions experienced in the period of analysis will be representative of conditions in the future period of interest, typically the lifespan of the project, e.g. 50- to 100-years.

- Wherever practical, regional approaches are used in the analysis of historical data to increase sample sizes and reduce uncertainties arising from sampling variability.

- Wherever practical, information about the physics of the hydrometeorological processes has been incorporated into the simulation procedures to augment the probabilistic information obtained from analyses of the historical data. This physics-based information is usually incorporated by placing limits on the range or magnitude of a hydrometeorological input.

- Unless specified otherwise, Monte Carlo sampling of hydrometeorological variables is limited to exceedance probabilities in the range from 0.998 to 0.002. This allows simulation of rare values but avoids excessive extrapolation of frequency curves and correlation relationships that are developed from sample sizes commonly available for data analysis. Sampling of precipitation magnitude is an important exception. Regional precipitation-frequency analyses utilizing very large datasets provide a robust framework that allows for Monte Carlo simulation of very rare storm magnitudes with exceedance probabilities in the range of 10^{-3} to 10^{-6}.

- Users are encouraged to conduct uncertainty analyses to develop a mean-frequency curve and uncertainty bounds for each hydrologic hazard curve. The uncertainty bounds provide important context for decision-making in application of the findings of the stochastic flood analyses.

- It is expected that the statistical characteristics of those hydrometeorological variables that are measured at end-of-month dates (such as historical snowpack) can be used to estimate the statistical characteristics for mid-month dates that are midway between adjacent end-of-month analyses. This approach allows computer simulations to be conducted twice-monthly on both mid-month and end-of-month dates and provides for representative sampling for seasonal differences.

2-0 SIMULATION OPTIONS FOR HYDROMETEOROLOGICAL INPUTS

There are two options for Monte Carlo simulation of hydrometeorological inputs used by the SEFM stochastic engine. These include standard Monte Carlo simulation methods and resampling methods. Both methods are briefly discussed in the following sections.

2-0.1 Standard Monte Carlo Simulation Methods

Standard Monte Carlo simulation methods (Jain[26], Salas et al[47]) are used for generation of some hydrometeorological inputs. This approach generally consists of assembly of a suitable dataset for the hydrometeorological variable, statistical analysis of the hydrometeorological variable of interest and developing a probability distribution(s) and/or probabilistic relationships with other physical or climatic measures or other hydrometeorological variables.

For the case on an independent hydrometeorological variable, standard Monte Carlo simulation procedures are used to generate values from the fitted probability distribution. For the case where a hydrometeorological parameter is correlated with another variable, Monte Carlo simulation procedures are used that preserve the correlation between the two variables and include a random term to account for the natural variability (unexplained variance) component.

For example, the maximum freezing level during a winter storm is an important hydrometeorological component for computing snowmelt runoff and determining if precipitation falls as rain or snow at a given elevation in a watershed. The maximum freezing level during a long-duration synoptic scale mid-latitude cyclone on the west coast of the U.S. is related to both the month of occurrence and the magnitude of the maximum 24-hour precipitation during the storm. Monte Carlo simulation methods are used in SEFM for stochastic generation of the maximum freezing level which accounts for the month of occurrence, the maximum 24-hour precipitation during the storm and the unexplained variance in the relationship.

2-0.2 Resampling Simulation Methods

Resampling is a type of Monte Carlo simulation where values of a hydrometeorological variable are selected at random from a dataset of observed values of that hydrometeorological dataset. This is often a simple and convenient approach to stochastic generation of values of hydrometeorological variables, particularly for complex situations where multiple variables are inter-related. The suitability of this approach improves as the dataset(s) of the observed variable(s) increase in size and the sample becomes more representative of the behavior of the hydrometeorological variables. In some cases, synthetic data can be generated to augment the observed values and to provide representative values at both the low and high ends of the data range where few or no observations are available in the historical record.

The initial reservoir elevation at the start of the simulation provides an example of a resampling method in SEFM. It is generally expected that reservoir level tracks, to some extent, the seasonal variation of antecedent precipitation. Reservoir levels will generally be higher in wet years than in dry years and there is often a large human component wherein reservoir operating procedures are imposed.

Resampling for initial reservoir elevation can be executed as follows. A dataset of reservoir levels would be assembled comprised of the time-series of observed mean daily reservoir levels. Another dataset of antecedent precipitation would be assembled comprised of the cumulative precipitation for a representative precipitation station in the watershed measured from some reference date such as the start of the water-year (October 1st). The two datasets would be merged to provide linkage between reservoir elevation and antecedent precipitation for a common date. A probability distribution would be fitted to the antecedent precipitation data for each mid-month and end-of-month during the storm season (up to 24 probability distributions for the year). In the simulation procedures, a storm date (month and day) would first be selected (see flowchart in Figure 1-5), and then a value of antecedent precipitation for the selected mid-month or end-of-month would be generated from the appropriate probability distribution using standard Monte Carlo sampling procedures. A year within the available reservoir data range would then be selected with antecedent precipitation similar to the sampled antecedent precipitation in the first step to provide a complete date (month-day-year) and the initial reservoir level would be selected from the linked dataset for that date. These procedures would preserve the seasonal relationship for initial reservoir elevation that accounts for antecedent precipitation, reservoir operations and natural variability.

2-0.3 Use of a Continuous Watershed Model for Resampling

The choice of a watershed model that can conduct flood simulations in both continuous and event modes provides the opportunity for extensive use of resampling methods. Continuous watershed models can generate long time-series of soil moisture conditions, snowpacks, streamflows and reservoir levels that are linked by the common date.

This allows watershed state variables for these hydrometeorological variables to be stored where the date provides the seasonal linkage and the collective dataset reflects variability in antecedent precipitation for the watershed and sub-basins. This format allows many of the hydrometeorological inputs to be resampled from the linked datasets after a storm date and year are selected (see flowchart Figure 1-5). This is an attractive approach that preserves many of the complex inter-relationships between the hydrometeorological variables. The watershed model would still be executed in event mode for flood simulations to reduce computation time for the multi-thousand flood-simulations.

2-1 WATERSHED LAYOUT - HYDROLOGIC RUNOFF UNITS (HRU'S)

A key element in the stochastic approach is the selection of realistic initial hydrometeorological conditions in the watershed at the onset of a storm. This requires that a distributed approach be used in modeling the rainfall-runoff process so that the spatial variability of soil moisture, soil moisture storage characteristics, soil infiltration rate, snowpack, and the possibility of frozen ground conditions can be properly considered in computing runoff.

To accommodate the distributed approach, the watershed is divided into numerous sub-areas. These sub-areas are comprised of polygons of land area, termed Hydrologic Runoff Units (HRUs) that have common mean annual precipitation, elevation, and soil infiltration characteristics. Runoff is computed separately for each HRU and then aggregated to the sub-basin level to obtain the runoff response of each sub-basin. An example depiction of HRUs is shown in Figure 2-1.5.

2-1.1 Delineation of Mean Annual Precipitation Zones

Mean Annual Precipitation (MAP) often varies widely across mountainous watersheds. This spatial variability requires that a watershed be sub-divided into zones of similar mean annual precipitation to facilitate the allocation of antecedent precipitation, allocation of winter snowpacks, and computation of soil moisture budgets.

SEFM Operation – Hydrologic computations that utilize zones of mean annual precipitation are based on the median value of the mean annual precipitation in each zone.

Guidance and Experience – Sufficient zones should be employed to adequately describe the variability of monthly antecedent precipitation, snowpack, and soil moisture that occurs due to differences in the magnitude of monthly and annual precipitation.

The PRISM Climate Group[41] has developed maps of mean annual precipitation for the United States and Canada for the 1981-2010 period using their PRISM[9,10] model (Figure 2-1.1). PRISM is an expert system that uses point and digital elevation model data to generate gridded estimates of climate parameters. It is highly recommended that those maps be used for delineation of zones of mean annual precipitation for the SEFM. An example delineation of mean annual precipitation zones is shown in Figure 2-1.2 for the American River watershed in central California along with tabular listing of values shown in Table 2-1.

Table 2-1 – Zones of Mean Annual Precipitation for the American River Watershed

MEAN ANNUAL PRECIPITATION (Inches)											
Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Range	20-28	28-32	32-36	36-40	40-44	44-48	48-52	52-56	56-60	60-64	64-72
Median	26 in	30 in	34 in	38 in	42 in	46 in	50 in	54 in	58 in	62 in	67 in
Area (mi^2)	29.2	75.6	125.5	100.0	100.6	279.8	356.8	242.7	195.1	198.8	154.1
Area (%)	1.6%	4.1%	6.8%	5.4%	5.4%	15.1%	19.2%	13.1%	10.5%	10.7%	8.3%

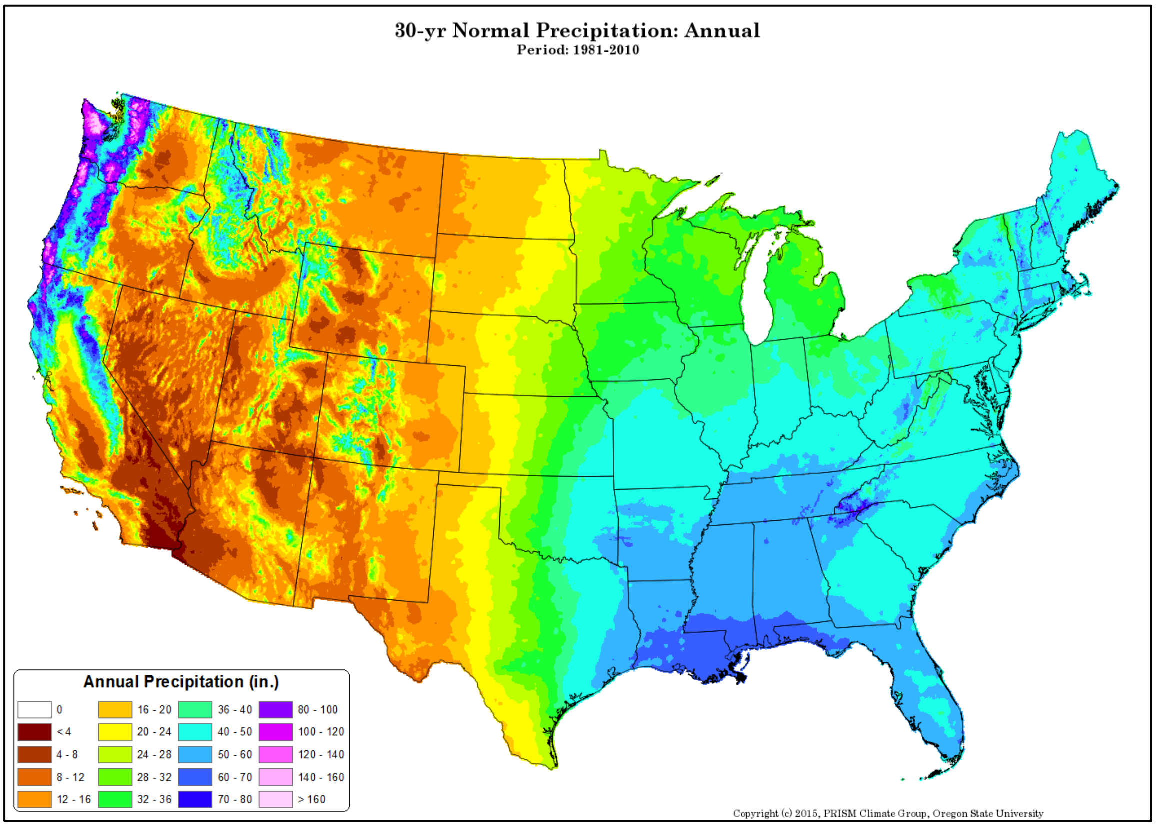


Figure 2-1.1 – PRISM Map of Mean Annual Precipitation
Courtesy of PRISM Climate Group, Oregon State University

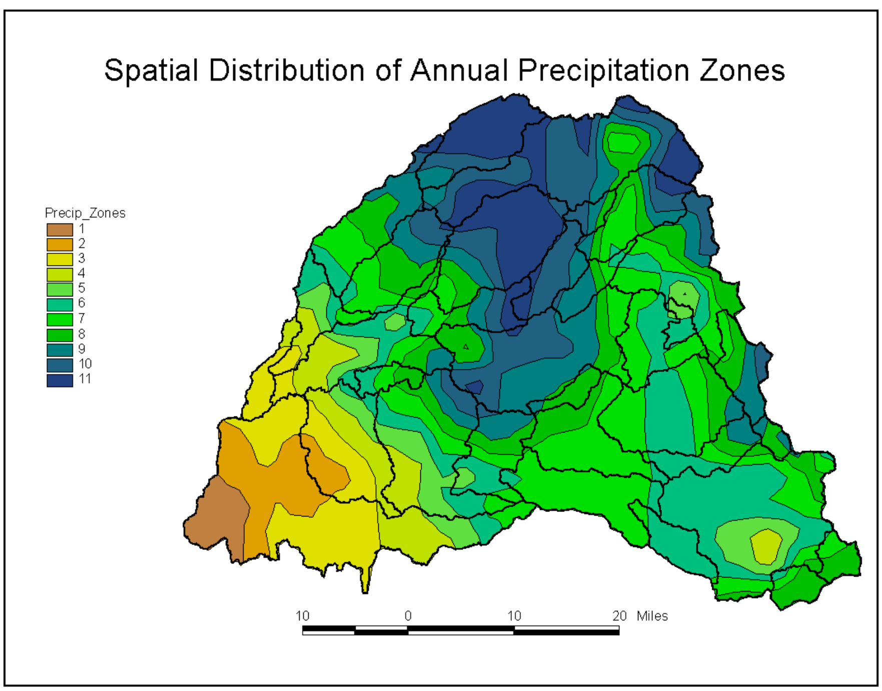


Figure 2-1.2 – Zones of Mean Annual Precipitation for American River Watershed, CA

2-1.2 Delineation of Elevation Zones

Elevation information is needed in allocating snowpack, application of evapotranspiration, and to account for temperature changes that occur with elevation in mountain areas. This information is required for soil moisture accounting, snowmelt computations and for checking for frozen ground conditions.

SEFM Operation – Hydrologic computations that utilize zones of elevation are based on the median elevation in each zone.

Guidance and Experience – Selection of upper and lower bounds for each of the elevation zones should be based on a hypsometric curve for the watershed to ensure proper apportioning of areas. This is particularly important where elevation anomalies such as escarpments or widespread plateaus are present in the watershed. If the hypsometric curve (elevation-area relationship) does not have abrupt changes in slope, elevation increments of 500-1,000 feet may be used as is common practice in hydrologic modeling.

Elevation information is available from USGS topographic maps and Digital Elevation Model (DEM) data. It is recommended that smoothing routines be used to developed smooth elevation contours to avoid excessive crenulation. This smoothing helps to reduce the number of individual polygons that result when zones of mean annual precipitation, elevation, and soils are intersected to identify HRUs.

DEM information at a scale of 1:24,000 was used to develop the elevation zones for the American River watershed depicted in Figure 2-1.3 and tabular values are listed in Table 2-2.

Table 2-2 – Elevation Zones for the American River Watershed

ELEVATION ZONES (Feet)									
Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Range	300-2400	2400-3200	3200-4000	4000-4800	4800-5600	5600-6400	6400-7200	7200-8000	8000-12000
Median	2000 feet	2800 feet	3600 feet	4400 feet	5200 feet	6000 feet	6800 feet	7600 feet	8400 feet
Area (mi^2)	424.5	194.0	175.1	206.4	244.0	224.5	193.7	126.9	69.2
Area (%)	22.8%	10.4%	9.4%	11.1%	13.1%	12.1%	10.4%	6.8%	3.7%

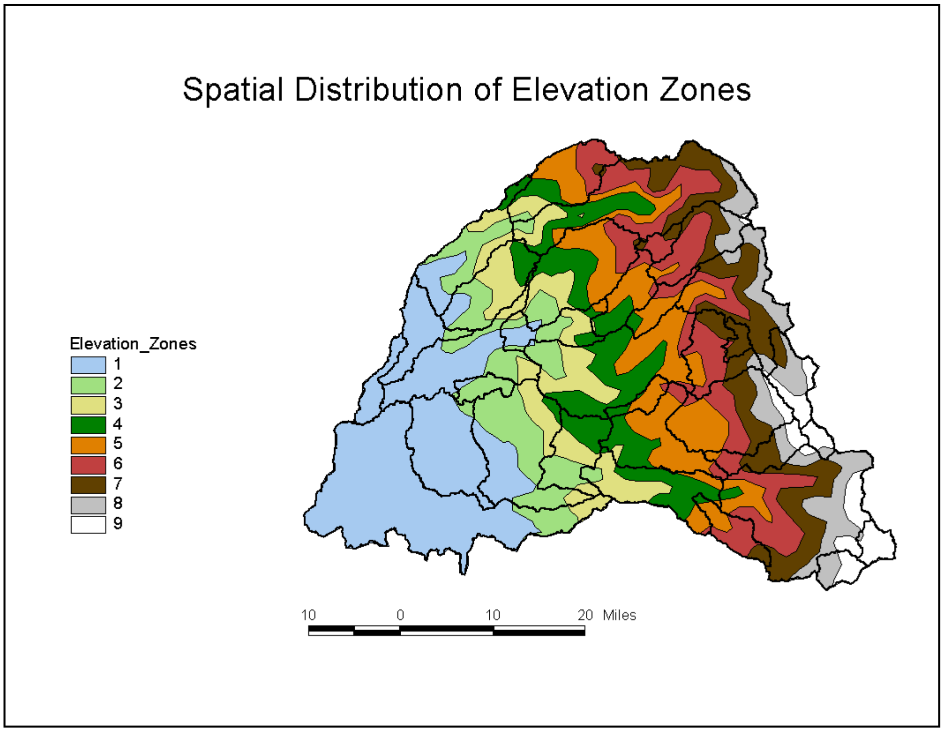


Figure 2-1.3 – Elevation Zones for American River Watershed, CA

2-1.3 Delineation of Soil Zones

Soil zones are used to delineate contiguous areas with similar hydrologic soil characteristics. SEFM can accommodate up to ten soil zones, where each soil zone represents a unique combination of depression storage, maximum and minimum surface infiltration rate, deep percolation rate, soil moisture storage capacity and sub-surface storage. Preliminary information about the soil characteristics in a watershed can be obtained from the NRCS SSURGO and STATSGO databases[66]. The soil properties for a soil zone should subsequently be refined through calibration of the hydrologic model using observed climatic and streamflow data.

SEFM Operation – Hydrologic computations that utilize soils zones are based on the hydrologic soil characteristics for the particular zone.

Guidance and Experience – Soils information is available from the Natural Resources Conservation Service (NRCS), US Geological Survey, and state agencies. The NRCS maintains three GIS compatible soil databases; Soil Survey Geographic (SSURGO), State Soil Geographic (STATSGO) and the National Soil Geographic (NATSGO). The SSURGO database provides the most detailed level of information and contains mapping at scales from 1:12,000 to 1:63,360. STATSGO was designed for regional, large river basin or multi-county scale analyses. STATSGO soils data is mapped at a resolution of 1:250,000. The information in STATSGO is based on more detailed surveys that have been aggregated to larger areal units. The NATSGO database contains data with the coarsest resolution at 1:2,000,000.

A soil survey for any large area will typically encompass numerous NRCS soil associations. It will normally be necessary to group several soil associations (having similar soil characteristics) together in forming a soil zone to reduce the number of soil zones to a manageable number. The soil properties for a soil zone should subsequently be refined through calibration of the watershed model using observed climatic and streamflow data. An examples of GIS mapping of soil zones determined through STATSGO are shown in Figure 2-1.4 and tabular values are listed in Table 2-3.

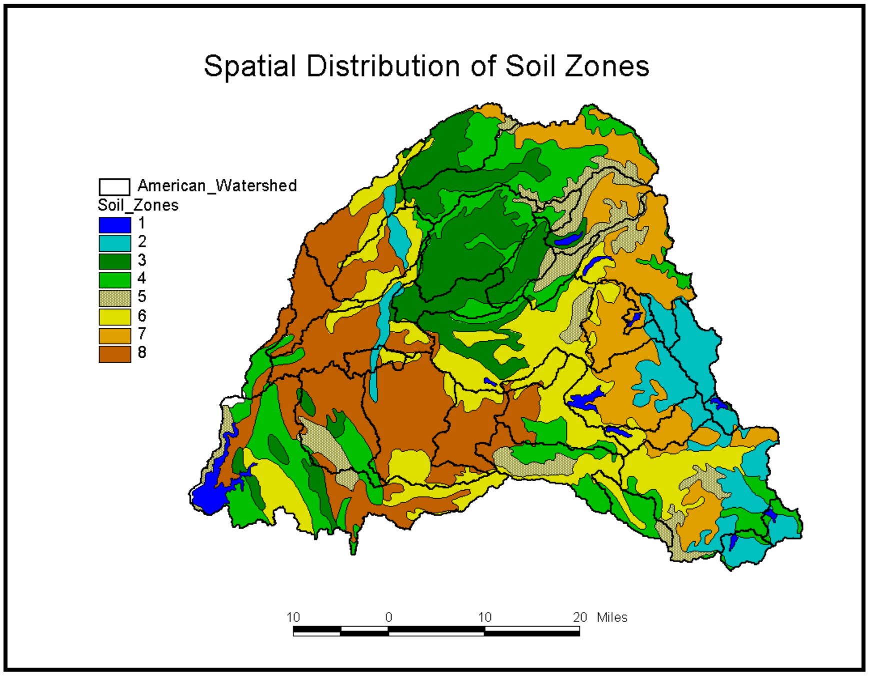


Figure 2-1.4 – Delineation of Soil Zones for American River Watershed, CA

Table 2-3 – Final Calibrated Parameter Set of Soil Characteristics for American River Watershed

SOIL ZONE	MEDIAN SOIL DEPTH (in)	(f_d) DEEP PERCOLATION (in/hr)	(f_c) MINIMUM SURFACE INFILTRATION (in/hr)	(f_{max}) MAXIMUM SURFACE INFILTRATION (in/hr)	(S_{max}) EFFECTIVE SOIL MOISTURE STORAGE CAPACITY (in)	COMMENTS
1	0	0.000	0.000	0.0	0.0	water bodies
2	5	0.022	0.071	3.2	3.8	very shallow soils over bedrock
3	15	0.016	0.071	3.2	11.3	
4	25	0.048	0.100	3.2	9.1	
5	35	0.023	0.065	3.2	13.7	
6	50	0.035	0.094	3.2	20.4	
7	36	0.023	0.060	3.2	12.6	underlain by deep outwash soils
8	40	0.078	0.136	3.2	17.1	Underlain by fractured and/or vertically tilted bedrock

2-1.4 Delineation of Sub-Basins

In watershed modeling, sub-basins are selected based on a variety of considerations. It is common in hydrologic modeling that sub-basin boundaries are chosen in a manner to best provide for hydrologic homogeneity. However, the use of the distributed HRU approach essentially eliminates the need to subdivide the watershed for purposes of hydrologic homogeneity.

Considerations in selecting the size of sub-basins and sub-basin boundaries include:

- In allocating the spatial pattern of precipitation, each sub-basin has a uniform precipitation amount applied throughout the sub-basin. Therefore, sub-basins should be sufficiently small to account for the spatial variability of precipitation over the watershed (Figure 1-4) as represented by the collection of sub-basins.
- Sub-basin boundaries should be selected based on the need for obtaining simulated flows from the model at specific locations of interest such as at streamflow gage locations, at junctions of major tributaries, and at the inlet to a reservoir(s). In particular, calibration of the watershed model to historical floods requires that sub-basin outlets or computation nodes coincide with the location of streamflow gages.
- Sub-basins may also be selected in a manner to differentiate areas within the watershed that have different topographic and/or channel hydraulic characteristics that would be reflected in runoff hydrographs or channel routing of the flood.

An example sub-basin layout is depicted in Figure 2-1.6 for the American River watershed in central California. As discussed above, sub-basin boundaries are not required to be coincident with boundaries of HRU polygons. Partial coverage of an HRU on a sub-basin is accounted for through GIS which sums the contribution of each HRU to a given sub-basin.

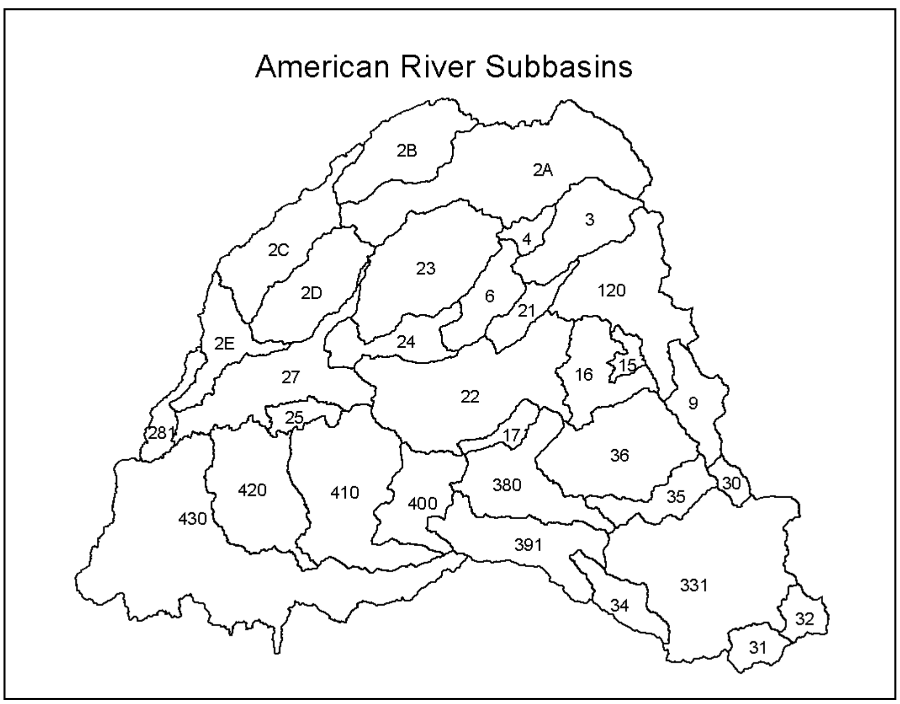


Figure 2-1.6 – Delineation of 33 Sub-basins for American River Watershed, CA

2-1.5 Delineation of Hydrologic Runoff Units (HRUs)

The delineation of the HRU polygons is obtained by intersection of the subbasins, zones of mean annual precipitation, elevation, and soils characteristics. Figure 2-1.5 depicts HRUs for the A.R. Bowman watershed in Oregon. It should be noted that each polygon represents a specific combination of mean annual precipitation, elevation, and soil characteristics, and that a given combination may be repeated for numerous polygons at various locations in the watershed. An example HRU polygon is shown in blue in Figure 2-1.5.

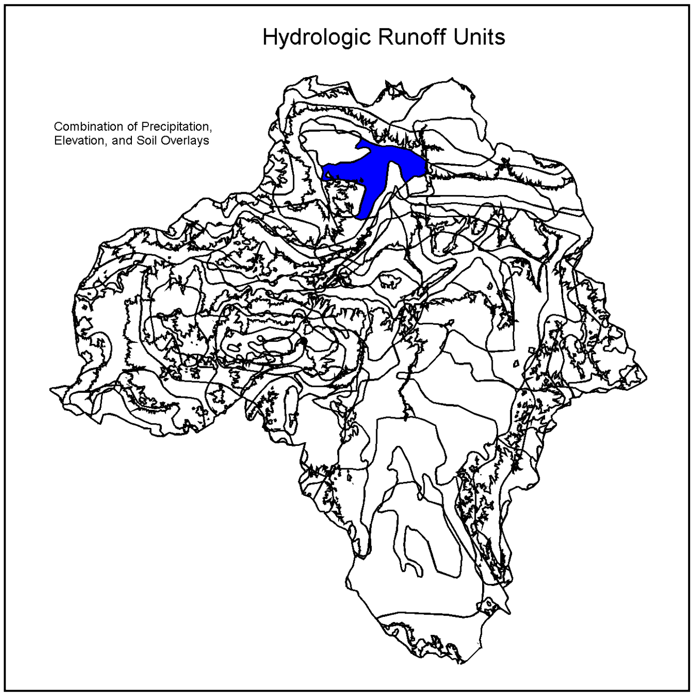
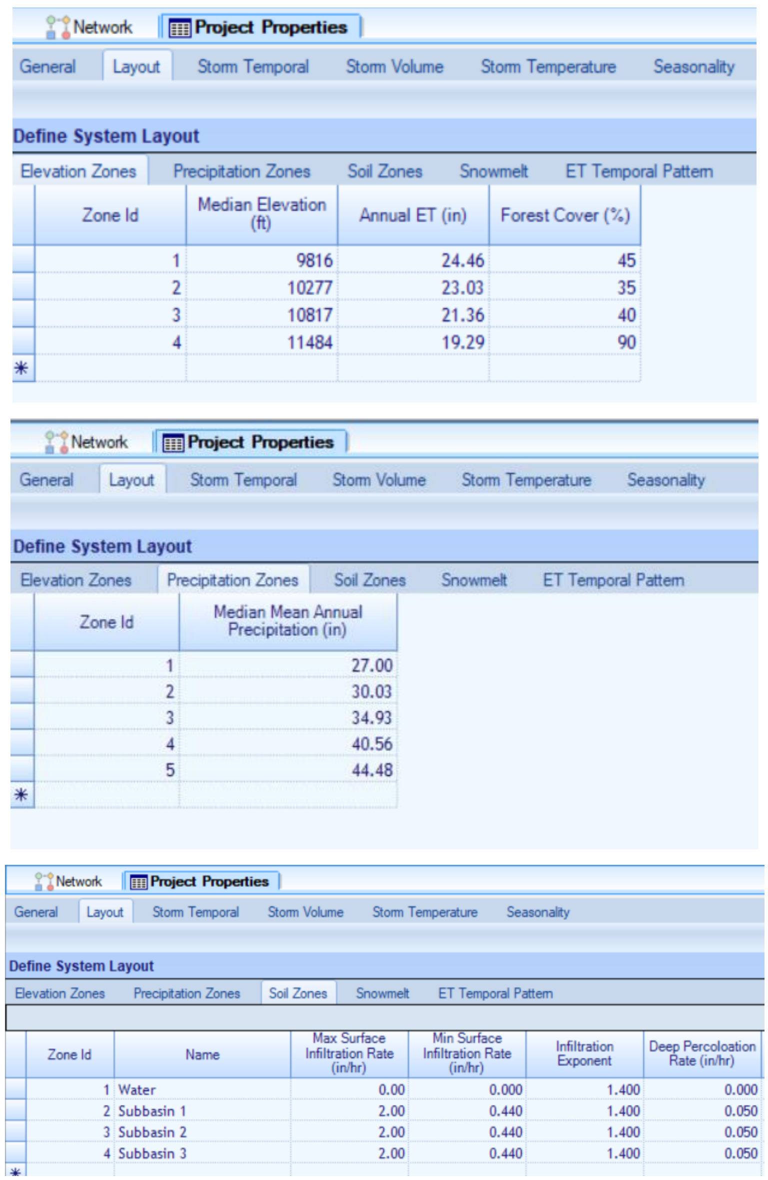


Figure 2-1.5 – Delineation of HRUs for A.R. Bowman Watershed, OR

2-1.6 Data Entry Formats

Data entry includes inputting information for defining the zones of mean annual precipitation, elevation, and soils characteristics on the *Project Properties Screen*. The median value of mean annual precipitation is entered for each zone of mean annual precipitation. The median elevation is entered for each elevation zone. For each soil zone, the values of interception, depression storage, maximum and minimum surface infiltration rate, deep percolation rate, soil moisture storage capacity, and sub-surface storage is entered. Additional information about soils characteristics is described in section 2-13 on *Soil Characteristics/Infiltration.* An example of the data input format for defining the zones of elevation, mean annual precipitation, and soils characteristics is shown in Screen Shot 2-1.1.



Zone Id	Median Elevation (ft)	Annual ET (in)	Forest Cover (%)
1	9816	24.46	45
2	10277	23.03	35
3	10817	21.36	40
4	11484	19.29	90

Zone Id	Median Mean Annual Precipitation (in)
1	27.00
2	30.03
3	34.93
4	40.56
5	44.48

Zone Id	Name	Max Surface Infiltration Rate (in/hr)	Min Surface Infiltration Rate (in/hr)	Infiltration Exponent	Deep Percoloation Rate (in/hr)
1	Water	0.00	0.000	1.400	0.000
2	Subbasin 1	2.00	0.440	1.400	0.050
3	Subbasin 2	2.00	0.440	1.400	0.050
4	Subbasin 3	2.00	0.440	1.400	0.050

Screen Shot 2-1.1 – Example Data Entry for Zones of Elevation, Mean Annual Precipitation, and Soils Characteristics

Data entry is also needed for defining the total area of each HRU in each sub-basin. SEFM can accommodate up to 99 zones of mean annual precipitation, elevation, and soils, although most projects typically have ten or fewer zones for each group. Each unique HRU is identified by a six-digit sequence of zone numbers for elevation, mean annual precipitation, and soil characteristics.

HRU's are developed using Geographical Information System (GIS) tools for intersecting the subbasin, mean annual precipitation, elevation, and soil type layers. The intersected layers are then saved to a comma delimited (.CSV) file that can be imported into SEFM. An Excel template is included with SEFM called *HRUTemplate.xlsx* and can be used to produce the HRU data in the correct .CSV format (Figure Screen Shot 2-1.2)

	A	B	C	D	E
1	EZONE	PZONE	SZONE	area_sq_mi	
2	1	2	1	0.109155	
3	1	2	4	0.507197	
4	1	3	4	0.40569	
5	2	2	4	0.137545	
6	2	3	4	0.489704	
7	3	2	4	0.057403	
8	3	3	4	0.363414	
9	3	4	4	0.208225	
10	3	5	4	0.050195	
11	4	2	4	0.105326	
12	4	3	4	0.316801	
13	4	4	4	0.604808	
14	4	5	4	0.670859	
15					

Screen Shot 2-1.2 – Example HRU Data Entry Format for Importing into SEFM

2-2 SEASONALITY OF EXTREME STORMS

The term *seasonality of extreme storms* is intended to describe the frequency of occurrence of extreme storms on a monthly basis (Figure 2-2.1a and 2-2.1b). An extreme storm is defined as any storm where the precipitation amount for a chosen duration exceeds some specified threshold. The threshold for inclusion of storms in the seasonality analysis is usually chosen as a frequency level (i.e. 10-year recurrence interval) rather than a precipitation amount to provide a common measure of the rareness of a storm. The storm duration used in the seasonality analysis is the same duration that will be used as the key duration (Table 2-2.1) in developing the watershed precipitation-frequency relationship.

Assumptions/Expectations – The seasonality characteristics of extraordinary storms is expected to be the same as the seasonality of the most extreme storms in the observed record.

***SEFM Operation* –** Frequency information about the seasonality of historical extreme storms is used for Monte Carlo selection of the storm date for each storm/flood simulation. Twice-monthly storm dates are possible, mid-month and end-of-month, which are then used for Monte Carlo selection of other hydrometeorological inputs. Use of twenty-four time increments is deemed sufficient for sub-division of the year to depict the natural seasonal variability in hydrometeorological inputs such as soil moisture, snowpack, reservoir level, etc.

Precipitation Magnitudes Not Limited by PMP – Precipitation magnitudes for flood simulations are not limited by Probable Maximum Precipitation (PMP) values. This decision was made based on several considerations. First, there are notable uncertainties in estimates of PMP (Micovic et al[107], which raises the question of what "PMP value" should be used as the upper limit of precipitation? Second, adoption of an uncertain upper limit could significantly bias the estimates of the likelihood of extreme floods. Lastly, the existence of an upper limit to precipitation is an assumption that has never been verified. There are many scientists that contend that precipitation magnitudes are unbounded with extreme precipitation magnitudes becoming less likely as the magnitude increases (Micovic et al[107]). For this situation, the relevant question is - *what is the slope of the precipitation-frequency relationship at the extreme upper end of the precipitation-frequency relationship*? Is the slope sufficiently small, that for engineering applications the change in likelihood is not significant or is the slope sufficient that it must be explicitly considered? For these reasons, the decision was made to not use PMP estimates to limit precipitation magnitudes for flood simulations.

Imposed Constraints – In general, the most extreme storms observed in a region tend to occupy the central body of the seasonality histogram (Figure 2-2.1b). Uncertainties exist in the plausibility of very extreme precipitation magnitudes occurring at the time-of-year represented by the tails of the seasonality distribution (Figure 2-2.1a). This issue was addressed by using the findings from seasonality studies of PMP as guidance in constraining the selection of storm dates for the most extreme precipitation magnitudes.

Imposition of a constraint on storm seasonality is optional in SEFM. One option is to constrain storm dates for precipitation magnitudes that equal or exceed PMP estimates to the months where 100% of PMP is allowed based on NWS Hydrometeorological Reports or site-specific PMP studies. A second option is to allow precipitation magnitudes to exceed PMP estimates for all months based on the findings of the seasonality analysis. Extreme precipitation magnitudes are simply less-likely in the tails of the distribution for this second option.

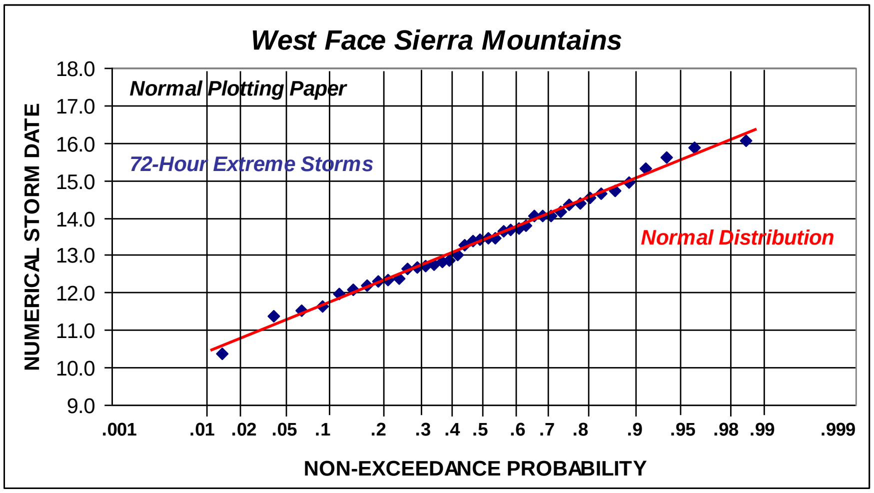


Figure 2-2.1a – Probability-Plot of Seasonality Data for 72-Hour Duration Storms on the West Face of the Sierra Mountains in California

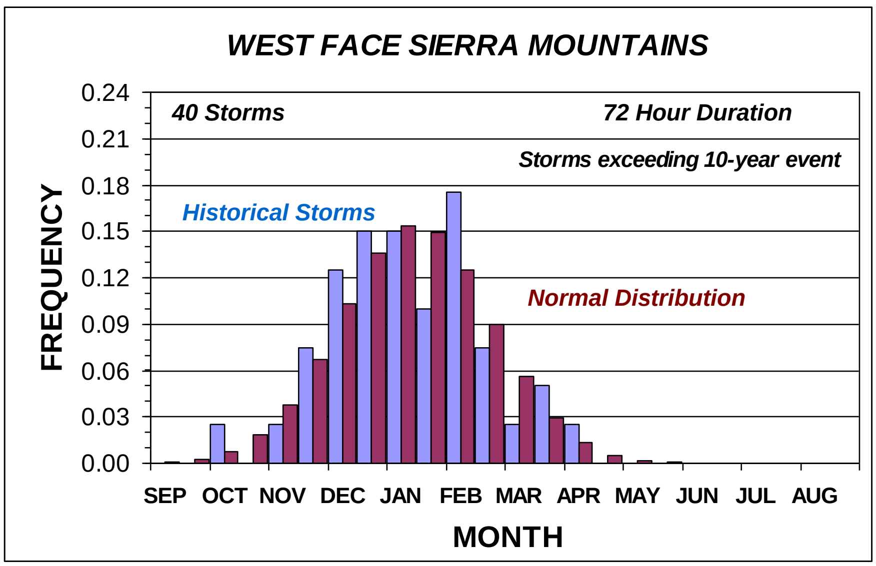


Figure 2-2.1b – Example Seasonality Frequency Histogram for the West Face of the Sierra Mountains, Central California

Guidance and Experience – Seasonality data commonly exhibit irregular shapes when viewed as a frequency histogram. Oftentimes, these irregular shapes are simply the result of sampling variability such as seen in the historical storm data shown in Figure 2-2.1b. In these situations, it is appropriate to fit a probability distribution to the data and to use quantile estimates from the fitted probability distribution to provide a smooth progression into, through, and out of the storm season. An example of this approach is shown by the frequency histogram for the Normal distribution depicted in Figure 2-2.1b based on the Normal probability distribution fitted to seasonality data depicted in Figure 2-2.1a.

In other cases, the seasonality frequency histograms exhibit complex irregular shapes that have a basis in the storm climatology. This often occurs in locations where both a winter and summer storm season are common including a mixed population of storm types. In these situations, the project meteorologist may elect to do minor smoothing of the histogram based on experience in the region and information obtained from other climatic/meteorological sources. Figure 2-2.2 depicts seasonality data for the Upper Columbia Watershed (courtesy of BChydro) with separate cool and warm seasons. Beta distributions have been fitted to the seasonal data, and the probability density functions have been expressed in a frequency histogram format for comparison to the observed data.

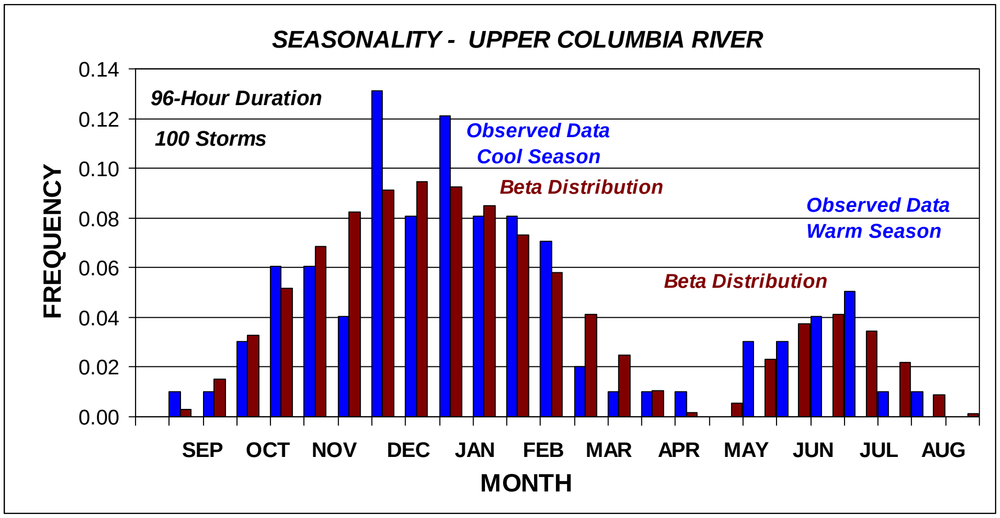
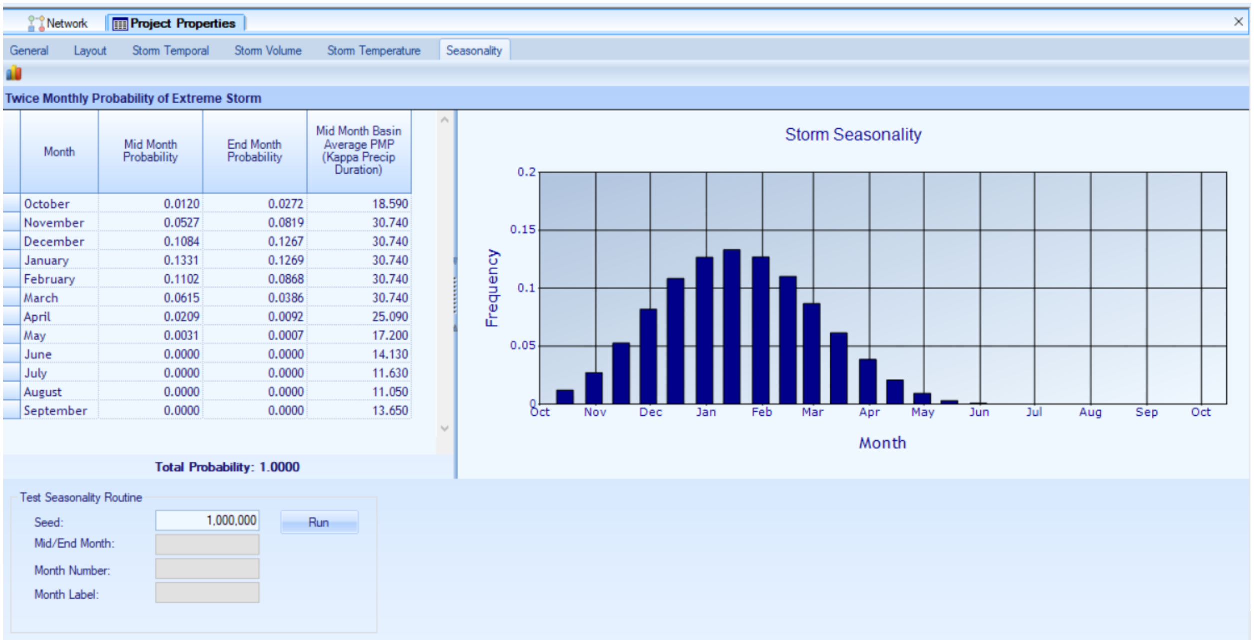


Figure 2-2.2 – Example Seasonality Frequency Histograms Fitted by Beta Distributions

Options for Input of Seasonality Data into the Stochastic Model – Seasonality data are entered into the model using a twice-monthly frequency histogram format to provide flexibility in describing the seasonality characteristics. The use of a histogram format allows for irregular shapes to be entered that may not be amenable to fitting with conventional probability distributions. The histogram may be smoothed/adjusted by meteorologists based on experience and other sources of information.

Data Entry Format – For purposes of analysis and data entry, the calendar year is divided into 24 time intervals with two intervals per month. The data entry begins with the time interval from October 1st through October 15th and ends with the time interval from September 16th through September 30th. The frequency of extreme storms is entered as a frequency histogram with the frequency for each of the 24 intervals entered as a decimal. The 24 twice-monthly probabilities must sum to unity. Screen Shot 2-2.1 depicts the data entry for the frequency histogram corresponding to the Normal Distribution shown in Figure 2-2.1b.

Data entry also includes mid-month basin-average PMP values (inches) for the key duration (Table 2-2.1). Basin-average PMP values are entered for the storm size corresponding to the same watershed area as used for development of the watershed precipitation-frequency relationship. Mid-month PMP values can be obtained from NWS Hydrometeorological Reports for the study area or from site-specific PMP studies.



Screen Shot 2-2.1 – Example Data Entry Format for Seasonality of Extreme Storms

2-2.1 Considerations in Conducting Seasonality Analysis

There are several factors to be considered in conducting a seasonality analysis which includes:

- Storm type and associated storm areal coverage
- Homogeneous region with regard to storm type
- Storm duration
- Threshold for storm selection
- Precipitation gage types available for storm detection
- Number of gages needed for identification of storms to be included in seasonality analysis

Storm Type and Storm Areal Coverage **–** SEFM flood simulations are conducted for a specific storm type and therefore the seasonality analysis must be conducted for a specific storm type. If a watershed is subjected to a mixed population of storm types, a separate application of SEFM is required for each storm type that can produce floods of a magnitude that affect a project of interest. Information on storm typing is described in Section 2.10, *Precipitation Magnitude-Frequency for Storm Generation*.

Synoptic-scale mid-latitude cyclones and tropical storms have large areal coverage and typically have durations of 24-hours and longer. These storm types are readily detectable from the NOAA cooperative network of precipitation stations measuring on a daily basis. By comparison, mesoscale storms with embedded convection such as Mesoscale Convective Complexes (MCCs) have smaller areal coverage where the majority of precipitation typically occurs in a 6-hour time frame. These storm types are identifiable with precipitation measurements from hourly gages and measurements from daily gages do not have the temporal resolution to be useful. Local storms (isolated thunderstorms) typically have very short durations where the majority of precipitation occurs in 2-hours or less and have the smallest areal coverage. Local storms are often identifiable by only one or precipitation measurements at hourly gages.

Homogeneous Climatic Region - The seasonality analysis is conducted using precipitation measurements within a climatologically homogeneous region. Storm types at sites within this homogeneous region would be expected to have the same seasonality characteristics as that of the watershed under study. Meteorologists and climatologists familiar with the study area should identify the boundaries for the homogeneous region.

Selection of the Duration for Seasonality Analysis – The storm duration used in the seasonality analysis is the same duration that is used as the key duration in developing the watershed precipitation-frequency relationship. Table 2-2.1 lists key durations that are typically used for developing watershed precipitation-frequency relationships.

Table 2-2.1 – Durations Typically Used in Seasonality Analyses

STORM TYPE	KEY DURATION (Hours)
Local Storm	2
Mesoscale Storm with Embedded Convection	6
Synoptic -Scale Mid-Latitude Cyclones and Tropical Storms	48 or 72

Selection of Storm Threshold - There are two conflicting goals in selecting a threshold for identifying extreme storms. One goal is to set a high threshold so that only very extreme storms are considered in the analysis. A second goal is to have a representative dataset of sufficient size to reduce uncertainties arising from sampling variability. Given these two considerations, the threshold is usually set at as rare a frequency level as possible that will still provide a sufficiently large sample size. Sample sizes of 40 to 50 storms are usually adequate to reasonably describe the seasonality of extreme storms. A threshold level set at a 10-year recurrence interval is usually sufficient to yield adequate sample sizes, depending upon the size of the study region, storm type and the number of precipitation gages.

Types of Precipitation Gages - The type of precipitation gages available for the seasonality analysis is a major factor in determining the procedures for the seasonality analysis. Observational day gages (daily gages) recording once-per-day at a fixed time each day have been common since about 1880. Automated gages measuring primarily on hourly intervals (hourly gages) have been operational since 1940. There are many more daily gages than hourly gages in the NOAA cooperative network and thus the density of the network of hourly gages is often insufficient for estimating/detecting the areal coverage of precipitation produced by convective cells.

Number of Gages Needed to Identify Storms for Analysis - The most extreme storms are selected for conducting the seasonality analysis. The measures used for identifying the most extreme storms are precipitation magnitude, storm rarity and storm areal coverage. A practical measure of storm areal coverage is the number of precipitation gages where precipitation has exceeded the frequency threshold for storm identification. This measure of areal coverage works well for synoptic-scale long-duration storms but is less effective for shorter-duration storm types with smaller areal coverage. In this latter case, it is common that a storm is only measured at one or two gages. The procedures for identification of storms to be included in the seasonality analysis are discussed below.

2-2.2 Seasonality Analysis Procedures

Procedures for conducting a seasonality analysis are described below. An example dataset is listed at the end of this section and the findings of the seasonality analysis are depicted in Figures 2-2.5b and 2-2.6.

Step 1 – For a given storm type, assemble precipitation annual maxima series for each gage
For each precipitation gage, assemble an annual maxima series of precipitation amounts and dates of occurrence for the duration of interest.

Step 2 – Compute surrogate measure of storm rarity
For each precipitation gage, compute the mean of the annual maxima series precipitation data. For each precipitation measurement at a given gage, compute a surrogate measure of storm rarity as the ratio of the precipitation measurement to the mean of the annual maxima series.

Step 3 - Set threshold frequency level
Use a 10-year recurrence interval for the frequency threshold. If this choice does not yield a sufficient sample size of 40 to 50 storms or more, then reduce the frequency threshold to a 5-year recurrence interval (see Step 6).

Step 4 – Identify storm dates that exceed threshold
For each precipitation gage, order the annual maxima series precipitation data from largest to smallest amount. Use a non-parametric plotting position formula (Cunnane[6]) to assign recurrence intervals to the annual maxima data:

$$T = \frac{N+1-2\phi}{i-\phi} \approx \frac{N}{i-0.4} \qquad (2\text{-}2.1)$$

where: T is the recurrence interval (years), N is the number of years of record, i is the rank of the data ordered from largest to smallest (1 to N), and ϕ is 0.40.

Identify the storm dates where the precipitation exceeded the frequency threshold.

Step 5 – Identify the number of gages where storm threshold was exceeded
Sort the storm events by storm date where the storm threshold was exceeded. Count the number of gages where the storm threshold was exceeded for a given storm event.

Step 6 – Select minimum number of gages required for registering precipitation over the threshold
Review the results of Step 5 and select the minimum number of gages to achieve a sample size of 40 to 50 storm events. Alternatively, set the minimum number of gages required for registering a storm, and alter the storm threshold level to achieve a sufficiently large sample size.

For the case of mesoscale storms with embedded convection and local storms, the density of the network of hourly gage may be too low for good storm identification. In this case, use the surrogate measure of storm rarity (Step 2) for identifying the storm dates for the rarest storms to be included in the seasonality analysis.

Step 7 – Create a storm catalog of storm dates and locations

Create a storm catalog of the storms to be included in the seasonality analysis by retaining the storm date, gage location where the surrogate measure of precipitation rarity was greatest, precipitation amount, and the number of gages where the storm threshold was exceeded for each storm event.

Step 8 – Fit probability distribution(s) to seasonality data

Transform the storm catalog dates from a calendar basis to a decimal monthly numeric (1.000 for January 1st through 12.968 for December 31st). For seasonality analyses that span the December to January boundary, add twelve to those months in the cool season beginning with January. See Figure 2-2.5a for an example of the numeric storm date spanning the December-January boundary. The numeric storm date is computed as:

$$NumericDate = Month + \frac{(Day - 1)}{Days\,in\,Month} \qquad (2\text{-}2.2)$$

Compute sample statistics and use method of moments to fit a probability distribution to the seasonality data and to estimate distribution parameters. The four-parameter Beta distribution (Benjamin and Cornell[4]) and the Normal distribution have been found to be useful in describing seasonality data. If the four-parameter Beta distribution is used, care must be exercised in setting the lower and upper bounds for storm dates to include the possibility of numeric dates outside of those experienced in the historical data. Meteorologists should be consulted for assistance in setting the lower and upper bound numerical dates.

See section 2-11.2.2 for a brief discussion of using the method of moments for fitting the four-parameter Beta distribution.

Step 9 – Assemble frequency histogram based on fitted probability distribution(s)

After solving for the distribution parameters, use the cumulative distribution function of the fitted distribution to assemble a frequency histogram for twice-monthly time intervals for input into SEFM. This can be readily accomplished using Microsoft Excel that has built-in functions for the Beta and Normal distributions. Figure 2-2.4 depicts a computed frequency histogram based on 96-hour duration for the Upper Columbia River watershed in British Columbia[56].

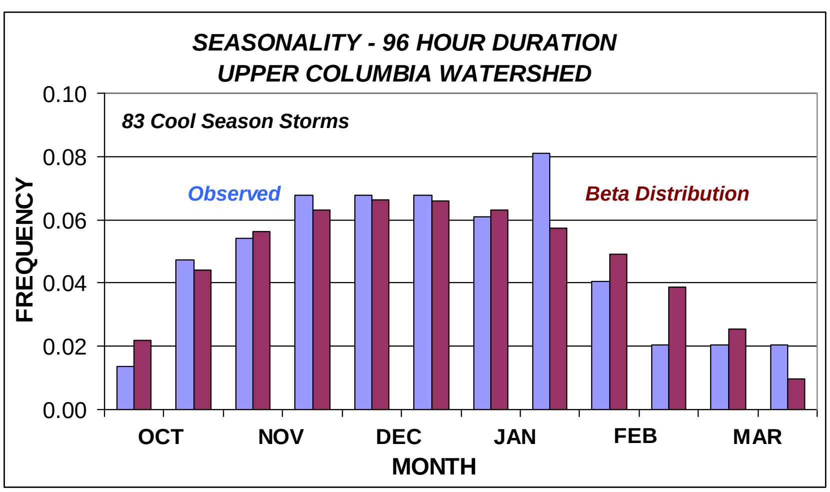


Figure 2-2.4 – Beta Distribution Fit to 96-Hour Seasonality Data in the Early-Fall through Winter Periods for the Upper Columbia River Watershed

An example of the results of a seasonality analysis for synoptic-scale general storms is shown in Figure 2-2.5a. Here it is seen that the seasonality of 72-hour extreme storms are well described by a Normal distribution. For this analysis, a minimum of 3 precipitation gages was required to register a storm on the leeward face of the Vancouver Mountains in BC or on the leeward face of the Olympic Mountains in WA. The resultant frequency histogram for storm seasonality that was used in SEFM is shown in Figure 2-2.5b.

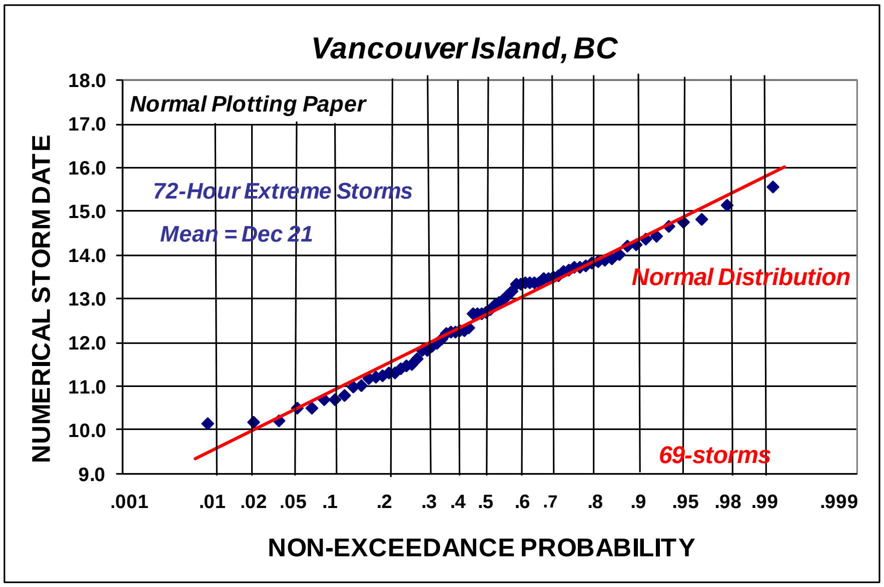


Figure 2-2.5a – Probability-Plot of Seasonality Data for 72-Hour Duration Extreme Storms on the Leeward Face of Vancouver Island Mountains, BC

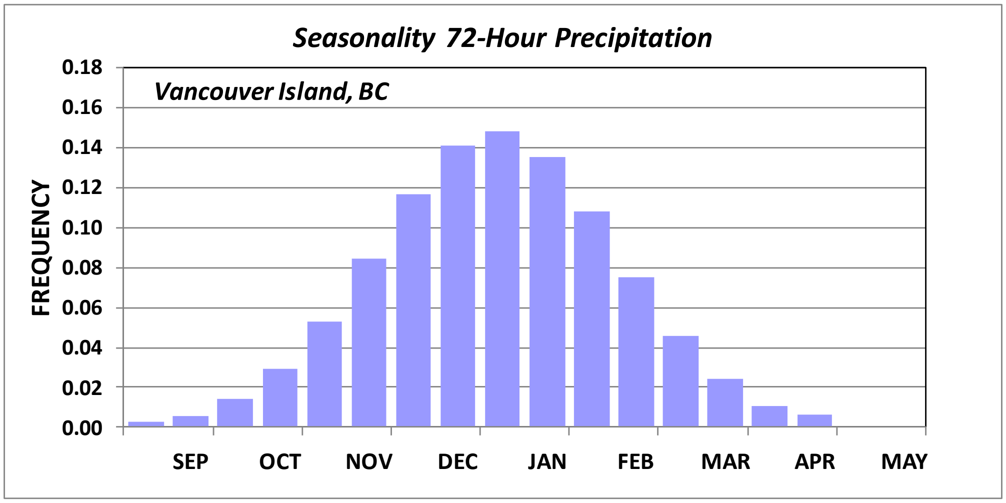


Figure 2-2.5b – Frequency Histogram for Historical 72-Hour Seasonality Data Fitted by Normal Distribution for 72-Hour Duration Extreme Storms for the Leeward Face of Vancouver Island Mountains, BC

Example Dataset for Multiple Gage SeasonalityAnalysis

Station ID	STATION NAME	72-HOUR PRECIPITATION (in)	RATIO TO 72-HOUR AT-SITE MEAN	MONTH	DAY	YEAR	NUMERIC DATE	NUMBER OF STATIONS OVER THRESHOLD
04-3397	GIANT FOREST	15.91	1.91	12	12	1937	12.35	8
04-2500	DOWNIEVILLE	12.60	1.55	2	28	1940	14.95	6
04-3397	GIANT FOREST	16.04	1.92	1	23	1943	13.71	7
04-8353	SONORA RS	7.55	1.74	2	3	1945	14.07	6
04-1700	CHESTER	6.11	1.30	2	6	1950	14.18	3
04-8928	TIGER CREEK PH	13.83	2.39	11	20	1950	11.63	62
04-5809	MONTGOMERY CREEK 2 S	8.46	1.33	12	28	1951	12.87	4
04-9855	YOSEMITE PARK HDQTRS	15.98	2.75	12	24	1955	12.74	72
04-9390	VOLTA POWER HOUSE	5.68	1.52	1	15	1956	13.45	3
04-1700	CHESTER	7.78	1.66	2	22	1956	14.74	5
04-6963	PLACERVILLE 2 W	6.26	1.27	4	3	1958	16.07	6
04-7811	SAN JOAQUIN EXP RANG	5.67	1.87	2	11	1962	14.35	20
04-1912	COLFAX	18.97	3.03	10	13	1962	10.39	58
04-3093	FLORENCE LAKE	14.45	3.36	2	2	1963	14.04	51
04-1161	BUCKS LAKE	23.40	2.62	12	23	1964	12.71	55
04-3397	GIANT FOREST	21.74	2.60	12	7	1966	12.19	9
04-1497	CANYON DAM	8.62	1.60	1	22	1967	13.68	14
04-7296	REDDING FIRE STN 2	7.64	1.42	1	13	1969	13.39	4
04-5026	LODGEPOLE	19.79	2.52	1	21	1969	13.65	50
04-3257	FRESNO YOSEMITE INTL	3.28	1.79	1	26	1969	13.81	3
04-5738	MODESTO	3.11	1.70	11	30	1970	11.97	3
04-9193	USONA 2 N	5.80	1.47	2	12	1973	14.39	3
04-5679	MINERAL	12.99	1.68	11	12	1973	11.37	4
04-7581	ROUND MOUNTAIN PG & E	10.44	1.43	1	16	1974	13.48	4
04-5026	LODGEPOLE	17.02	2.17	1	14	1980	13.42	24
04-8135	SHASTA DAM	15.80	1.81	12	4	1980	12.10	3
04-1149	BUCKHORN	12.40	1.72	11	17	1981	11.53	7
04-8332	SODA SPRINGS 1 E	10.34	1.64	12	21	1981	12.65	5
04-3384	GEORGETOWN R S	11.20	1.71	2	16	1982	14.53	6
04-1878	COARSEGOLD 1 SW	7.50	1.76	12	22	1982	12.68	10
04-1018	BOWMAN DAM	10.70	1.39	12	27	1983	12.84	6
04-6136	NEVADA CITY	17.95	2.50	2	19	1986	14.64	63
04-3257	FRESNO YOSEMITE INTL	3.00	1.64	3	20	1991	15.61	3
04-1653	CHALLENGE R S	17.21	1.84	12	11	1992	12.32	3
04-1700	CHESTER	10.96	2.33	1	10	1995	13.29	19
04-9482	WAWONA RANGER STATIO	13.50	2.04	3	11	1995	15.32	20
04-8332	SODA SPRINGS 1 E	10.40	1.65	12	13	1995	12.39	5
04-8554	STIRLING CITY R S	24.40	2.57	1	2	1997	13.03	21
04-9582	WEST POINT	5.82	1.36	2	3	1998	14.06	3
04-2920	EXCHEQUER DAM	4.24	1.51	3	26	1998	15.88	3
							13.41	**Mean**
							1.28	**Std Dev**

2-3 EXTREME STORM OVERVIEW

Extreme storms are complex phenomenon having attributes that vary in magnitude, temporal and spatial distribution. Four categories of storm types with differing spatial and temporal characteristics may be of interest for conducting flood simulations for a particular watershed. For those watersheds where the flood magnitudes of interest are generated by different storm types, a separate SEFM model will be needed for each storm type.

Probabilistic information is needed on watershed precipitation-frequency and spatial and temporal storm characteristics to conduct stochastic flood analyses. Development of these components for a given storm type requires extensive experience in regional precipitation-frequency analysis and meteorological experience in the spatial and temporal analysis of storms. This level of expertise requires that specialists be employed to develop the storm-related components.

The following paragraphs provide an overview of the storm-related components and details about the storm components are provided in Sections 2-4 through 2-7.

2-3.1 – Categories of Storm Types Used in SEFM

Four broad categories of storm types are used in SEFM, where the storm types are categorized from both a hydrologic/flood perspective and from an academic/meteorological perspective. Specifically, the size of the watershed will be a major factor in determining the storm type(s) and associated storm characteristics that produce flood magnitudes of interest on a particular watershed. The four categories of storm types are:

- Mid-Latitude Cyclones (synoptic-scale)
- Tropical Storms and Tropical Storm Remnants (synoptic-scale)
- Mesoscale Storms with Embedded Convection (mesoscale)
- Local Storms (small-scale)

Mid-Latitude Cyclone

Mid-latitude cyclones are synoptic-scale low pressure systems with cyclonic circulation that form in the mid-latitudes. Mid-latitude cyclones and associated frontal systems can produce low to moderate-intensity precipitation for several days over very large areas. This storm type is of interest for larger watersheds in the eastern U.S. and for intermediate and large watersheds in the western U.S.

Tropical Storms and Tropical Storm Remnants

Tropical storms are synoptic-scale low pressure systems that form in the tropical latitudes and travel northward with landfalls on coastal areas of the Gulf of Mexico and coastal areas of the Atlantic Ocean. Tropical Storm Remnant is a generic term applicable to precipitation associated with a tropical storm meteorological environment, particularly high levels of atmospheric moisture brought northward from the tropics. This is a synoptic-scale storm type where precipitation is associated with an approaching or departing tropical storm or hurricane and has a storm track within roughly 200 miles of the watershed of interest. Tropical storms and tropical storm remnants can produce precipitation over large areas and may have embedded convective cells that can produce localized flash flooding. This storm type is of interest for larger watersheds generally within several hundred miles of the Gulf of Mexico or Atlantic Coast in the eastern U.S.

Mesoscale Storms with Embedded Convection

Mesoscale storms with embedded convection is a generic storm type that is intended to include Mesoscale Convective Complexes (MCCs) and other warm-season mesoscale and sub-synoptic scale storms with embedded convective cells (thunderstorms). These are relatively short-duration events with the majority of precipitation occurring within a 6-hour to 12-hour period. This storm type has characteristics that can cause widespread precipitation with locally high precipitation intensities that can generate high rates of runoff and flash flooding. This is a storm type that can produce large floods on intermediate size watersheds, generally less than about 2,000 mi^2 for watersheds in the eastern U.S.

Local Storms

Local storm is the term given to relatively small-scale convective events (thunderstorms) which occur in the warm season. The areal coverage and duration of these storms are limited, typically less than a nominal 100 mi^2 and several hours in duration. This storm type is of interest for small watersheds in the western U.S. and for Local Intense Precipitation (LIP) analyses conducted for nuclear facilities.

2-3.2 – Storm-Related Components Needed for Flood Simulations

Several storm-related components are needed for execution of SEFM which include:

- Watershed precipitation-frequency relationship for storm type of interest
- Scalable spatial and temporal storm templates developed from historical storms
- Scalable air temperature temporal patterns developed from historical storms (snowmelt cases)

2-3.3 – Watershed Precipitation-Frequency Relationship

A watershed precipitation-frequency relationship is needed for scaling of storm templates for generation of stochastic storms for flood simulations. The basin-average precipitation-frequency relationship is developed for the watershed area for a duration (key duration) that is representative of the hydrologic response time of the watershed and reservoir. Table

The precipitation-frequency relationship for the watershed is developed from the findings of several analyses including:

- L-moment regional precipitation-frequency analysis for point precipitation for a climatic region encompassing the watershed of interest
- Analyses of the spatial and temporal characteristics of historical storms on the watershed and transpositionable to the watershed
- Development of a relationship between point precipitation and areal precipitation for the watershed size of interest
- Development of the basin-average watershed precipitation-frequency relationship using Monte Carlo methods

An example of watershed precipitation-frequency relationship for the 1,660-mi^2 Friant watershed on the San Joaquin River in southern California is shown in Figure 2-3.1. Development of uncertainty bounds for the precipitation-frequency relationship is an important element of the analysis. Figure 2-3.2 depicts a stacked histogram depicting the contribution to the total uncertainty from the various sources of uncertainty. The relative height of the histogram bars directly relate to the width of the uncertainty bounds for various annual exceedance probabilities.

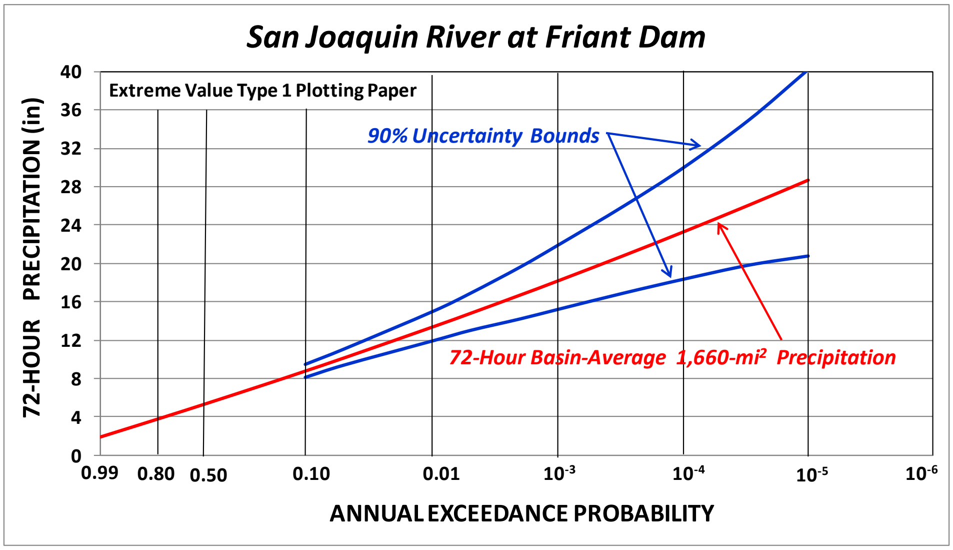


Figure 2-3.1 – Basin-Average 72-Hour Precipitation-Frequency Relationship for 1,660-mi² Friant Watershed on San Joaquin River in Southern California

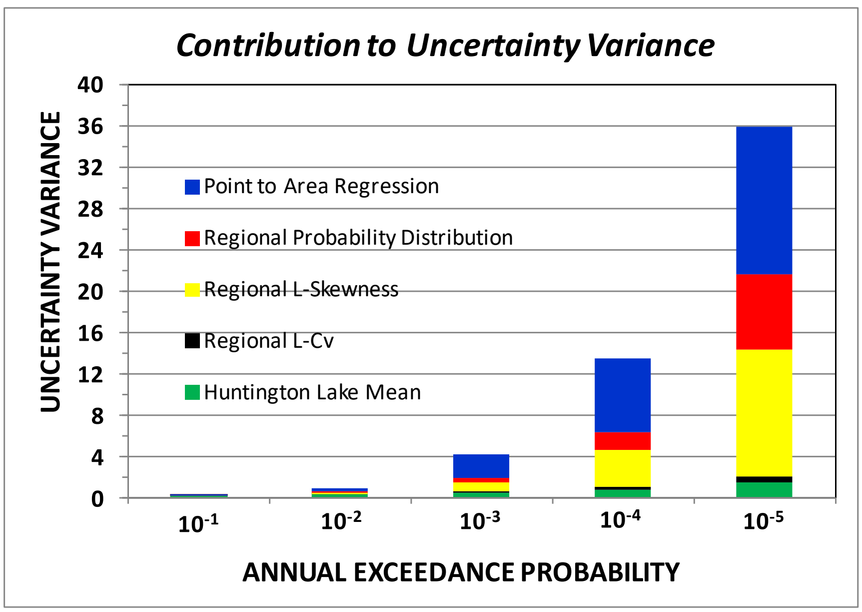


Figure 2-3.2 – Stacked Histogram Depicting Magnitude of Uncertainty Contributed to the Total Uncertainty by Various Sources of Uncertainty

2-3.4 – Scalable Spatial and Temporal Storm Templates

A collection of scalable storm templates is needed for depicting the diversity of the spatial and temporal patterns of precipitation for the watershed. Each scalable storm template is developed from an historical storm on the watershed or an historical storm transposed to the watershed. The spatial and temporal patterns of the historical storm are stored in a dimensionless format which allows them to be scaled by a precipitation magnitude selected by Monte Carlo procedures from the watershed precipitation-frequency relationship.

The number of scalable storm templates to be developed is dependent upon the number of suitable storms available and is typically about 12 to 24 storm templates. Each storm template has a specific spatial pattern and there is a collection of temporal patterns, one for each sub-basin, for the watershed. Figure 2-3.3 depicts the spatial pattern of 72-hour precipitation for the March 8-13, 1995 storm for the Friant watershed. Figure 2-3.4 depicts the basin-average temporal pattern for the March 8-13, 1995 storm which is the areal average of all temporal patterns for the 33 sub-basins.

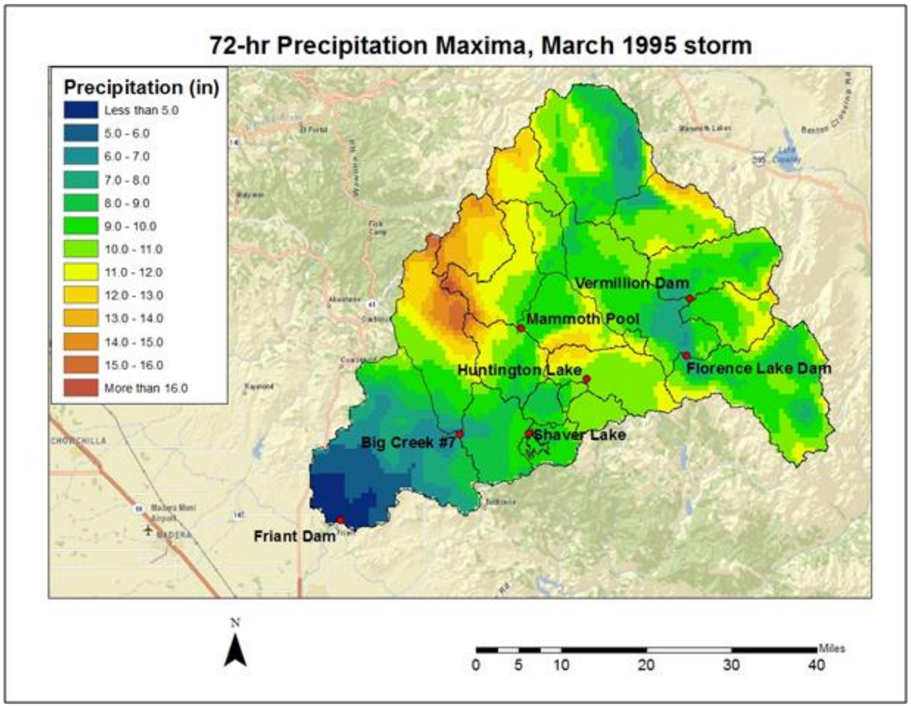


Figure 2-3.3 – Spatial Distribution of 72-Hour Precipitation for Storm of March 8-13 1995 for Friant Watershed in Southern California

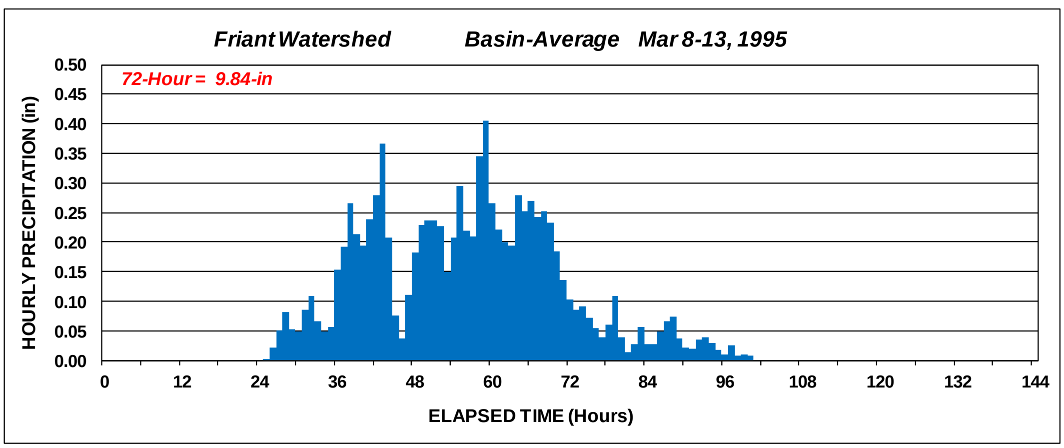


Figure 2-3.4 – Temporal Pattern of Basin-Average 72-Hour Precipitation for Storm of March 8-13 1995 for Friant Watershed in Southern California

2-3.5 – Scalable Air Temperature Temporal Patterns

A scalable air temperature pattern is also needed in cases where snowpack and snowmelt are a consideration. The historical air temperature patterns for the 1000-mb air temperature and freezing level are stored in a manner that allows them to be scaled by the Monte Carlo selected values of 1000-mb air temperature and freezing level for a given flood simulation.

Each spatial storm template, collection of temporal storm patterns and the air temporal pattern are a matched set that are applied together in stochastic generation of a storm. Figure 2-3.5 depicts the air temperature temporal pattern observed for the storm of March 8-13, 1995 for the Friant watershed.

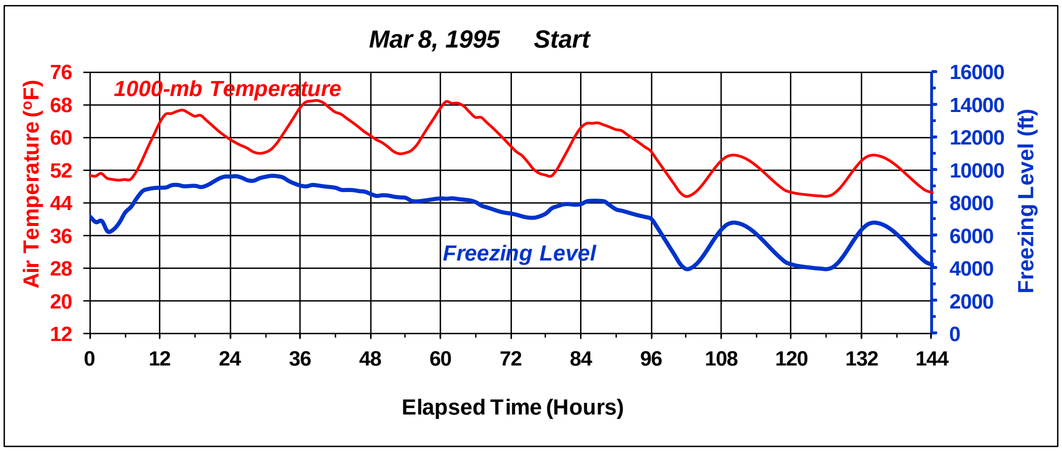


Figure 2-3.5 – Air Temperature Temporal Pattern for Storm of March 8-13 1995 for Friant Watershed in Southern California

2-4 STORM TYPING

Storm typing is required for several storm-related analyses for application of SEFM. The watershed precipitation-frequency relationship is developed for a specific storm type. Therefore, all annual maxima used for regional precipitation-frequency analysis must be produced by the specified storm type. Similarly, the spatial and temporal storm templates for stochastic generation of storms are also developed by analysis of historical storms where the chosen storms are produced by the specified storm type.

2-4.1 – Categories of Storm Types Used in SEFM

Four broad categories of storm types are used in SEFM, where the storm types are categorized from both a hydrologic/flood perspective and from a scientific/meteorological perspective. Table 2-4.1 lists the four categories of storm types and typical key durations used in precipitation-frequency analyses and seasonality analyses. The key duration is reflective of the time-scale for the various storm types with consideration given to the hydrologic response time of the watershed and reservoir of interest. Specifically, the size of the watershed will be a major factor in determining the storm type(s) and associated storm characteristics that produce flood magnitudes of interest on a particular watershed. The four categories of storm types are:

- Mid-Latitude Cyclones (synoptic-scale)
- Tropical Storms and Tropical Storm Remnants (synoptic-scale)
- Mesoscale Storms with Embedded Convection (mesoscale)
- Local Storms (small-scale)

Table 2-4.1 – Categories of Storm Types and Typical Key Durations

STORM TYPE	KEY DURATION (Hours)
Synoptic -Scale Mid-Latitude Cyclones (MLC)	48 or 72
Synoptic -Scale Tropical Storms and Tropical Storm Remnants (TSR)	48 or 72
Mesoscale Storms with Embedded Convection (MEC)	6 or 12
Local Storms (LS)	2

The four storm types are discussed in the following sections. Examples of typical spatial and temporal patterns for the four storm types are provided where the spatial images are from SPAS analyses (Parzybok and Tomlinson[115]).

Mid-Latitude Cyclone (MLC)

Mid-latitude cyclones are synoptic-scale low pressure systems with cyclonic circulation that form in the mid-latitudes. Mid-latitude cyclones and associated frontal systems generally produce low to moderate-intensity precipitation that can persist for several days over very large areas. This storm type is of interest for large watersheds throughout the US.

Figure 2-4.1a depicts an example of the broad areal coverage of a mid-latitude cyclone and Figure 2-4.1b shows the typical temporal pattern of long-duration low to moderate intensity precipitation. Figure 2-4.1c shows an atmospheric river originating over the Pacific Ocean that provided atmospheric moisture inflow to the Nov 6-7, 2006 mid-latitude cyclone that produced extreme precipitation and widespread flooding in western Washington.

General Storm – The term *General Storm* was commonly used by the NWS through the mid-1990s, particularly in preparing Hydrometeorological Reports for estimation of Probable Maximum Precipitation (PMP). General Storm was a generic term that encompassed mid-latitude cyclones and associated frontal systems and also included the occurrence of embedded clusters of thunderstorm cells. The term Mesoscale Convective Complexes (MCCs) is now used to describe storm characteristics that include embedded clusters of thunderstorm cells. Therefore, the term General Storm is replaced in application of SEFM by two storm types: Mid-Latitude Cyclones; and Mesoscale Storms with Embedded Convection. Each of these storm types have different spatial and temporal storm characteristics which produce differing flood characteristics with regard to flood peak flows, runoff volumes and flood hydrograph shapes.

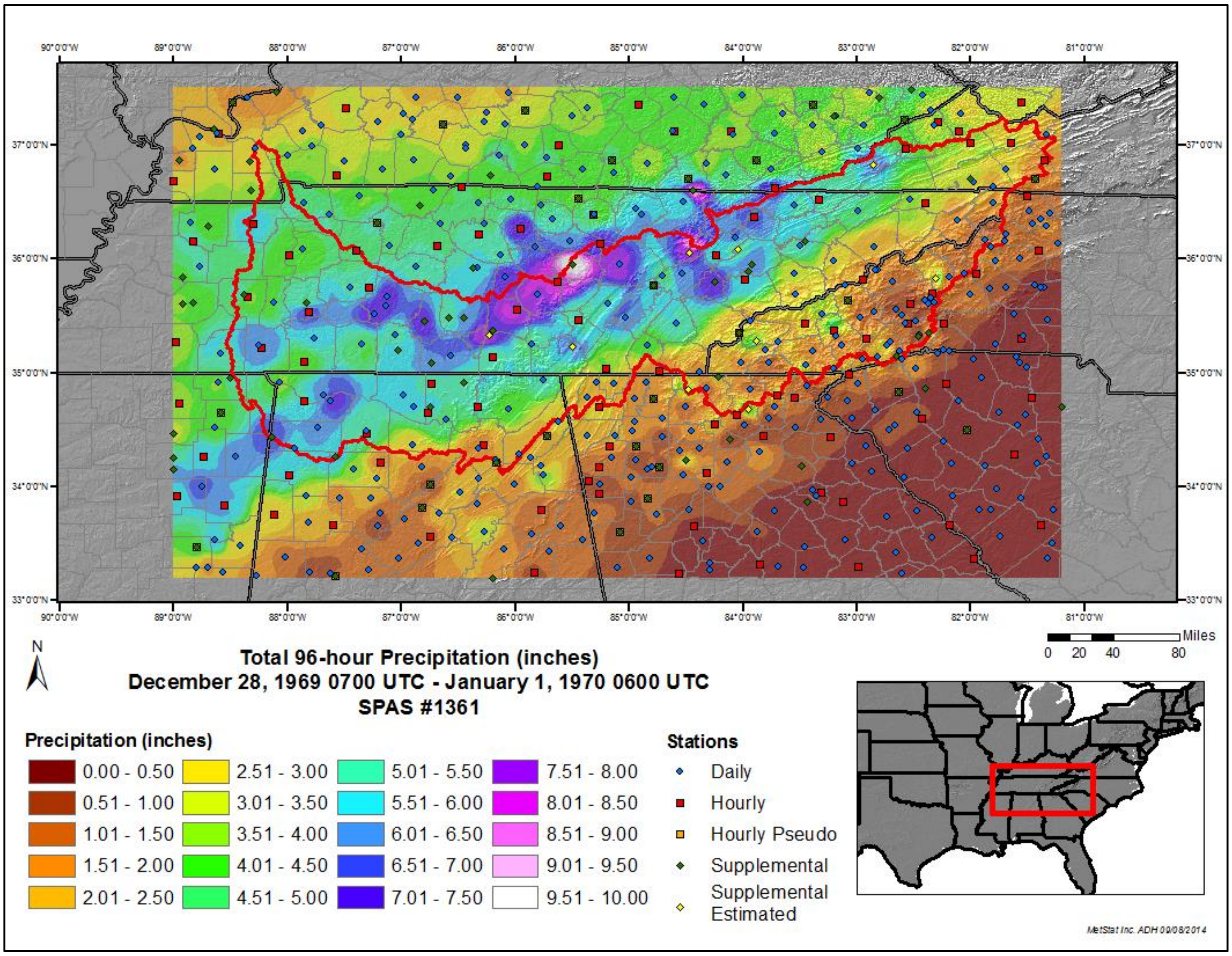


Figure 2-4.1a – Example Spatial Pattern for a Mid-Latitude Cyclone, SPAS Analysis Courtesy of MetStat

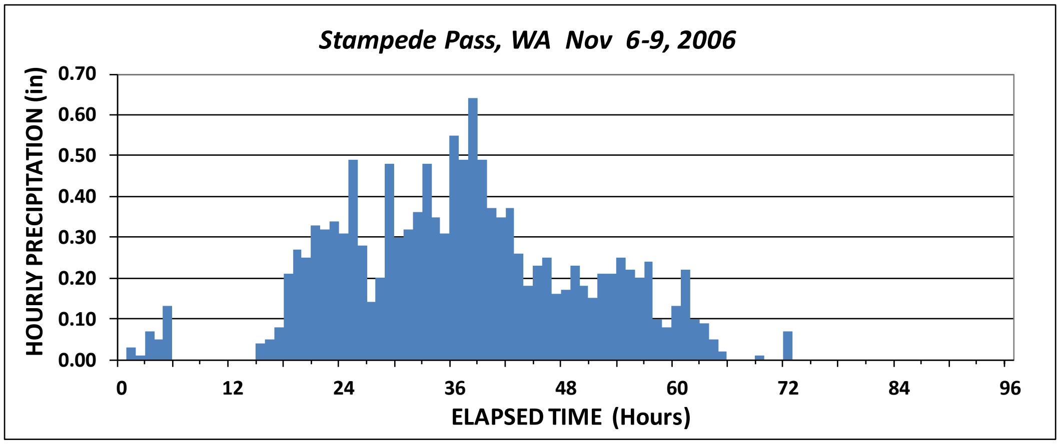


Figure 2-4.1b – Example Temporal Pattern for a Mid-Latitude Cyclone Recorded at a Precipitation Station

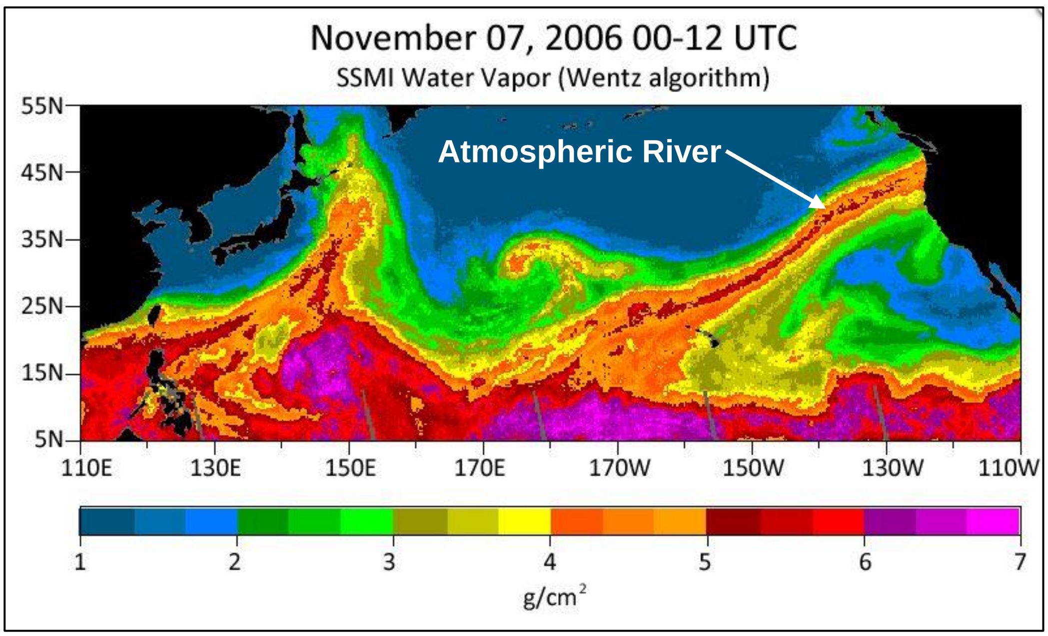


Figure 2-4.1c –Atmospheric River Moisture Inflow for Storm of Nov 6-7, 2006 in Western Washington, Courtesy of NOAA Earth System Research Laboratory

Tropical Storms and Tropical Storm Remnants (TSR)

Tropical storms are synoptic-scale low pressure systems that form in the tropical latitudes and travel northward with landfalls on coastal areas of the Gulf of Mexico and Atlantic Ocean. Tropical Storm Remnant is a generic term applicable to precipitation associated with a tropical storm meteorological environment, particularly high levels of atmospheric moisture brought northward from the tropics. This is a synoptic-scale storm type where precipitation is associated with an approaching or departing tropical storm or hurricane and has a storm track within roughly 200 miles of the watershed of interest. Tropical storms and tropical storm remnants can produce precipitation over large areas and may have embedded convective cells that can produce localized flash flooding. This storm type is of interest for larger watersheds generally within several hundred miles of the Gulf of Mexico or Atlantic Coast in the eastern U.S.

Figure 2-4.2a depicts an example of the broad areal coverage of a tropical storm and Figure 2-4.2b shows the typical temporal pattern of long-duration moderate to high-intensity precipitation.

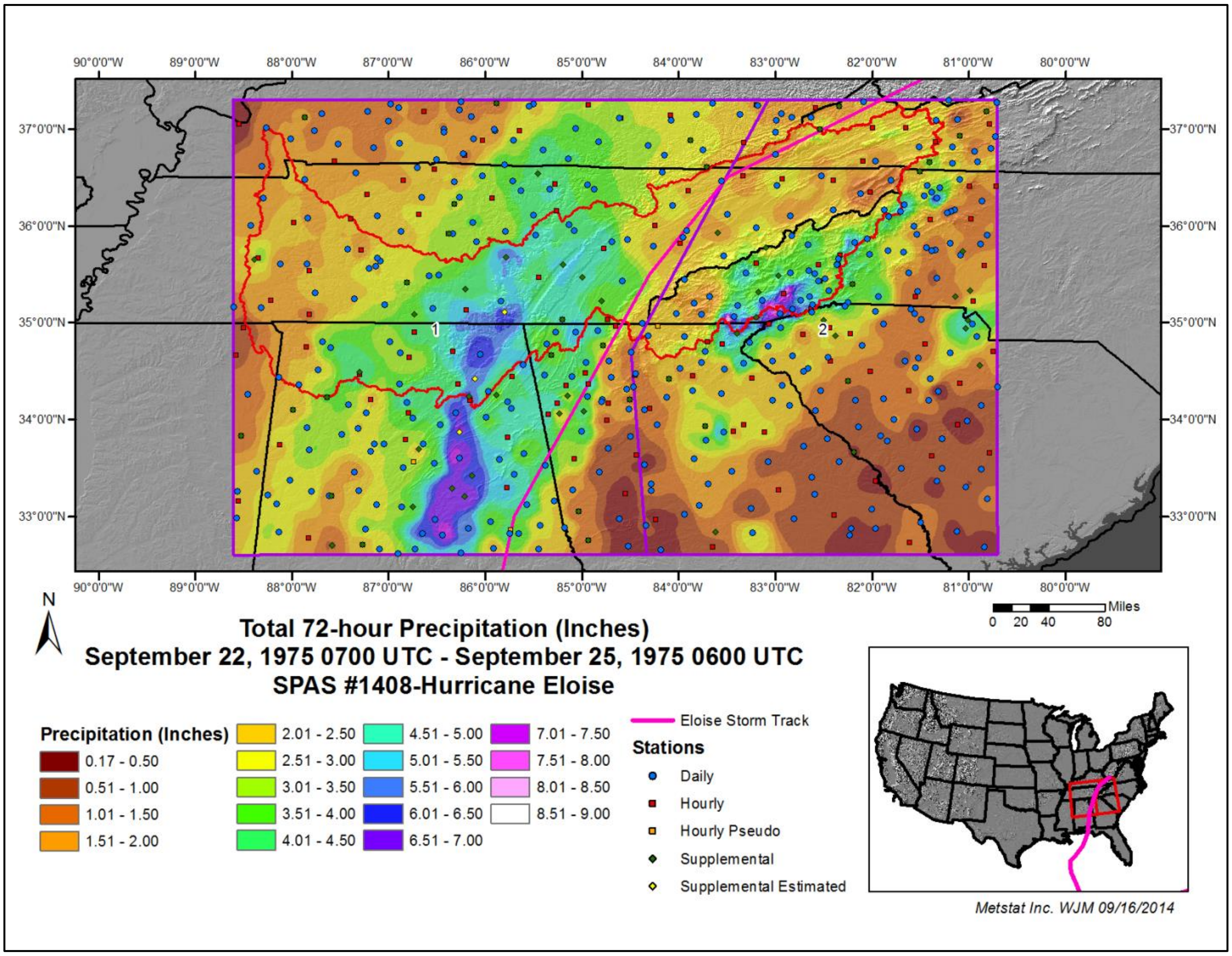


Figure 2-4.2a – Example Spatial Pattern for a Tropical Storm
SPAS Analysis Courtesy of MetStat

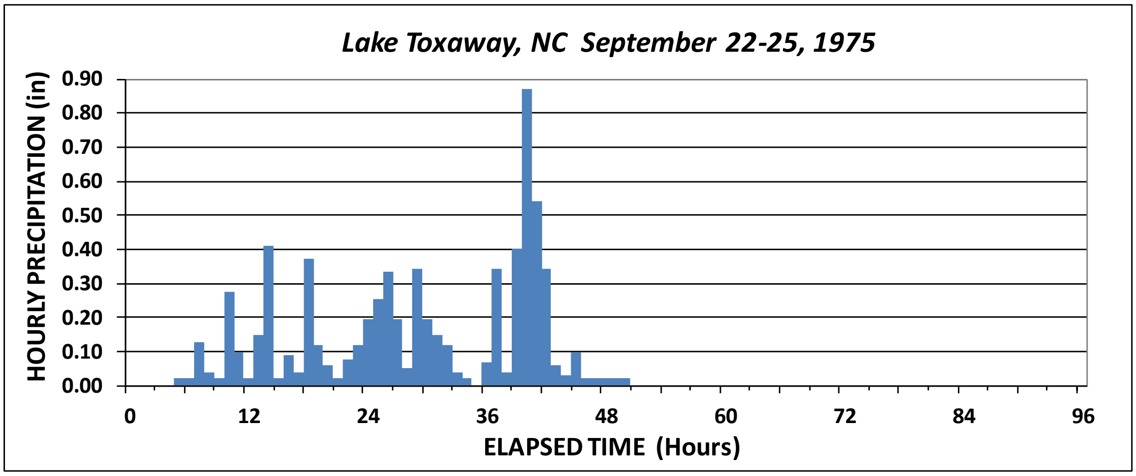


Figure 2-4.1b – Example Temporal Pattern for Tropical Storm Recorded at Lake Toxaway, NC

Mesoscale Storms with Embedded Convection (MEC)

Mesoscale storms with embedded convection is a generic storm type that is intended to include Mesoscale Convective Complexes (MCCs) and other warm-season mesoscale and sub-synoptic scale storms with embedded convective cells (thunderstorms). These are relatively short-duration events with the majority of precipitation occurring within a 6-hour to 12-hour period. This storm type has characteristics that can cause widespread precipitation with locally high precipitation intensities that can generate high rates of runoff and flash flooding. This is a storm type that can produce large floods on intermediate size watersheds, generally less than about 2,000 mi^2 for watersheds in the eastern U.S.

Figure 2-4.3a depicts an example of a sizeable mesoscale storm with embedded convection and Figure 2-4.3b shows one example of a temporal pattern of a moderate- duration storm with localized very-high intensity precipitation.

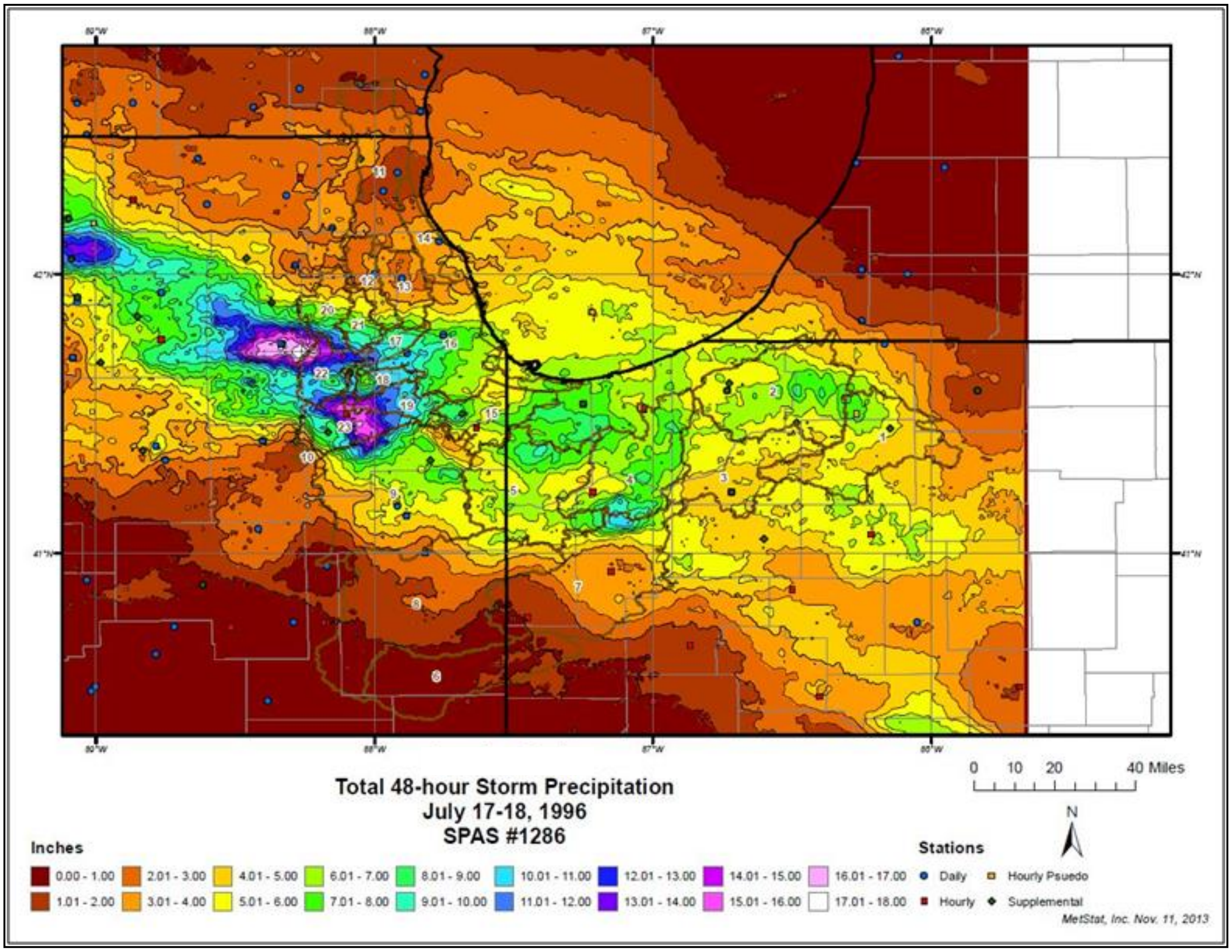


Figure 2-4.3a – Example Spatial Pattern for a Mesoscale Storm with Embedded Convection, SPAS Analysis Courtesy of MetStat

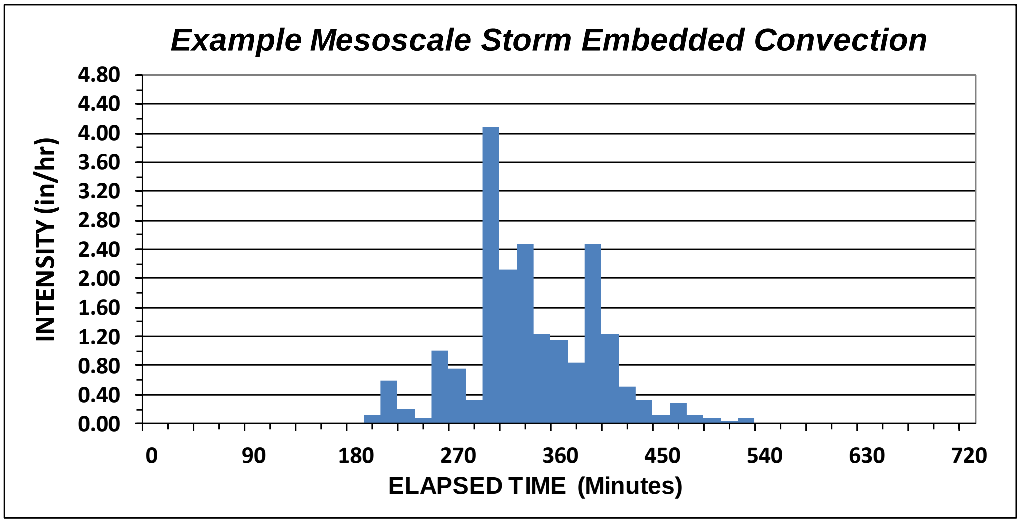


Figure 2-4.3b – Example Temporal Pattern for a Mesoscale Storm with Embedded Convection Recorded at a Precipitation Station

Local Storms (LS)

Local storm is the term given to relatively small-scale convective events (thunderstorms) which occur in the warm season. The areal coverage and duration of these storms are limited, typically less than a nominal 100 mi^2 and several hours in duration. This storm type is of interest for small watersheds in the western U.S. and for Local Intense Precipitation (LIP) analyses conducted for nuclear facilities.

Figure 2-4.4a depicts an example of the limited areal coverage of a local storms and Figure 2-4.4b shows the typical temporal pattern of a short- duration storm with localized very-high intensity precipitation.

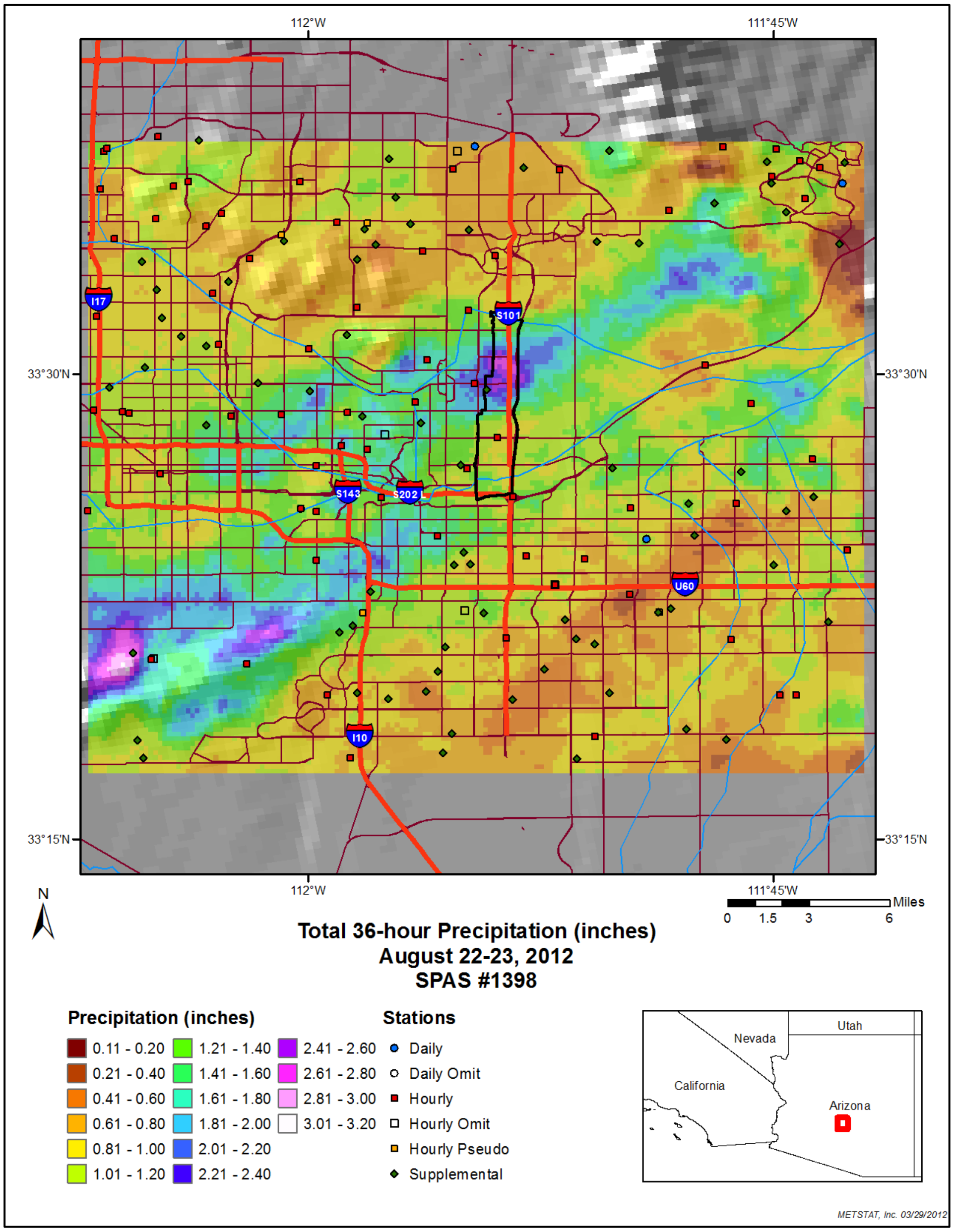


Figure 2-4.4a – Example Spatial Pattern for a Local Storm, SPAS Analysis Courtesy of MetStat

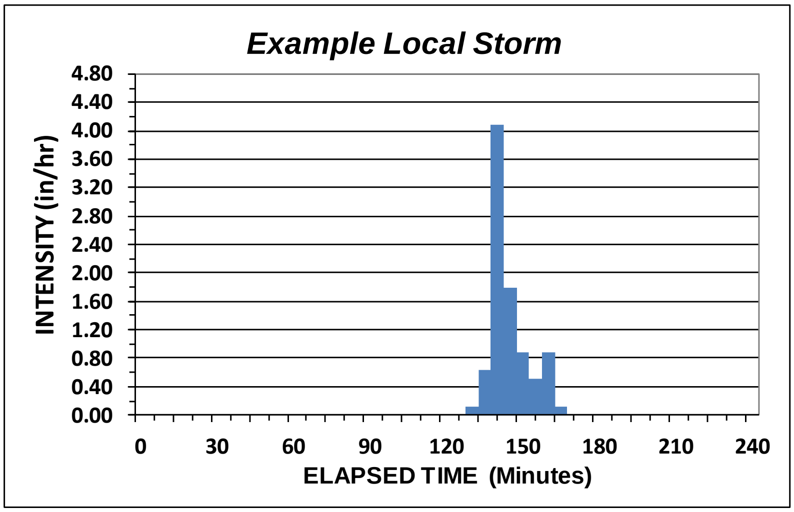


Figure 2-4.4b – Example Temporal Pattern for a Local Storm Recorded at a Precipitation Station

2-4.2 –Storm Typing

Storm typing and development of a Database of Daily Storm Types (DDST) is a task for meteorologists working in concert with specialists in analyses of extreme precipitation events. Storm typing is an important element for assembly of precipitation annual maxima datasets for development of the watershed precipitation-frequency relationship and development of spatial and temporal storm templates.

A brief example of a DDST is described below. In this example, several factors were considered in determining the storm type for a given day including:

- Daily weather map and synoptic pressure patterns for multiple pressure levels
- Percentage of precipitation stations in study area with 0.50-in or more of daily precipitation
- Largest daily precipitation amount reported
- Measure of precipitable water for day (mm)
- Measure of Convective Available Potential Energy (CAPE)

All storms with noteworthy precipitation amounts were typed by manual methods using the information listed above. The findings from manual storm typing were used to create a set of rules for automated storm typing to complete the DDST. A data field was allocated in the DDST and codes established to distinguish days which were typed by manual methods versus days that were typed by automated procedures. The following codes were used:

A – days where automated procedures were used for storm typing (Automated)
M1 – first day of date match for a 2-day noteworthy storm (Manual)
M2 – second day of date match for a 2-day noteworthy storm (Manual)
MM – part of multiple date sequence for a noteworthy storm (Manual)
MT – date match for a noteworthy Tropical Storm (Manual, Tropical)
T – storm type was set based on the NOAA tropical storm database (Tropical)

Table 2-4.2 depicts a sample of numerical storm codes used in the example DDST. The excerpt of the DDST shows the MLC storm of May 2-3, 1984 and the MEC storm of May 7-8, 1984.

Technical details about the creation of a Database of Daily Storm Types are described in Appendix E of a precipitation-frequency analysis conducted for the Tennessee Valley (MGS Engineering et al[122]).

Table 2-4.2 – Storm Types and Numerical Codes for the DDST

STORM TYPES AND NUMERICAL CODES		
Storm Type and Sub-Type	**Acronym**	**Numerical Code**
Mid-Latitude Cyclone	MLC	10
Mid-Latitude Cyclone with Embedded Convection	MLC/EC	13
Tropical Storm Remnant	TSR	20
Tropical Storm Remnant with Embedded Convection	TSR/EC	23
Mesoscale Storm with Embedded Convection	MEC	30
Mesoscale Storm without Embedded Convection	MEC/NEC	33
Local Storm	LS	40
Local Storm – cool season storm , Not of Interest	LS/NOI	49
Dry Day – No precipitation over 0.50-inch threshold reported by Century Network	DRY	99

Table 2-4.2 – Example Storm Types and Numerical Codes for the DDST

#	YearMoDy	REPORTING % Stations w/Rain	NETWORK Max Daily Rain (in)	Precipitable Water (mm)	Convectective Available Potential Energy (CAPE)	STORM METHOD	TYPE CODE
37734	19840424	0.00	0.00	16.0	45	A	99
37735	19840425	0.00	0.00	19.7	0	A	99
37736	19840426	0.03	0.52	23.9	96	A	40
37737	19840427	0.19	2.62	30.8	357	A	40
37738	19840428	0.42	3.80	38.7	1786	A	33
37739	19840429	0.44	2.14	32.2	782	A	30
37740	19840430	0.29	2.67	43.0	50	A	10
37741	19840501	0.06	1.70	9.0	0	A	40
37742	19840502	0.49	2.37	24.3	0	M1	10
37743	19840503	0.89	4.03	38.5	485	M2	10
37744	19840504	0.35	1.00	25.5	270	A	10
37745	19840505	0.08	1.50	20.9	23	A	40
37746	19840506	0.43	4.98	24.0	47	A	10
37747	19840507	0.70	5.27	40.4	1660	MM	30
37748	19840508	0.78	4.47	42.0	946	M1	30
37749	19840509	0.00	0.85	8.4	0	A	40
37750	19840510	0.00	0.00	10.9	0	A	99
37751	19840511	0.00	0.00	21.1	11	A	99
37752	19840512	0.00	0.00	27.8	73	A	99
37753	19840513	0.00	0.00	31.0	281	A	99
37754	19840514	0.08	0.71	42.8	1710	A	40
37755	19840515	0.00	0.00	11.0	0	A	99
37756	19840516	0.00	0.00	13.1	0	A	99
37757	19840517	0.00	0.00	11.1	0	A	99
37758	19840518	0.00	0.00	14.8	0	A	99
37759	19840519	0.00	0.00	17.9	1	A	99

2-5 PRECIPITATION MAGNITUDE-FREQUENCY FOR STORM GENERATION

Development of the precipitation-frequency relationship applicable to a specific watershed for a specific storm type involves a series of complex tasks. These tasks are conducted by specialists in the field of regional precipitation-frequency analysis and analysis of the spatial and temporal characteristics of extreme storms.

This section provides information for using the watershed precipitation-frequency relationship within SEFM and also provides some brief background on aspects of the development and application of the watershed precipitation-frequency relationship. Figure 2-5.1 depicts an example of a watershed precipitation-frequency relationship and 90% uncertainty bounds. This frequency relationship is for the 1,660-mi^2 Friant watershed on the San Joaquin River in southern California.

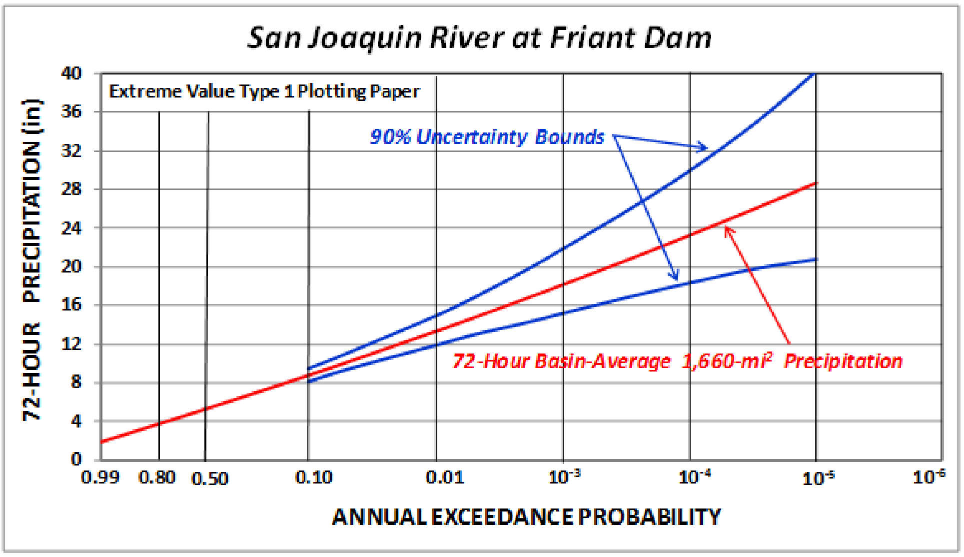


Figure 2-5.1 – Example Watershed Precipitation-Frequency Relationship for Friant Dam on the San Joaquin River in Southern California

Storm Types and Key Durations – The watershed precipitation-frequency relationship is developed for a specific storm type and duration. The term *key duration* is used to describe the duration that is used for developing the watershed precipitation-frequency relationship where the key duration is reflective of the time-scale for the storm type of interest with consideration given to the hydrologic response time of the watershed and reservoir being analyzed. Table 2-4.1 lists the four broad categories of storm types and typical key durations used in precipitation-frequency analyses.

Table 2-5.1 – Categories of Storm Types and Typical Key Durations

STORM TYPE	KEY DURATION (Hours)
Local Storms	2
Mesoscale Storms with Embedded Convection	6 or 12
Synoptic -Scale Mid-Latitude Cyclones	48 or 72
Synoptic -Scale Tropical Storms and Tropical Storm Remnants	48 or 72

Basin-Average Precipitation – The watershed precipitation-frequency relationship depicts basin-average precipitation. This is an areal average value where the spatial distribution of precipitation that aggregates to this basin-average will be incorporated during a flood simulation via spatial storm templates (Section 2-6). Similarly, the spatially varying temporal patterns for the sub-basins in a watershed will be incorporated when the storm templates are scaled for a flood simulation.

Assumptions/Expectations – The watershed precipitation-frequency characteristics observed in the recent past will be representative of conditions in the near-future.

SEFM Operation **–** Monte Carlo sampling is conducted for selection of values of basin-average precipitation from the watershed precipitation-frequency relationship for use in flood simulations. The basin-average precipitation values selected by Monte Carlo procedures are used to scale the spatial and temporal storm templates selected for a given flood simulation (see Section 2-6).

Precipitation Magnitudes Not Limited by PMP – Precipitation magnitudes for flood simulations are not limited by the estimate of Probable Maximum Precipitation (PMP). The reasons supporting this decision are presented in the discussion of storm seasonality (Section 2-2).

Imposed Constraints – There are no constraints placed on precipitation magnitude. However, there is an option that allows control of the months when the PMP magnitude can be exceeded. This optional constraint is described in the discussion of storm seasonality (Section 2-2).

Guidance and Experience – The identification/selection of the regional probability distribution is always a point of discussion amongst analysts and practitioners. Experience in conducting regional precipitation-frequency analyses in the U.S.[22,44,48,51,54,55,61,89,91,92] and developing watershed precipitation-frequency relationships (Schaefer et al[108,109,118,119,120,121,122]) has shown that the regional probability distribution resides near the Generalized Extreme Value (GEV) distribution for the Local Storm, Mesoscale Storm with Embedded Convection and Mid-Latitude Cyclone storm types.

The three-parameter GEV is a special case of the four-parameter Kappa distribution[22,23]. The Kappa distribution is used in the SEFM because of its flexibility. It can emulate the GEV as well as describe precipitation-frequency relationships that are near-GEV. This flexibility is particularly important when the primary interest is in extreme storms and estimation of precipitation amounts with very low exceedance probabilities. It is also convenient for conducting uncertainty analyses that consider alternative probability models near the GEV.

The four-parameter Kappa distribution expressed in inverse form is:

$$P_{n\text{-}hour} = \xi + \frac{\alpha}{\kappa}\left\{1 - \left(\frac{1 - F^{h}}{h}\right)^{\kappa}\right\} \qquad (2\text{-}5.1)$$

where: $P_{n\text{-}hour}$ is the precipitation quantile estimate for the *n*-hour duration; ξ, α, κ, and h are distribution parameters for location, scale and two shape parameters, respectively; and (F) is the non-exceedance probability.

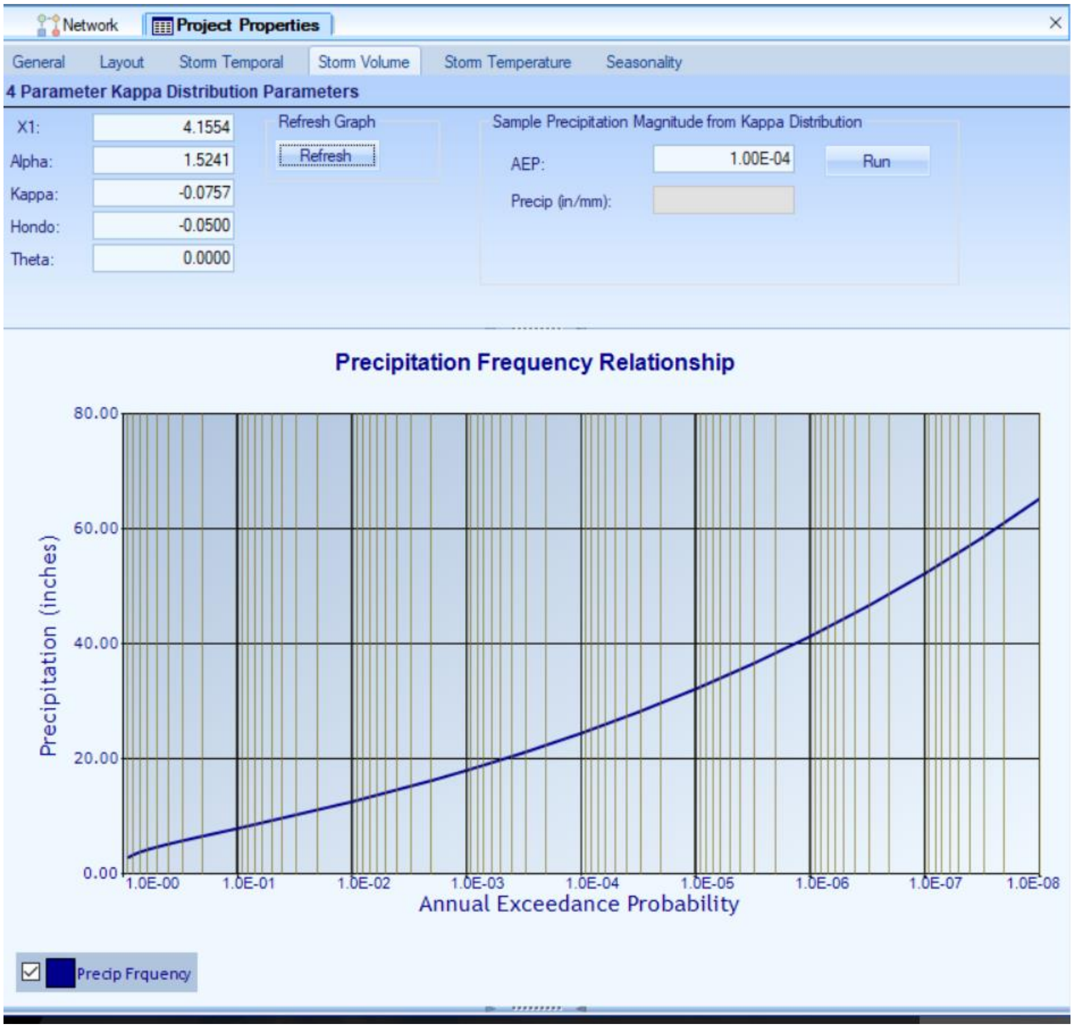
The four-parameter Kappa distribution includes the GEV distribution as a special case where the second shape parameter *h* has a value of zero. Use of the Kappa distribution with an *h* parameter value near zero allows fine-tuning of the shape of the probability distribution in the vicinity of the GEV distribution. The Kappa distribution, with *h* parameter values in the range of +0.10 to -0.10 have commonly been found to best describe precipitation annual maxima data in regional analyses with very large datasets for Local Storms, Mesoscale Storms with Embedded Convection and Mid-Latitude Cyclones.

The findings for Tropical Storms and Tropical Storm Remnants are more variable apparently dependent upon the number of tropical storm events that occur in a given year and the distance from coastal areas. The four-parameter Kappa distribution was also found to adequately describe the behavior of the precipitation annual maxima for Tropical Storm Remnants (Schaefer et al[109]).

Data Entry Format – Data entry consists of entering the distribution parameters (ξ, α, κ, and h) for the four-parameter Kappa distribution. Screen Shot 2-5.1 shows the data entry for the distribution parameters for the watershed precipitation-frequency relationship shown in Figure 2-5.1. Table 2-5.2 lists the 72-hour basin-average mean, regional L-moments and standard product moments.

Table 2-5.2 – L-Moment Statistics and 4-Parameter Kappa Distribution Parameters for the 72-Hour Basin-Average Precipitation-Frequency Relationship for Friant Watershed

L-Moment Statistics for 1,660-mi^2 Friant Watershed			
Basin-Average Mean	**L-Cv**	**L-Skewness**	**Regional *h***
5.71-in	0.2240	0.1850	-0.01
4-Parameter Kappa Distribution Parameters			
Location (ξ)	**Scale (α)**	**Shape (κ)**	**Shape (*h*)**
4.636	1.7941	-0.0260	-0.01
Standard Product Moments			
Basin-Average Mean	**Coefficient of Variation**	**Coefficient of Skewness**	**Coefficient of Kurtosis**
5.71-in	0.419	1.29	6.23



Screen Shot 2-5.1 – Example Data Entry Format for Watershed Precipitation-Frequency Relationship

2-6 SPATIAL AND TEMPORAL STORM TEMPLATES

Scalable spatial and temporal storm templates are the mechanisms by which storms are scaled to a specific basin-average magnitude for a flood simulation. Each historical storm has a unique spatial and temporal template that is used for scaling of storms. The spatial and temporal templates for 10 to 25 historical storms are typically used to provide the diversity in spatial and temporal patterns for flood simulations. The majority of the storm templates are from storms that occurred on the watershed. Additional storm templates can be developed from extreme storms that occurred within a compatible climatic region and have been transposed to the watershed of interest. Development of the scalable storm templates is a task for specialists in the fields of meteorology and extreme storm analysis.

A *spatial storm template* lists the areal-average precipitation for each sub-basin in the watershed which aggregates to the basin-average value for the watershed. This format allows scaling the basin-average precipitation for the watershed to a specific magnitude while preserving the spatial distribution of precipitation for the sub-basins. Figure 2-6.1 depicts the spatial distributions for two storms on the 1,660-mi^2 Friant watershed on the San Joaquin River in southern California.

The term *temporal storm template* refers to the collection of dimensionless temporal patterns, one for each sub-basin, which provides for spatially varying temporal patterns that preserve the spatial distribution of precipitation and can depict storm movement. The temporal pattern for each sub-basin is stored as a dimensionless mass curve which allows for scaling to the basin-average precipitation magnitude for the watershed. For each sub-basin, the precipitation magnitude for the key duration is used in the denominator for creating the dimensionless mass curve.

Figures 2-6.2a through 2-6.2e, depict the spatial diversity of temporal patterns for locations around the Friant watershed for the storm of December 15-22, 2010. Figure 2-6.3 shows the basin-average temporal pattern which is an areal-average for the watershed. The basin-average temporal pattern is not used in watershed modeling, but is useful for conveying the general temporal pattern for a storm.

The system of spatial and temporal storm templates provides an easy way to store, view, and apply the spatial and temporal distributions of precipitation. The term *prototype storm* is used to identify a spatial and temporal template for a specific historical storm (i.e. prototype storm of Dec 15-22, 2010).

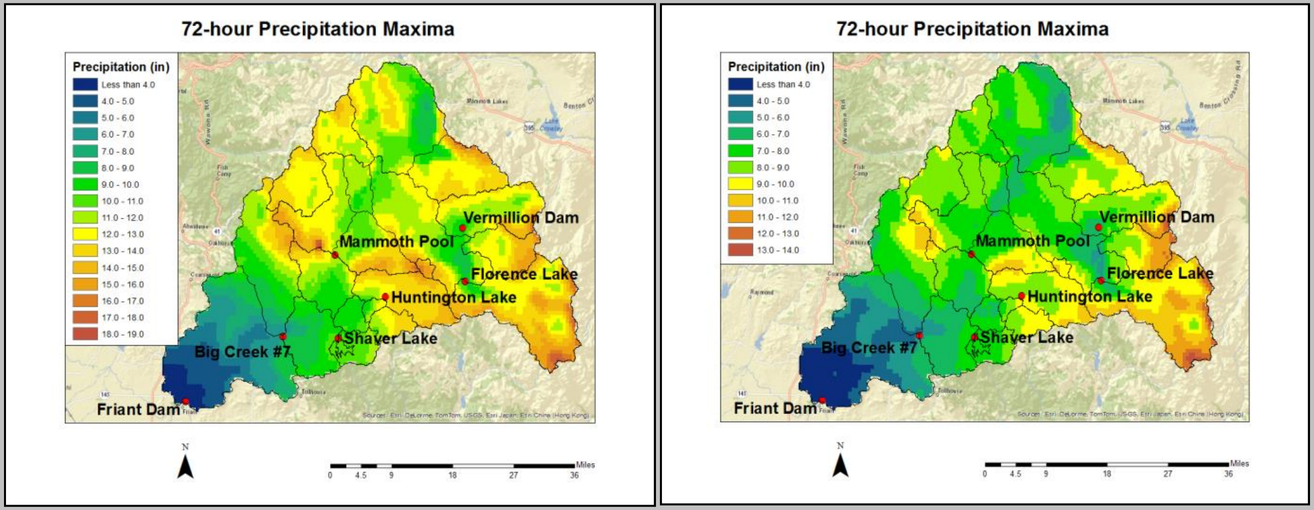
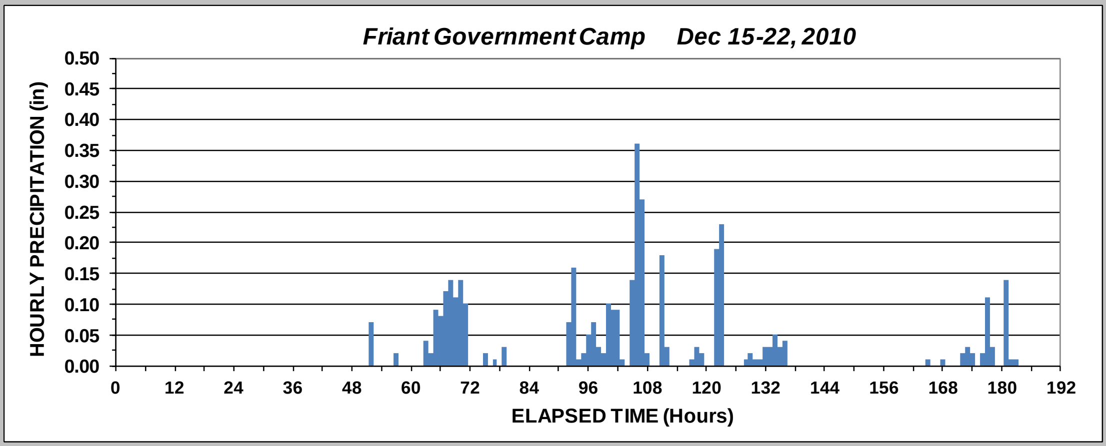
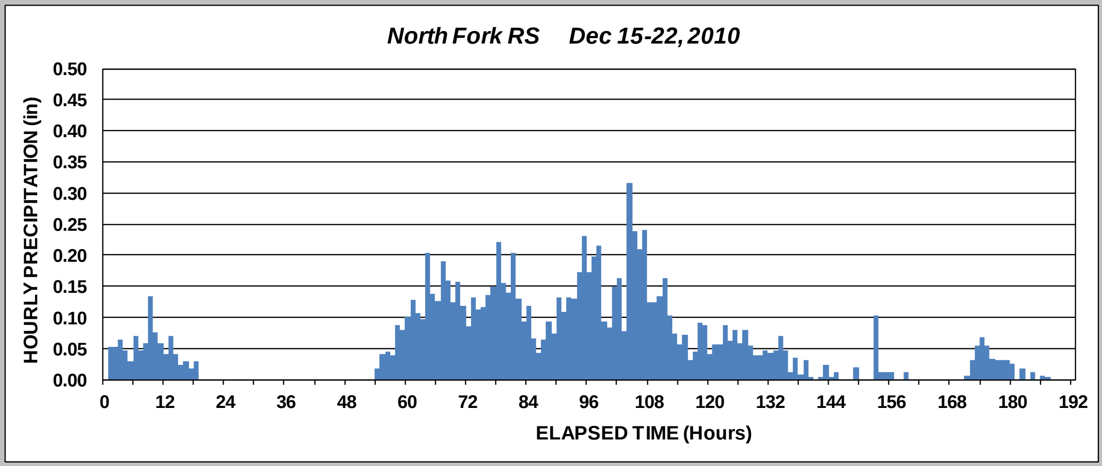


Figure 2-6.1 – Spatial Distribution of 72-Hour Precipitation for Storms of Dec 28-Jan 6, 2007 and Dec 15-24, 2010 on the Friant Watershed on the San Joaquin River in Southern California





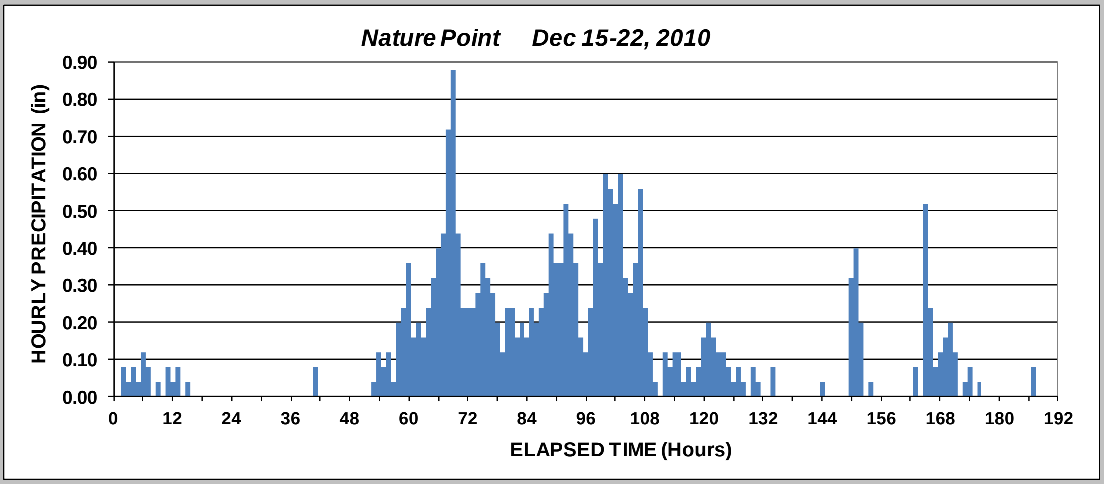
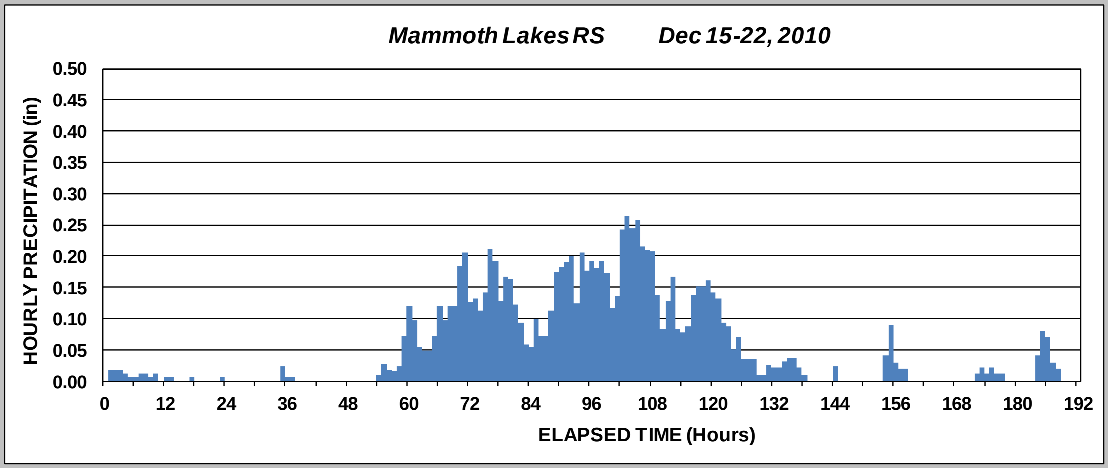


Figure 2-6.2a-c – Temporal Distributions of Precipitation for Storm of Dec 15-22, 2010 on Sub-basins of the Friant Watershed in Southern California



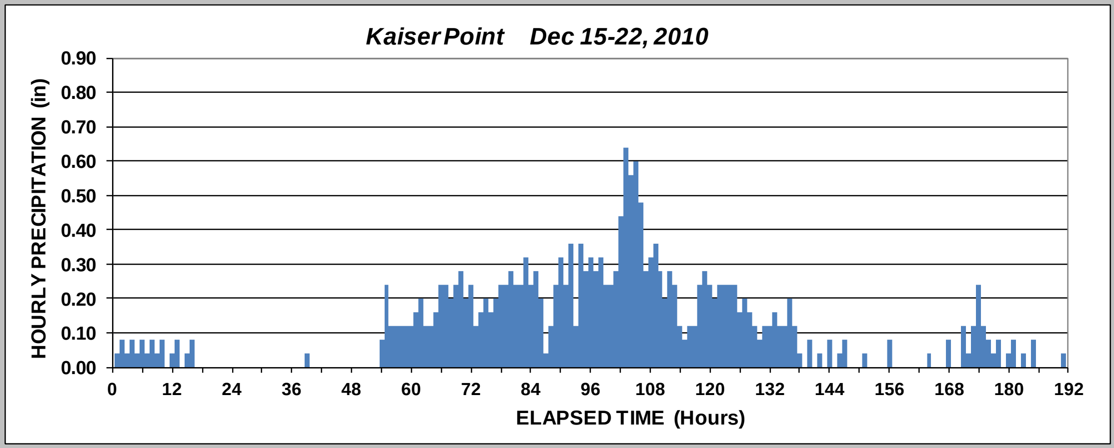


Figure 2-6.2d-e – Temporal Distribution of Precipitation for Storm of Dec 15-22, 2010 on Sub-basins of the Friant Watershed in Southern California

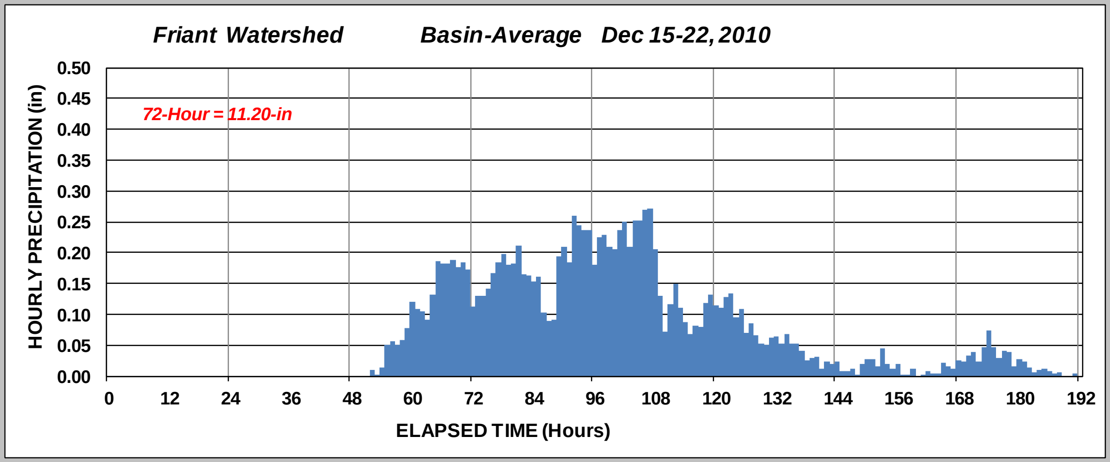


Figure 2-6.3 – Basin-Average Temporal Distribution of Precipitation for Storm of Dec 15-22, 2010 on Friant Watershed in Southern California

Storm Type – The historical storms used for developing the spatial and temporal storm templates must be for the storm type of interest, consistent with the annual maxima data used to develop the watershed precipitation-frequency relationship (Section 2-5).

SEFM Operation – Monte Carlo sampling is conducted for selection of basin-average precipitation from the watershed precipitation-frequency relationship (Section 2-5). A spatial and temporal storm template for a specific storm is selected by Monte Carlo sampling from the collection of spatial and temporal patterns (typically 10-25 storm templates). Storm templates are typically considered equally-likely unless there is evidence to weight individual storms differently. The basin-average precipitation value selected by Monte Carlo procedures is used to scale the spatial and temporal storm templates selected for a given flood simulation.

Assumptions/Expectations – It is assumed the collection of prototype spatial and temporal storm templates provides a representative sample of the diversity of spatial and temporal patterns for the storm type and watershed of interest. This assumption can be verified by assembling probability-plots of depth-duration values for the collection of candidate storms for a range of durations. The findings of the probability-plots may be used to confirm equally-likely weighting for the storms or provide information for assigning a different likelihood of occurrence to one or more storms.

Figure 2-6.4 shows probability-plots of depth-duration values for a key duration of 48-hours. A review of the probability-plots shows the storm data to be well-behaved and have high diversity in depth-duration values for all durations. This collection of storm templates would be judged to be representative of storm temporal characteristics for the watershed and the individual storms should be weighted as equally-likely.

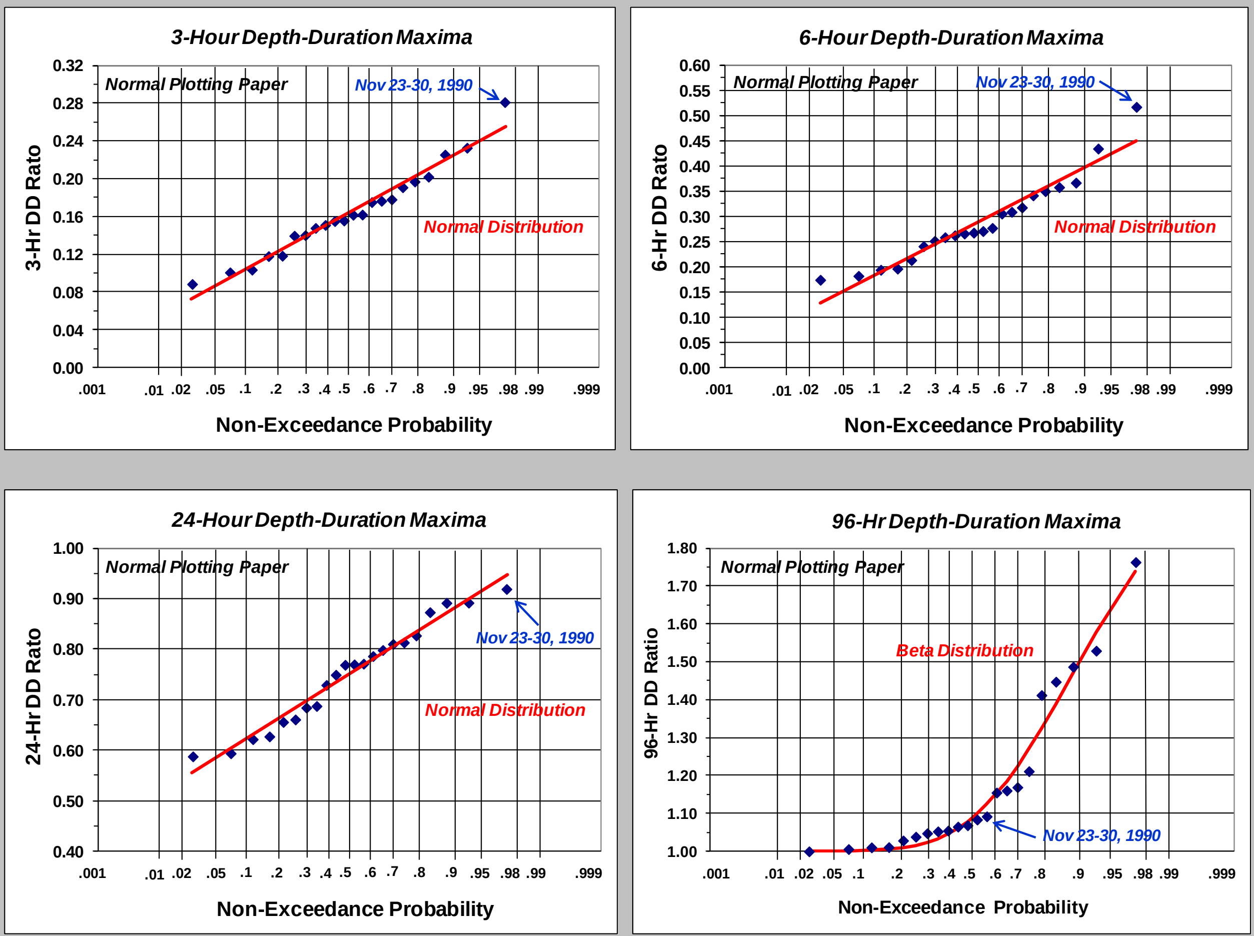


Figure 2-6.4 – Examples of Probability-Plots of Depth-Duration Values for a Collection of Storm Templates

The watershed precipitation-frequency relationship for the key duration is preserved through Monte Carlo simulation procedures. It is expected that a representative sample of temporal storm templates will reasonably preserve the watershed precipitation-frequency relationships for other durations in addition to the key duration. This can be visualized as follows. A Monte Carlo sample of say 10,000 annual maxima for the key duration (Figure 2-5.1) would also generate 10,000 precipitation maxima for all other durations of interest when the spatial and temporal storm templates are applied. The watershed precipitation-frequency relationships for these durations would be expected to be similar to the precipitation-frequency relationship that would be developed if the same procedures described in Section 2-5 would be applied to data for these other durations.

The preservation of precipitation-frequency relationships for a range of durations via the storm templates greatly reduces the sensitivity of the choice of the key duration used in developing the watershed precipitation-frequency relationship.

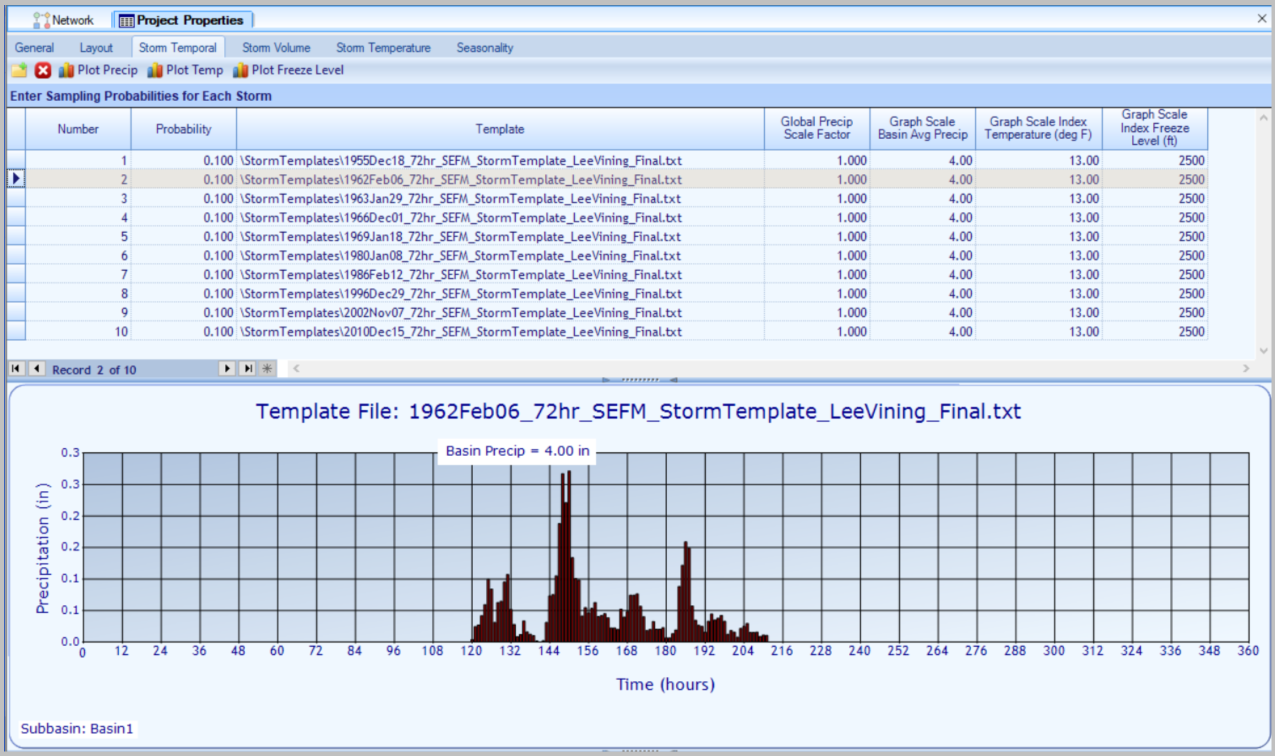
Augmenting Historical Storms with Transposed or Synthetic Storms – Situations may arise where there is a need to augment the sample set of historical storms with additional storms. The most common situation is when one or more extreme storms have occurred in a climatically compatible region and it is desirable to transpose that storm(s) to the watershed of interest.

The situation may also arise where there are an inadequate number of historical storms or there is a desire to include a specific storm temporal or spatial pattern in the collection of prototype storms. Synthetic storms may be added as prototype storms as assembled by any number of methods in current usage such as Hydrometeorological Reports for PMP and region-specific analyses. Particular care should be exercised in using synthetic storms to avoid extreme temporal and/or spatial patterns that would not be an element of a representative sample for the suite of prototype storms. The depth-duration values for these storms should be added to the probability-plots of depth-duration values (as shown in Figure 2-6.4) to provide a check on the suitability of the transposed or synthetic storm(s).

Guidance and Experience – The probability-plots of depth-duration values for the collection of prototype storms provides an objective measure of the representativeness of the prototype storms. Another check on the suitability of the prototype storms can be made by scaling the storms to a large magnitude basin-average precipitation, such as a 1:10,000 AEP. The incremental precipitation patterns can then be examined to determine if any of the patterns contain anomalous behavior or are otherwise implausible. This situation can occur when small-magnitude storms are scaled to rare AEPs. The final check before adoption of the collection of prototype storms is to conduct flood simulations and determine if any of the prototype storms produce unusual flood characteristics relative to the flood responses for the other prototype storms. The remedy for unusual storm/flood behavior is to either adjust the storm weightings (likelihood) or eliminate the storm from the suite of prototype storms.

File Format for Storm Templates – The spatial and temporal storm template for each prototype storm is stored in a separate ASCII text file that is read by SEFM. The file format is fixed field with narrative describing the template data which allows for easy readability of the storm template data and is described in detail in the Appendix.

Data Entry Format –The prototype storms are listed on the data entry form and sampling weights are identified for each storm. The prototype storms are weighted equally-likely unless there is evidence to indicate that one or more storms are unusual with regard to their depth-duration values or produce unusual flood characteristics relative to the collection of prototype storms. The data entry format is shown in Screen Shot 2-6.1.



Screen Shot 2-6.1 – Data Entry Screen for Storm Temporal Patterns

2-7 AIR TEMPERATURE TEMPORAL TEMPLATES FOR SNOWMELT COMPUTATIONS

Air temperatures during a storm can be an important factor for winter floods when precipitation falls as rain onto snow-covered ground. The stochastic generation of air temperatures throughout the watershed is accomplished by replicating the temporal patterns of air temperatures observed in historical storms. A Monte Carlo resampling approach is used that explicitly maintains the relationship between the temporal pattern of precipitation and the temporal pattern of air temperature.

Temporal patterns for historical storms are analyzed by meteorologists and extreme storm specialists for 1,000-mb air temperatures (approximately sea-level) and for freezing level. These analyses are based on available temperature data for the watershed and nearby locations and which include: daily maximum and daily minimum temperatures; hourly temperature data; and radiosonde data. Figure 2-7.1a and 2-7.1b depict examples of the temporal patterns of precipitation and 1,000-mb air temperature and freezing level for the storm of Nov 6-10, 2002 on the Friant watershed in southern California.

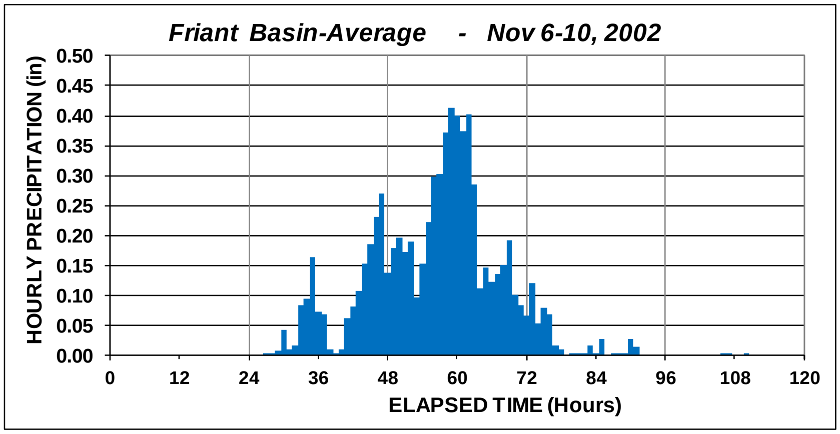


Figure 2-7.1a – Temporal Pattern of Precipitation for Storm of Nov 6-10, 2002 for Friant Watershed on San Joaquin River in Southern California

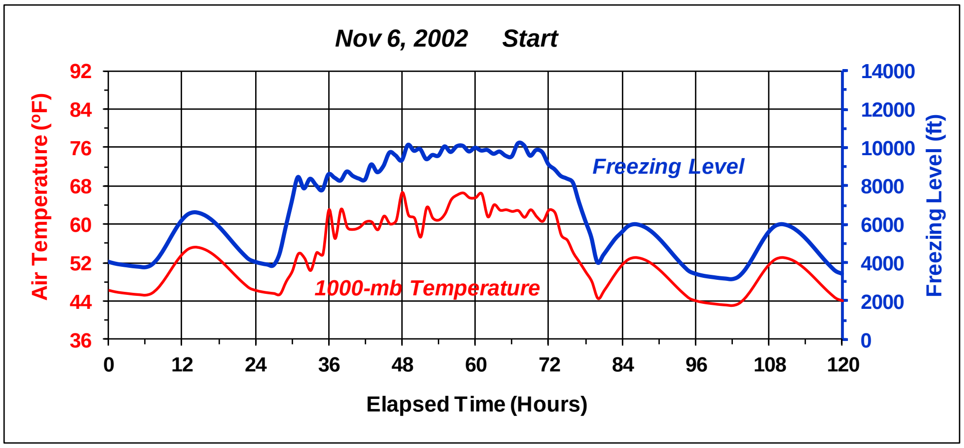


Figure 2-7.1b – 1,000-mb Air Temperature Temporal Pattern and Freezing Level Temporal Pattern for Storm of Nov 6-10, 2002 for Friant Watershed on San Joaquin River in Southern California

Storm Type – The long-duration synoptic-scale mid-latitude cyclone is the storm type that occurs in the cool season and is responsible for rain-on-snow events in the U.S.

Freezing Level on Day of Maximum 24-Hour Precipitation – Analysis of freezing level data during storms provides information on the behavior of air temperature profiles to be expected during storms. Computation of freezing level has the further advantage of allowing a more direct interpretation of the hydrologic implications with regard to the elevation where precipitation falls in the solid versus the liquid phase. Information on freezing level has often been found to be critical for watershed model calibration because it determines the proportion of the watershed that receives liquid precipitation and can yield runoff.

Studies[88,104,106] have found that freezing level varies with the magnitude of the 1000-mb air temperature and the magnitude of the 24-hour precipitation on the day of maximum 24-hour precipitation during the storm. Higher freezing levels are generally associated with higher 1000-mb air temperatures and larger 24-hr precipitation amounts. The physical interpretation is that deep layers of warm, moisture-laden air are conducive to large precipitation events. Therefore, very high freezing levels would be expected during very extreme storms.

Air Temperature Temporal Templates – The air temperature temporal templates for 1,000-mb air temperature and freezing level are stored as indexed patterns (time-series) for later scaling for application in a flood simulation. The indexing temperature for the 1,000-mb air temperature pattern is the maximum average 12-hour air temperature during the period of maximum 24-hour precipitation. The indexing air temperature for the example in Figure 2-7b is 65.8°F. The indexed 1,000-mb air temperature temporal pattern is created by subtraction of the indexing temperature from each ordinate of the 1,000-mb air temperature temporal pattern.

Similarly, the indexing freezing level for the freezing level temporal pattern is the maximum average 12-hour freezing level during the period of maximum 24-hour precipitation. The indexing freezing level for the example in Figure 2-7b is 9,800-feet. The indexed freezing level temporal pattern is created by subtraction of the indexing freezing level from each ordinate of the freezing level temporal pattern.

File Format for Air Temperature Storm Templates – The air temperature temporal templates for 1,000-mb air temperature and freezing level for each prototype storm are stored in the ASCII text file that contains the spatial and temporal storm templates (Section 2-6) for that prototype storm. The file format is fixed field with narrative describing the template data which allows for easy readability of the storm template data and is described in detail in the Appendix.

SEFM Operation – During the stochastic simulations, the indexing 1000-mb air temperature (°F) and indexing freezing level (feet) are stochastically generated for the day of maximum 24-hour precipitation. These values are then used to scale the 1000-mb air temperature temporal pattern and the freezing level temporal pattern. Scaling is accomplished by addition of the indexing 1,000-mb air temperature to the ordinates of the indexed 1,000-mb air temperature temporal pattern and addition of the indexing freezing level to the ordinates of the indexed freezing level temporal pattern. Linear interpolation is then used with the scaled 1000-mb air temperature and freezing level temporal patterns to produce air-temperature temporal patterns for each of the elevation zones within the watershed.

The 1000-mb and freezing level temporal patterns provide the data needed for allocating the time-series of air temperatures for each elevation zone. These air temperatures are then used for computation of snowmelt for each HRU.

Figure 2-7.2 depicts an example of air temperature temporal patterns for the storm of Nov 6-10, 2002 where the index 1,000-mb air temperature was 63.0°F and the index freezing level was 11,000-feet. These air temperature temporal patterns provide a perspective on how air temperatures would be applied to HRUs in the various elevation zones.

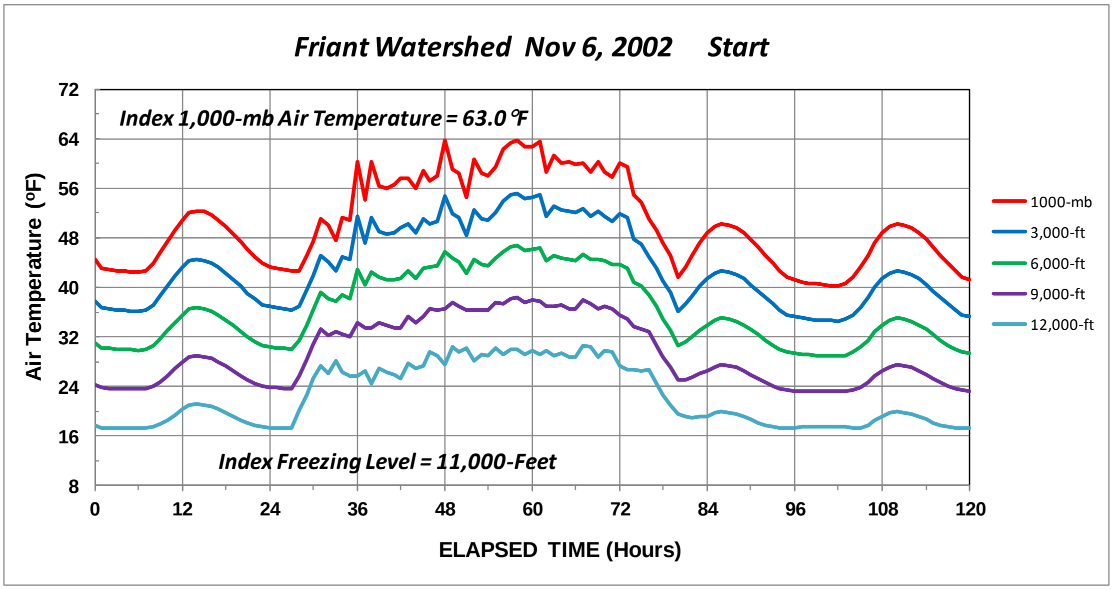


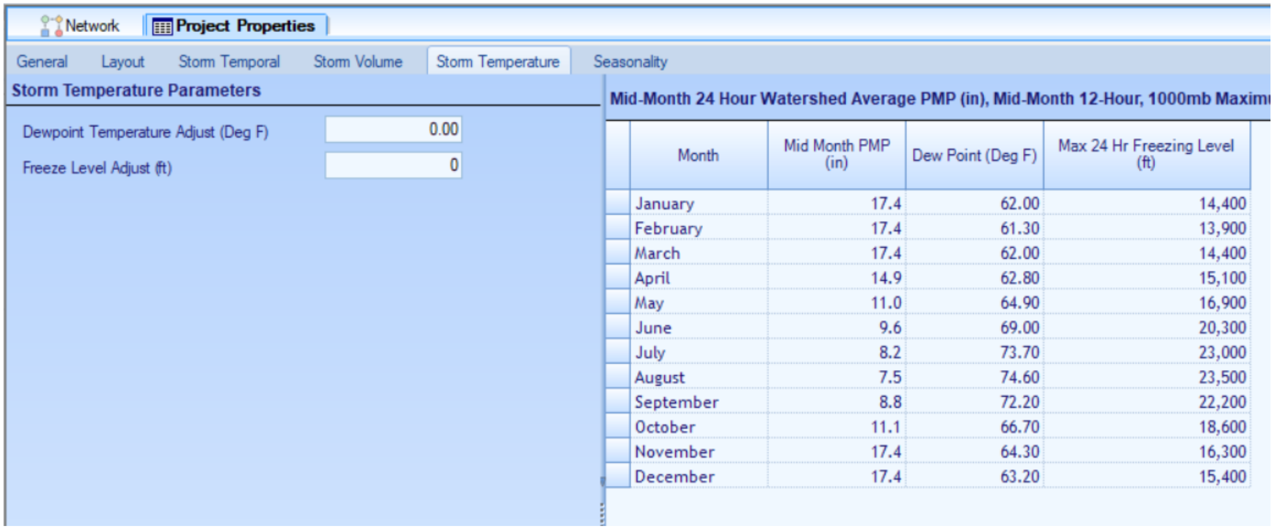
Figure 2-7.2 – Example of Air Temperature Temporal Patterns for Storm of Nov 6-10, 2002 for Friant Watershed

Assumptions/Constraints –The mid-month 1,000-mb dewpoint temperature is bounded on the upper end by the mid-month PMP dewpoint, and limited on the lower end by the minimum dewpoint temperature (atmospheric moisture) capable of generating a selected 24-hour watershed precipitation (Figure 2-7.3). Atmospheric moisture is near 100% relative humidity during major storm events and thus dewpoint temperatures are nearly equal to air temperatures. A minor adjustment of a few degrees Fahrenheit is needed to yield an air temperature given the dewpoint temperature.

The maximum mid-month freezing level is set by meteorologists based on the historical record of freezing level and judgments made for atmospheric conditions during very extreme storms.

Data Entry Format –Data entry consists of entering the mid-month PMP dewpoints (°F), mid-month 24-hour PMP values for the watershed and mid-month maximum allowable freezing levels. These values are used in the Monte Carlo procedures for selection of the indexing value of the 1,000-mb air temperature and indexing value of the freezing level. As discussed above, the indexing values represent maximum average 12-hour values during the period of maximum 24-hour precipitation and are used to scale the air temperature temporal templates for use in snowmelt computations. The data entry format is shown in Screen Shot 2-7.1.

Two addition inputs are required that adjust the outputs of the simulations for 1,000-mb air temperature and freezing level. These adjusts are used in calibration of SEFM in matching historical flood-frequency curves for volume. The default values of the adjustments are 0°F for 1,000-mb air temperature and 0-ft for freezing level and are shown in Screen Shot 2-7.1.



Month	Mid Month PMP (in)	Dew Point (Deg F)	Max 24 Hr Freezing Level (ft)
January	17.4	62.00	14,400
February	17.4	61.30	13,900
March	17.4	62.00	14,400
April	14.9	62.80	15,100
May	11.0	64.90	16,900
June	9.6	69.00	20,300
July	8.2	73.70	23,000
August	7.5	74.60	23,500
September	8.8	72.20	22,200
October	11.1	66.70	18,600
November	17.4	64.30	16,300
December	17.4	63.20	15,400

Screen Shot 2-7.1 – Data Entry Format for use with Air Temperature Temporal Templates

2-7.1 Simulation of Air Temperature Temporal Patterns

The air temperatures during a storm are not random, but are related to the magnitude of the storm. For a given storm efficiency, higher dewpoints are needed to support the higher levels of atmospheric moisture required to produce greater precipitation magnitudes. During extreme storms, the relative humidity is near 100-percent, thus air temperatures and dewpoint temperatures are nearly the same. As a result, the air/dewpoint temperature during an extreme storm and the magnitude of precipitation for the period of heavy precipitation are correlated variables. A physics based probability model is used in the SEFM for Monte Carlo selection of 1000-mb air temperatures (near sea-level) that is based on monthly maximum dewpoints and storm magnitude.

Analysis of freezing level data from storms provides information on the behavior of air temperature profiles to be expected during very extreme storms. Computation of freezing level has the further advantage of allowing a more direct interpretation of the hydrologic implications with regard to the elevation where precipitation falls in the solid versus the liquid phase. Information on freezing level has often been found to be critical for watershed model calibration because it determines the proportion of the watershed that receives liquid precipitation and can yield runoff.

Studies[88,104,106] have found that freezing level varies with the magnitude of the 1000-mb air temperature and the magnitude of the 24-hour precipitation on the day of maximum 24-hour precipitation during the storm. Higher freezing levels are generally associated with higher 1000-mb air temperatures and larger 24-hr precipitation amounts. The physical interpretation is that deep layers of warm, moisture-laden air are conducive to large precipitation events. Therefore, very high freezing levels would be expected during very extreme storms.

Figure 2-7.3 depicts an example of the physics-based framework for constraint of 1,000-mb dewpoint temperatures used in stochastic simulations for selection of the index value of 1,000-mb dewpoint temperature. A four-parameter Beta distribution (Benjamin and Cornell[4]) is used to describe the behavior of dewpoint temperature between the upper and lower bounds.

Studies of air-temperature lapse-rates (Schaefer et al[88,104] and USBR[106]) during the period of maximum 24-hour precipitation for major storms in the coastal mountains of the western U.S. and British Columbia has shown the air temperature lapse rates to be near Normally distributed (Figure 2-7.4). This finding is used in the stochastic simulations for selection of the indexing freezing level.

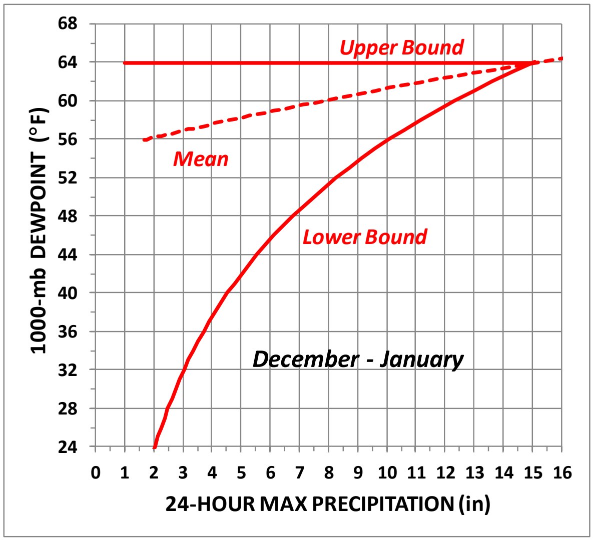


Figure 2-7.3 – Example of Bounding Conditions for 1,000-mb Dew-Point Temperature as Function of Maximum 24-Hour Precipitation in Long-Duration Mid-latitude Cyclones

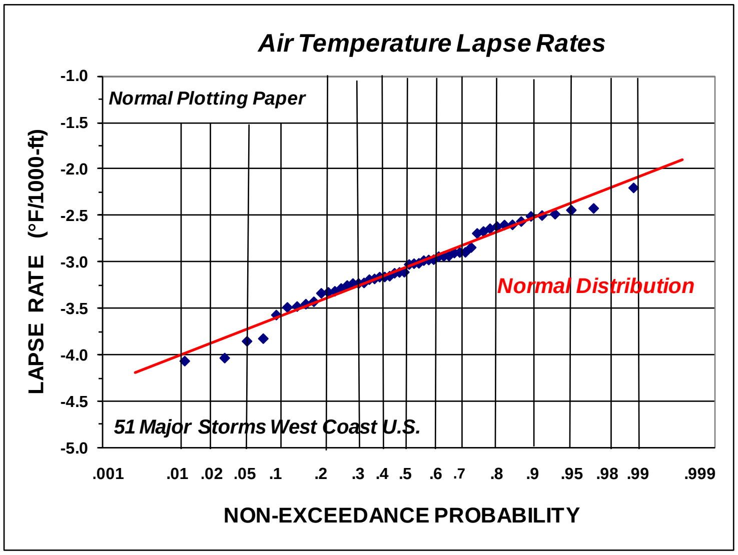


Figure 2-7.4 – Probability-Plot of Air Temperature Lapse-Rates During Maximum 24-Hour Precipitation for 51 Major Storm Events in Coastal Mountain Areas of Western US and BC

An example of Monte Carlo simulation of freezing levels for mid-December is shown in Figure 2-7.5 for the Friant watershed in southern California. Note the general trend of increased freezing level with maximum 24-hour precipitation and the relatively high degree of natural variability.

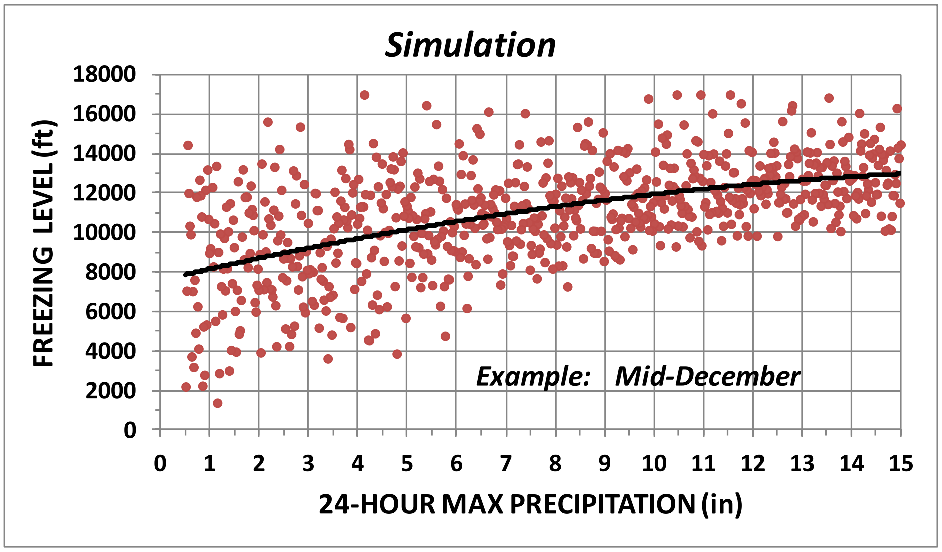


Figure 2-7.x – Example of Stochastic Simulation of Freezing Level During Maximum 24-Hour Precipitation for Mid-December for Friant Watershed in Southern California

2-8 SETTING STATE VARIABLES FOR INITIAL WATERSHED CONDITIONS

Several of the hydrometeorological inputs to SEFM are needed for setting initial watershed conditions at the start of a flood simulation. The hydrometeorological input parameters for a watershed model that vary seasonally with precipitation and other climatic inputs are termed *state variables* because they describe the state of the hydrologic conditions at a given point in time. The list of state variables needed for setting initial watershed conditions includes:

- Soil moisture conditions for all soil moisture storages for each HRU
- Streamflow for the outlet of each sub-basin
- Reservoir level and reservoir discharges for all reservoirs

If snowpack and rain-on-snow floods are considerations, then the following state variables are also needed:

- Snowpack, snow-water equivalent (SWE) for each HRU
- Snow density for each HRU

If frozen ground and rain-on-frozen ground are considerations, the following state variable is needed:

- Average air temperature for prior 14-days for all elevation zones (antecedent temperature)

Use of a Resampling Approach for Setting the Values of State Variables – A resampling approach is used within the SEFM stochastic engine for selecting the values of state variables for setting the initial watershed conditions at the start of a flood simulation. Specifically, values of the state variables are resampled (randomly selected) from either historical data or from computer simulated values of the state variables. The manner in which the sample set of values of the state variables are obtained/developed is dependent upon several factors including:

- Can the state variable be observed and measured directly, such as reservoir level, or must it be estimated from computer simulation, such as a soil moisture storage
- If the state variable is measured directly, is the record length sufficient to provide an adequate sample size for resampling
- If values of the state variable(s) are obtained through computer simulation, are the length of record and quality of data for the hydrometeorological time-series used to generate the state variables(s) adequate to provide a representative sample with adequate sample size

For the case of state variables for streamflows, river levels and reservoir levels, sufficient historical data are typically available to allow direct use of the historical data in a resampling approach. The procedures for creating the sample set of values for streamflows, river levels and reservoir levels are described in Section 2-9.

There are two options for creating the values of state variables for hydrologic soil parameters and snowpack (SWE) for mid-month and end-of-month conditions. One option uses continuous watershed modeling to create the sample set of values for the state variables. The second option relies on frequency analyses and correlation analyses of hydrometeorological data such as precipitation and snowpack (SWE). Soil moisture accounting methods are then used within a Monte Carlo framework for computing values of the state variables.

Both methods are briefly described below and details are contained in Section 2-10 for the continuous watershed modeling approach and Section 2-11 for the probabilistic analysis approach.

Continuous Modeling to Create a Sample Set of State Variables – In this approach, a continuous watershed model is used along with hydrometeorological time-series for precipitation, potential evapotranspiration and snow-water equivalent for the zones of mean annual precipitation and elevation for developing a long time-series of values for hydrologic soil parameters for mid-month and end-of-month conditions. The precipitation time-series may be augmented with either data transposed from climatologically similar areas or synthetically generated data to provide magnitudes of state variables and/or combinations of conditions not seen in the historical record. Details about the continuous modeling approach to creating a sample set of values of the state variables are described in Section 2-10.

Probabilistic Analyses of Hydrometeorological Data to Create a Sample Set of State Variables
It is common in remote areas that insufficient hydrometeorological data are available to support using a continuous watershed model for developing a sample set of values for state variables. In these situations, the approach is to conduct frequency analyses and correlation analyses of the hydrometeorological data for precipitation and snowpack (SWE) for data sources within or near the watershed or from data sources within climatologically similar areas.

Monte Carlo simulation methods are used which preserve the dependencies between antecedent precipitation and snowpack to develop snowpack SWE values for mid-month and end-of-month conditions for the zones of mean annual precipitation and elevation within the watershed. Monte Carlo simulation methods are then used using precipitation, potential evapotranspiration and snowpack SWE along with soil moisture accounting methods to create the sample sets of values of the state variables for hydrologic soil parameters.

A single-event watershed model is often used when data are sparse and the findings of probabilistic analyses are used to develop the values of the state variables for hydrometeorological inputs. Details about the probabilistic analysis approach to creating a sample set of values of the state variables are described in Section 2-11.

2-9 SETTING STATE VARIABLES – STREAMFLOWS AND RESERVOIR LEVELS

Sample-sets of values of state variables for several of the hydrometeorological inputs can be created directly from historical data. In particular, streamflow is needed at the outlet of each sub-basin in the watershed for the start of flood simulations. River levels may also be needed for specific locations within the watershed. And reservoir level, and associated reservoir storage and reservoir discharge are needed for each reservoir in the watershed for the start of flood simulations. Sample sets of values for each of these state variables can usually be assembled from historical data.

2-9.1 Determining State Variables for Streamflow and Reservoir Level

Historical records of streamflow, river level and reservoir level are commonly available for high consequence dams and infrastructure. Time-series of streamflow and river level are usually available from the USGS, public water resource agencies or hydropower utilities. Measurements of reservoir level are typically available on a daily or hourly interval from the dam owner or dam operator.

SEFM Operation – For execution of SEFM, a linked database is created where the values for streamflow, river level and reservoir level are stored for mid-month and end-of-month dates in conjunction with the values of antecedent precipitation for those dates. The time-series of antecedent precipitation provides a common link between streamflow, river level and reservoir level and the climatological conditions that produced the observed conditions.

A separate linked database of antecedent precipitation is developed for use with the other hydrometeorological inputs for snowpack and state variables for hydrological soil parameters. This is discussed in more detail later in this section and in Section 2-10.

Guidance and Experience – It is usually inaccurate to use the reservoir rule curve for setting initial reservoir conditions. There is high natural variability in climatological conditions which often results in large differences in reservoir levels for very dry years versus very wet years. This climatic variability causes frequent departures from the reservoir rule curve. In addition, water resource decisions are often made throughout the year which results in departures from the rule curve. The combined effect is to generally have high variability in reservoir levels relative to what would be expected from review of the reservoir rule curve.

In cases where reservoir level data are unavailable, it may be necessary to use the reservoir rule curve along with anecdotal information on historical operations to create a reasonable sample set of reservoir levels. In some cases, it may be possible to use a continuous watershed model for simulation of reservoir levels to create a sample set of reservoir levels for use in flood simulations.

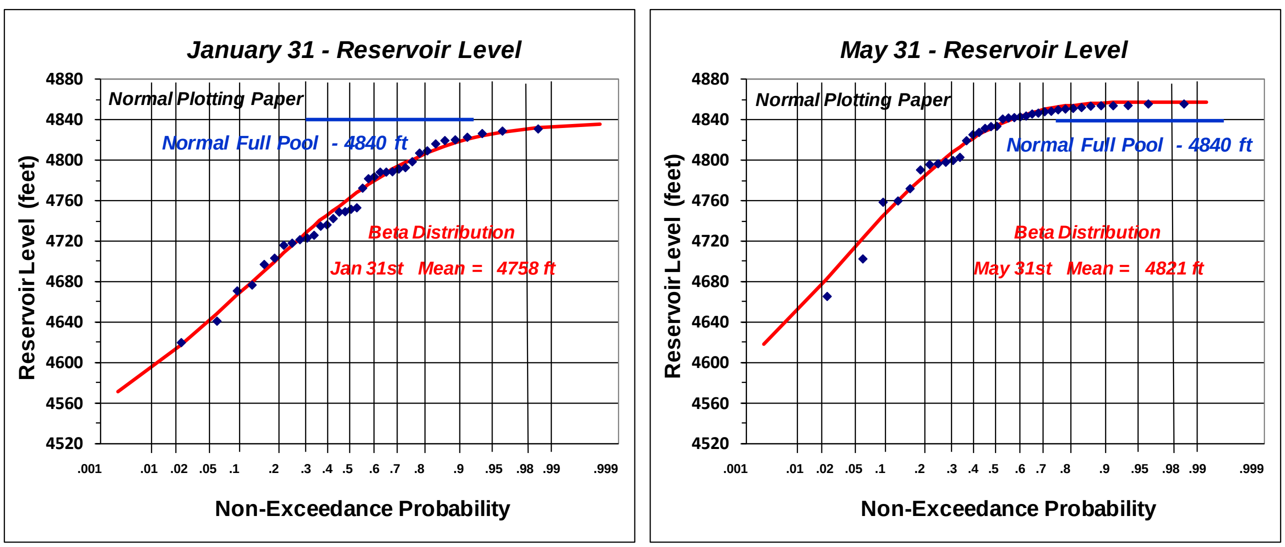
Another common case is that reservoir operations have changed recently and the current record of reservoir levels is inadequate to reasonably describe the seasonal variability that would be expected in reservoir levels. One option would be to use long time-series of precipitation and other hydrometeorological time-series in conjunction with a continuous watershed model to simulate a long-time-series of reservoir levels (Section 2-10) for use in flood simulations.

Imposed Constraints on Initial Streamflows and Reservoir Level(s) – Upper limits may be placed on initial streamflows and reservoir level(s) for production runs of SEFM. This is done to eliminate unrealistic initial conditions that may exist within the time-series of historical streamflows and reservoir levels. This situation occurs most commonly when a flood is already occurring on a given mid-month or end-of-month date. This would result in double-counting where the stochastic storm/flood was inserted within an on-going flood. The resampling approach allows for the possibility of wet antecedent soil conditions, high streamflows and high reservoir levels representative of seasonal conditions but provides a mechanism to prevent implausible and unrealistic antecedent conditions.

2-9.2 Assessing the Adequacy of Samples of Streamflows and Reservoir Levels

The adequacy of available samples of streamflows, river level and reservoir levels can be evaluated using probability-plots. Probability-plots should be created for the dataset of values for each state variable for each mid-month and end-of-month date. This will allow review of the range and diversity of a given hydrometeorological input and assessment of the representativeness of the sample.

Figures 2-9.1a,b depicts examples of reservoir levels for mid-winter and late-spring for a reservoir in the Sierra Mountains in central California. The reservoir is operated for both hydropower and irrigation water supply and is heavily drawn down at the end of the irrigation season and refills over the winter and spring snowmelt months. This type of reservoir operation, in combination with a highly variable climate, results in an extreme range of reservoir levels between very dry and very wet years. The likelihood of having a relatively low initial reservoir level can have a significant effect on maximum reservoir levels produced by a flood, the magnitude of spillway discharges and the resultant hydrologic hazard curves.



Figures 2-9.1a,b – Probability-Plots of Seasonal State Variables for Reservoir Level

Augmenting Historical Data – In reviewing the probability-plots, it is possible that the available hydrometeorological time-series are too short, or insufficiently representative, to provide for an adequate sample of the hydrometeorological inputs. There are two options for expansion of the sample-set of values for the state variables.

The first option is to fit the historical data by a 4-parameter Beta Distribution (Benjamin and Cornell[4]) or other suitable probability distribution to obtain values of each of the state variables for selected non-exceedance probabilities. Correlation analyses would also be conducted between each of the state variables and antecedent precipitation for the key station to determine representative values of antecedent precipitation to be used for the additional values of the state variables.

If probabilistic analyses are used to augment the sample-set of state variables, the expanded sample-set would be comprised of two components. The first component is the observed historical values for a sample size equal to the number of years of record. The second component is a set of the values of state variables along with their non-exceedance probabilities.

The second option is to use long time-series of precipitation and the other hydrometeorological time-series with continuous watershed modeling to compute additional values of the state variables for streamflows, river levels and reservoir levels. This may or may not be a practical solution for a given project.

2-9.3 Use of Time-Series of Antecedent Precipitation for Linking State Variables

The length of historical data and the period-of-record available for streamflow, river level and reservoir level are often different than the time-frame and length of records available for precipitation, air temperature and snowpack. Therefore, it is often necessary to assemble two databases for resampling of state variables. One database is used for selecting values for streamflows, river levels and reservoir level(s). The other database is used for selecting values for the hydrologic soil parameters, snowpack and antecedent air temperature for the various HRUs.

A common link between the two databases is provided by a representative value of antecedent precipitation for any given month/day of the year. Antecedent precipitation is defined as the cumulative precipitation from a specified start date and extends for a 12-month period. Ideally, the start date for antecedent precipitation is chosen at a time of the year that is hydrologically benign, where soil moistures are near the wilting point, storm activity is low and streamflows are low.

The term *key station* is given to the precipitation station that is used for providing representative values of antecedent precipitation for the various state variables in the watershed

Selecting a Key Station for Antecedent Precipitation – As discussed above, a key station for antecedent precipitation is needed to provide a common link for all state variables for a given magnitude of antecedent precipitation for a given month/day of the year. Ideally, the key station is chosen which is centrally located in the watershed and representative of typical climatological conditions for the watershed. The daily precipitation time-series for the key station must be sufficiently long to cover the time period for all of the state variables.

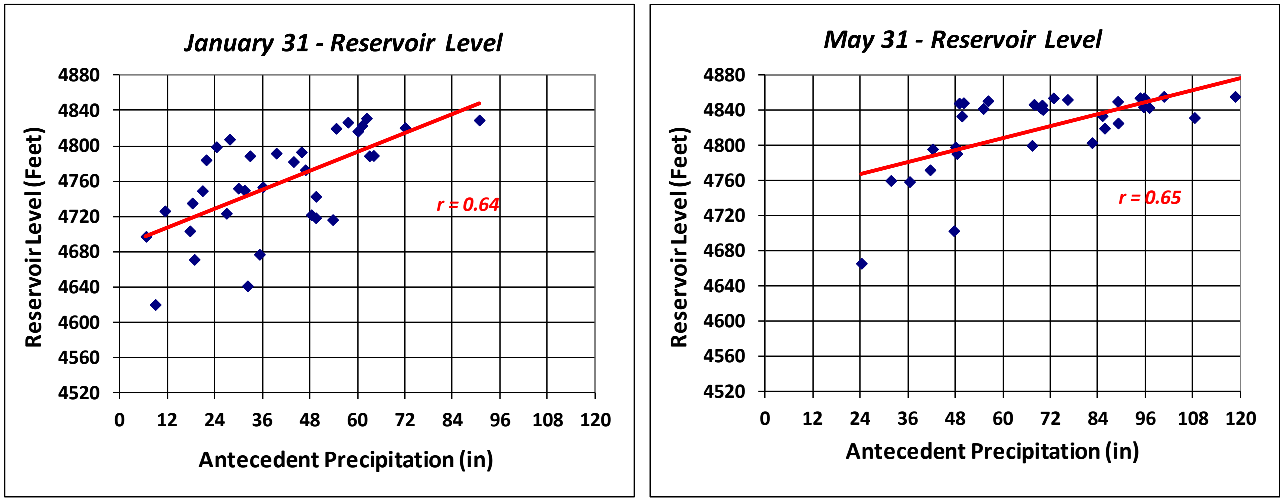
2-9.4 Execution of a Resampling Approach for Streamflows and Reservoir Levels

A variation of the standard Monte Carlo resampling approach is used for streamflows, river levels and reservoir levels to better emulate the level of correlation with the linking variable.

Use of a Shuffle Procedure in Resampling – Variability in selection of state variables within a resampling scheme can be created by using a "shuffle" selection procedure for the case of linked datasets. A shuffle selection is similar in concept to a shuffle with a deck of cards. Specifically, a selected number of values (n) for a specific state variable are chosen which have values of the linking variable nearest a previously selected value of the linking variable. One of the values of the state variables is then chosen at random from the n values.

For the case of streamflow, river level and reservoir level, the linking variable is antecedent precipitation at the key station. The number of values (n) chosen for the shuffle is based on the total sample size (N) and the magnitude of correlation with antecedent precipitation. A small (n/N) value would be chosen where the correlation is moderate to high and a larger (n/N) value would be chosen where the correlation is low. An n value of 1 results in the standard resampling scheme.

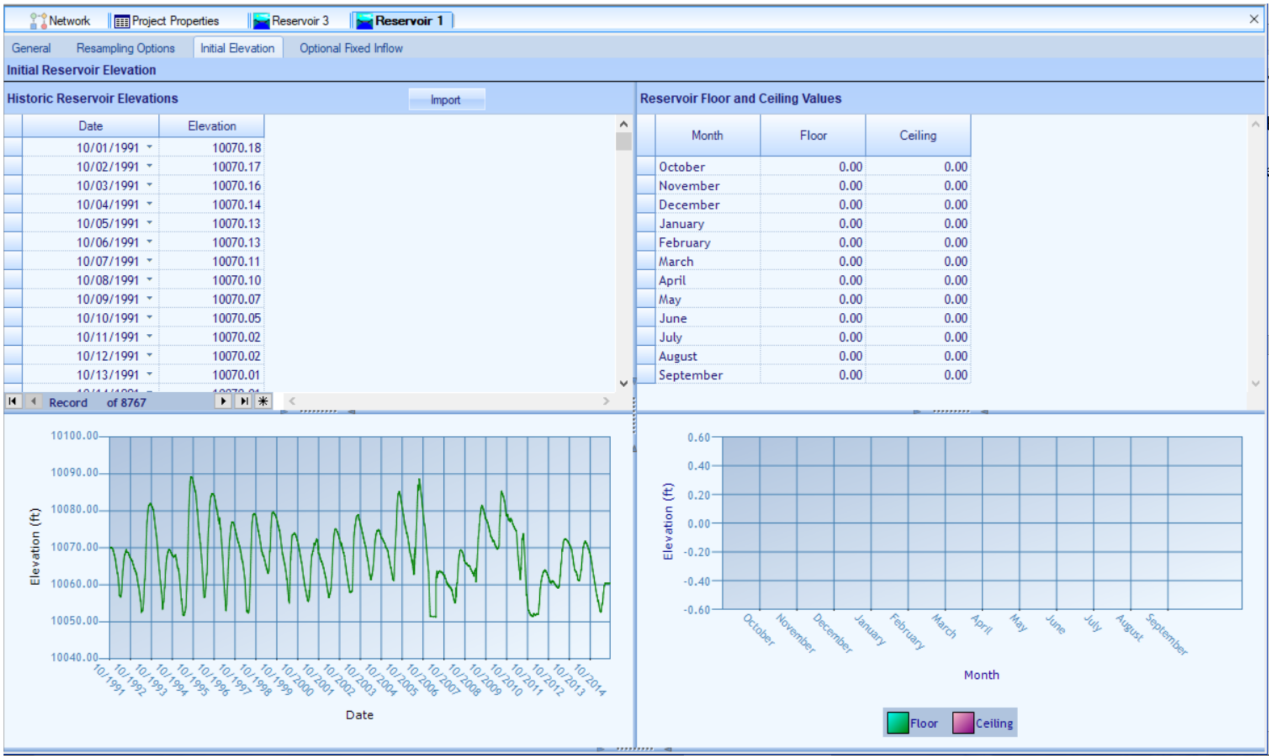
Guidance and Experience – Streamflows, river levels and reservoir levels often have a moderate level of correlation with antecedent precipitation for a given date. The level of correlation can be examined through scatter-plots and computation of correlation coefficients. This information can prove helpful in selecting the size of the shuffle for the resampling scheme to better replicate the natural scatter (unexplained variance) in the scatter-plots. Figures 2-9.2a,b depicts examples of scatter-plots and sample linear correlation coefficients for the reservoir in central California described previously (Figures 2-9.1a,b). A shuffle (*n*) value of 5 would reasonably capture the variability depicted in the scatter-plots shown below and provide for a greater number of combinations of values with the state variables for hydrologic soil parameters.



Figures 2-9.2a,b – Scatter-Plots of Seasonal State Variables for Reservoir Level Depicting Correlation with Antecedent Precipitation at Key Station

SEFM Operation – Selection of values of state variables for streamflows, river levels and reservoir levels for setting initial watershed conditions proceeds as follows.

1. A month and day would have been previously selected based on the seasonality of storms for the storm type/flood being analyzed;
2. A year is selected at random within the range of years for the state variables for hydrological soil properties (Section 2-10). The date for the mid-month/year or end-of-month/year is used to set the values for the state variables for hydrological soil parameters and snowpack SWE for the various HRUs.
3. The antecedent precipitation at the key station for the date chosen in Step 2 is noted.
4. The linked database of state variables for the chosen date for streamflows, river levels and reservoir levels is sorted by magnitude of antecedent precipitation. This provides a look-up table of state variables for streamflows, river levels and reservoir levels corresponding to the value of antecedent precipitation selected in Step 3.
5. The shuffle procedure is used for selection of state variables. Specifically, a selected number (*n*) of values for a specific hydrometeorological input are chosen which have antecedent precipitation values nearest the antecedent precipitation value chosen in Step 3. One of the values of the state variables is selected at random from the *n* values.



Screen Shot 2-9.1 – Data Entry Format for Resampling of State Variables for Streamflows and Reservoir Levels

2-10 SETTING STATE VARIABLES – CONTINUOUS WATERSHED MODELING

The preferred approach in SEFM is to use continuous watershed modeling to create the sample-set of values of the state variables for hydrologic soil parameters for each HRU. Hydrometeorological time-series for precipitation, potential evapotranspiration and snow-water equivalent for the zones of mean annual precipitation and elevation are used in conjunction with a continuous watershed model and soil moisture accounting methods for developing a long time-series of values of the state variables for the hydrologic soil parameters. For watersheds where snowpack and rain-on-snow floods are possible, continuous watershed modeling can also be used to create the time-series for snowpack, snow-water equivalent (SWE) for each combination of the zones of mean annual precipitation and elevation.

The hydrometeorological time-series for precipitation, potential evapotranspiration and snow-water equivalent may be developed using a number of different methods based on data availability. The sample-sets of values of the state variables for hydrologic soil parameters and snowpack are used in a Monte Carlo resampling approach for setting initial watershed conditions for flood simulations.

Hydrometeorological Time-Series for Continuous Watershed Modeling – Several hydrometeorological time-series are needed for developing the sample-set of values of the state variables for the hydrologic soil parameters. The hydrometeorological time-series required for continuous watershed modeling are listed below along with a summary of the sequence of tasks. More detailed information on the various tasks and topics is provided later in this section and an excellent reference for continuous watershed modeling and watershed model calibration is contained in the documents prepared by Anderson[97].

For large watersheds and complex hydropower systems, it is usually necessary to calibrate the watershed model and develop sample-sets of state variables for multiple locations in the watershed where streamflow data are available. The following list describes the sequence of tasks for a simple example; a mountainous watershed where streamflow data are available just upstream of the inlet to the reservoir at the outlet of the watershed.

1. Assemble daily time-series of precipitation for measurement sites located within and near the watershed. Use the precipitation data to develop a daily time-series of areal-average precipitation for the watershed and disaggregate the areal-average time-series to develop daily precipitation-time-series for the mid-point of each zone of mean annual precipitation.
2. Assemble daily time-series of air temperature for measurement sites located within and near the watershed. Use the air temperature data to develop air temperature time-series for the mid-point of each elevation zone. Air temperature data may be daily maximum and minimum temperatures or mean daily temperatures depending on the requirements of the chosen watershed model.
3. Develop daily time-series of potential evapotranspiration applicable to each elevation zone.
4. Use the daily time-series of precipitation and air temperature to develop a daily time-series of snowpack (SWE) for combinations of zones of mean annual precipitation and elevation where snowpack develops. This may also require a daily time-series of solar radiation depending on the requirements of the snow module used for modeling the accumulation and ablation of the snowpack.

5. If frozen ground is a consideration for flood simulations, use the daily time-series of air temperature to develop a time-series of the mean daily air temperature for the 14-days (two-weeks) prior to a given day for the mid-point of each elevation zone.
6. Assemble a daily time-series for unregulated (natural) streamflow volumes (in, mm) for the stream location where the watershed model is to be calibrated. This will usually require adjustments to the regulated streamflows where dams/reservoirs have modified the natural streamflows. Reverse reservoir routing (Zoppou[129]) can be used at a dam/reservoir to compute unregulated inflows to the reservoir.
7. Use the daily hydrometeorological time series to calibrate the watershed model to historical streamflow volumes (Step 1, Figure 2-10.1) to provide initial estimates of the hydrological soil properties for each HRU.

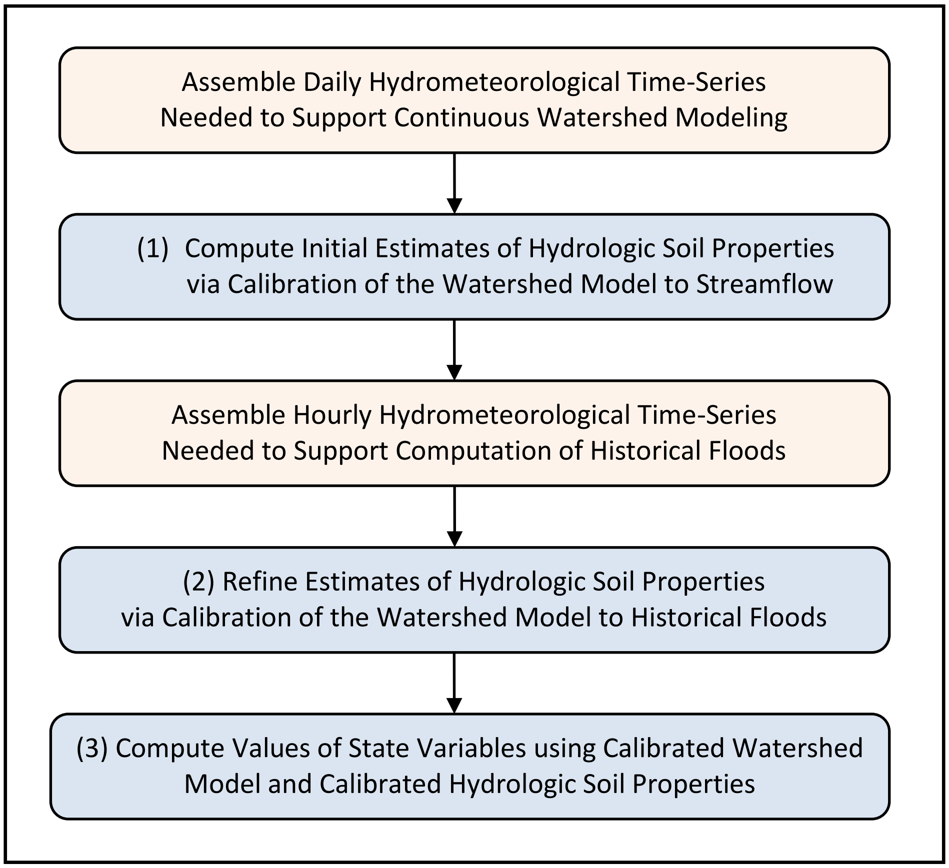


Figure 2-10.1 – Sequence of Tasks for Determining Values of State Variables for Initial Watershed Conditions for Hydrologic Soil Parameters

Calibration of the Watershed Model – This is an iterative process where initial estimates of the hydrologic soil properties such as surficial and subsurface soil moisture storage capacity, surface infiltration and deep percolation rates for the various soil zones are determined through calibration to observed streamflow volumes. This is accomplished using a watershed water budget equation and either a continuous watershed model or a hydrologic soil moisture accounting module. Equations 2-10.1a and 2-10.1b list the watershed water-budget equation that is to be solved at the chosen time-step for each HRU, where the units of measurement are inches (mm):

$$Runoff = Precip_{liquid} - Precip_{snow} + Snowmelt - PET - \Delta SoilMoistureStorage \quad (2\text{-}10.1a)$$

$$Streamflow = f(Runoff) \quad (2\text{-}10.1b)$$

where: *Streamflow* is a time-dependent function of the computed *Runoff*; and *Runoff* is computed from the runoff contribution from all HRUs.

This first iteration (Step 1, Figure 2-10.1) provides estimates of the initial state conditions prior to the occurrence of historical storms/floods. The estimates of the hydrologic soil properties are then refined through calibration to historical floods (Step 2, Figure 2-10.1). The calibrated hydrologic soil properties are then used in conjunction with the calibrated continuous watershed model to develop a long time-series of values of state variables for the various hydrologic soil parameters (Step 3, Figure 2-10.1). The values of the computed state variables from the calibrated watershed model are saved on a daily basis or for mid-month and end-of-month dates for the full length of the hydrometeorological time-series for use with the Monte Carlo resampling approach for flood simulations. Detailed information on calibration of watershed models is contained in Section 4, *Calibration of Watershed Models*.

SEFM Operation – For execution of SEFM, a linked database is created where the state variables for the hydrologic soil parameters and snowpack SWE are stored for mid-month and end-of-month dates in conjunction with the values of antecedent precipitation for these dates. The time-series of antecedent precipitation provides a common link between the state variables for hydrologic soil parameters and the climatological conditions that produced the observed conditions.

A separate linked database of antecedent precipitation is developed for use with the other hydrometeorological inputs for streamflows, river levels and reservoir levels This is discussed in more detail later in this section and in Section 2-9.

2-10.1 Data Sources for Precipitation and Air Temperature

Precipitation time-series are needed for each zone of mean annual precipitation and air temperature time-series are needed for each zone of elevation for calibration of the continuous watershed model to streamflow volumes (Step 1, Figure 2-10.1). Daily time-series are typically used but other time-steps may be used depending on the data sources available. The hydrometeorological time-series can be assembled from data at stations within and near the watershed using a variety of methods where each method has advantages and disadvantages with regard to accuracy and level of effort. Assembling the datasets and filling missing values is often the most time-consuming task in using a continuous watershed model.

Daily Precipitation Time-Series – Daily time-series of precipitation are required for each zone of mean annual precipitation where the individual precipitation time-series sums to the areal-average precipitation for the watershed. This often requires linear scaling of precipitation from available stations within and near the watershed. These time-series can be assembled by starting with the daily precipitation time-series for locations within and near the watershed. A daily time-series for areal-average precipitation for the watershed is computed using the precipitation data previously assembled. Daily precipitation time-series for the zones of mean annual precipitation are created by disaggregating/scaling the areal-average precipitation time-series to represent precipitation for the various zones of mean annual precipitation.

The National Weather Service River Forecasting Centers (NWSRFCs) typically prepare areal-average daily precipitation time-series for calibration of their watershed models for large river systems. It is usually worthwhile to contact the local NWSFRC to inquire if daily precipitation time-series have previously been developed that are applicable to the watershed of interest.

Daily Air Temperature Time-Series – Daily time-series of air temperatures are needed for each elevation zone for estimation of Potential Evapotranspiration (PET) and for computation of the time-series for snowpack Snow-water Equivalent (SWE). These may be a time-series of daily mean temperatures or times-series of maximum daily and minimum daily air temperatures. The choice will be dependent upon the data input requirements of the computational schemes for PET and snowpack SWE. Standard air temperature lapse rates may be used for dry and wet days to assemble air temperature time series for other elevation zones.

Antecedent Air Temperature Time-Series for Checking for Frozen Ground Conditions – Antecedent air temperature is used to determine whether a concrete frost exists in portions of the watershed at the onset of a storm for flood simulations. A concrete frost is a type of frozen ground condition that can occur when there is sufficient soil moisture and the areal extent of freezing is sufficient to form a contiguous frozen layer that impedes surface infiltration.

Antecedent air temperature is defined as the mean daily temperature averaged over the 14-days (2-weeks) prior to the occurrence of the storm. The time-series of average 14-day air temperature are needed for each elevation zone in the watershed. Standard air temperature lapse rates may be used for dry and wet days to assemble air temperature time series for other elevation zones. Values of 14-day mean daily air temperature are saved for mid-month and end-of-month dates.

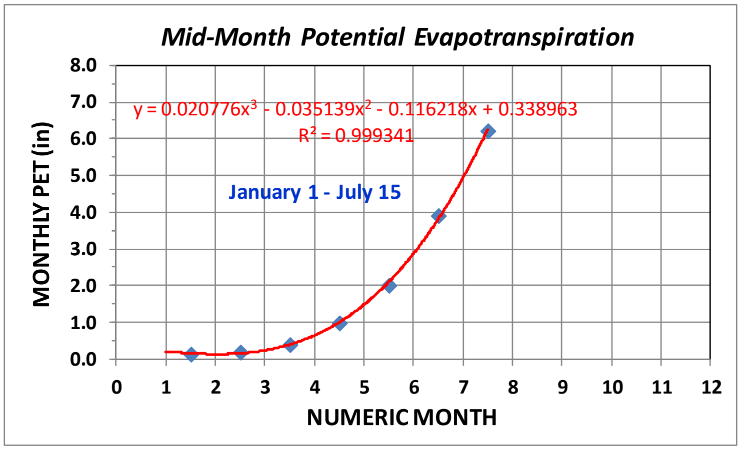
2-10.2 Data Sources for Potential Evapotranspiration

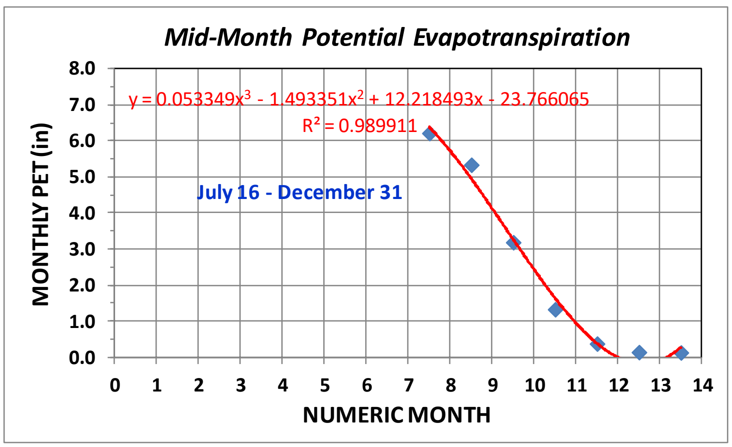
The magnitude of potential evapotranspiration is affected by numerous factors including: air temperature; dewpoint; solar radiation; duration/frequency/extent of cloud cover; wind; atmospheric pressure; and ground cover[33,63,70]. Recognizing the complexity and interaction of the many factors, a practical model for evapotranspiration for use in SEFM is attained by accounting for the variation of potential evapotranspiration by both time of year and by elevation zone. The use of zones of elevation for describing the variability of evapotranspiration is based on the recognition that many of the factors listed above vary with elevation. Use of elevation zones provides a practical approach to apportioning the variation of potential evapotranspiration throughout mountainous watersheds. In general, for a given time of year, lower evapotranspiration would be expected in zones of higher elevations that are associated with cooler temperatures, longer periods of precipitation (higher mean annual precipitation), greater cloud cover and higher relative humidity.

Daily Time-Series of Potential Evapotranspiration – Daily time-series of potential evapotranspiration (PET) can be developed using a variety of methods. One option is to use precipitation and air temperature time series, seasonal information on solar radiation and evapotranspiration estimation equations, such as Jensen-Haise[28] or Penman[46] to develop a daily time-series of PET.

A second option is to compute monthly or twice monthly PET values using evapotranspiration estimation equations in combination with data from published sources such as NOAA monthly Climatological publications, University agricultural research services, reservoir pan evaporation studies, and values that can be computed from Handbooks[33,63,70]. Curve fitting methods can then be used to develop all-season predictor equations for estimation of daily PET. Figures 2-10.2a,b depicts examples of this procedure.

A third option is to use NOAA or NCAR reanalysis results presented in the form of daily gridded datasets for historical conditions for very large areas of the U.S.





Figures 2-10.2a,b – Examples of Predictor Equations for Potential Evapotranspiration for January 1 through Mid-July and Mid-July through December 31

2-10.3 Data Sources for Snowpack

Data on snowpack snow-water equivalent (SWE), snow density, and depth of snow-on-ground are limited for most areas of the U.S. Snow courses and SNOTEL stations located in mountain areas of the western U.S. provide location specific measurements for snowpack. Snow course measurements of depth and SWE are typically available from as early as the 1920s for end-of-month dates beginning about January 31th and continuing through melt-out in the spring. SNOTEL stations were first installed in the early 1970s and typically provide precipitation, snow depth , SWE and air temperature measurements. There are very limited data on snow for low elevation areas of the eastern U.S. where snow on ground is very intermittent.

In mountain areas, snowpack accumulation can be quite different on northern versus southern slopes and windward versus leeward areas due to variation in precipitation, air temperature and solar radiation. This situation makes the estimation of the spatial distribution of snowpack difficult. The available snow measurement data from multiple sites are best utilized in model calibration for generating the time-series of daily snowpack throughout a watershed.

Data Sources for Snow Density – Representative values of snow density for mid-month and end-of-month dates are obtained by frequency analysis of snow depth and SWE data available from snow courses and SNOTEL sites within the watershed and from sites that are climatologically similar to the watershed of interest. Mean values of snow density needed for mid-month and end-of-month dates for all elevation zones for use in snowmelt computations.

2-10.4 Hydrometeorological Time-Series from Reanalysis Datasets

Gridded datasets of hydrometeorological variables on a daily time-step are becoming available as computer reanalysis of historical data is becoming more common. Gridded data of daily precipitation, temperature, potential evapotranspiration and snow-water equivalent may be available from agencies such as NOAA, NCAR and the PRISM Climate Group at Oregon State University. These datasets may have some utility in assembling hydrometeorological time-series for use in continuous watershed modeling for assembling the sample sets of state variables. It is possible that some reanalysis datasets can be used directly for creating the sample set of state variables for cases such as snowpack (snow-on-ground) in relatively low-orographic areas.

2-10.5 Data Sources for Daily Streamflow Volumes

Historical records of streamflow are commonly available for high consequence dams and infrastructure. Time-series of streamflow are usually available from the USGS, public water resource agencies or hydropower utilities. However, many of the watersheds where SEFM is applied will have dams and reservoirs upstream of the streamflow measurement site(s) that will distort the magnitude and timing of natural flows. In these cases, adjustments will be required to the regulated streamflows to produce natural streamflows for creating sample-sets of values of the state variables for hydrologic soil parameters.

Reverse reservoir routing (Zoppou[129]) may be used to produce the time-series of unregulated streamflows from the time-series of regulated streamflows. Reverse reserve routing can also be used to produce a time-series of reservoir inflows for situations where no streamflow data are available but daily reservoir level data are available. Reverse reservoir routing makes use of the change in reservoir storage and reservoir releases to back-calculate the reservoir inflow using the stage-storage relationship for the reservoir.

2-10.6 Use of Time-Series of Antecedent Precipitation for Linking State Variables

The length of historical data and the period-of-record available for precipitation, air temperature and snowpack level are often different than the time-frame and length of records available for streamflow, river level and reservoir level. Therefore, it is often necessary to assemble two databases for resampling of state variables. One database is used for selecting values for hydrologic soil parameters, snowpack and antecedent air temperature for the various HRUs. The other database is used for selecting values for streamflows, river levels and reservoir level(s).

A common link between the two databases is provided by a representative value of antecedent precipitation for any given month/day of the year. Antecedent precipitation is defined as the cumulative precipitation from a specified start date and extends for a 12-month period. Ideally, the start date for antecedent precipitation is chosen at a time of the year that is hydrologically benign, where soil moistures are near the wilting point, storm activity is low and streamflows are low.

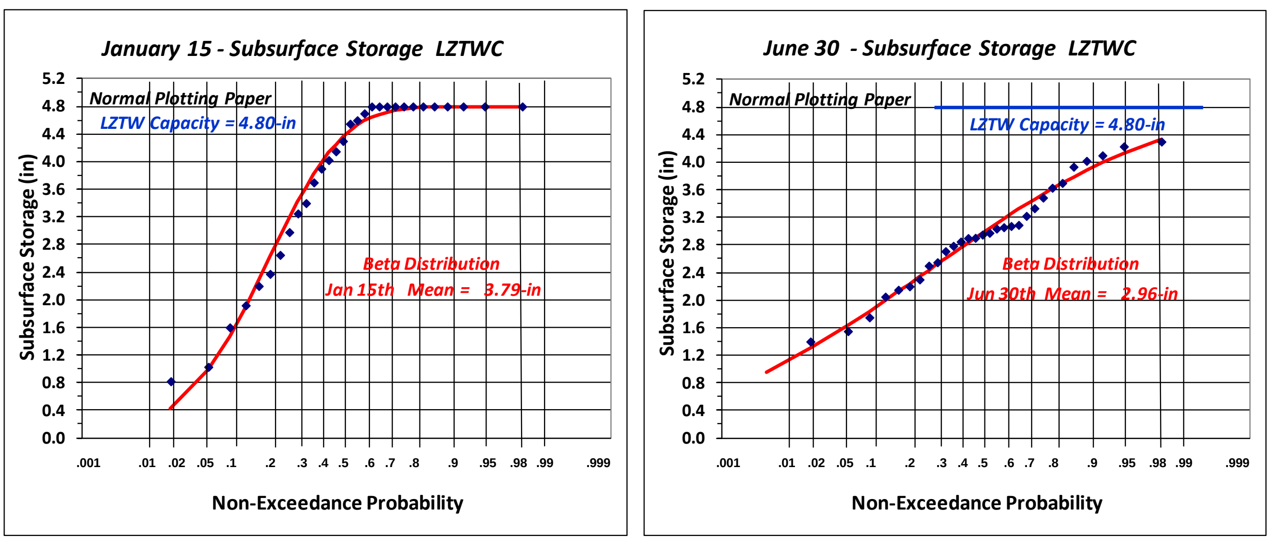
The term “key station” is given to the precipitation station that is used for providing representative values of antecedent precipitation for the various state variables in the watershed

Selecting a Key Station for Antecedent Precipitation – As discussed above, a key station for antecedent precipitation is needed to provide a common link for all state variables for a given magnitude of antecedent precipitation for a given month/day of the year. Ideally, the key station is chosen which is centrally located in the watershed and representative of typical climatological conditions for the watershed. The daily precipitation time-series for the key station must be sufficiently long to cover the time period all of the state variables.

2-10.7 Assessing the Adequacy of Sample Sets of Hydrologic Soil Parameters and Snowpack

The adequacy of the sample sets of values of state variables for hydrological soil parameters and snowpack can be evaluated using probability-plots. Probability-plots should be created for each state variable for each mid-month and end-of-month date. This will allow review of the range and diversity of a given hydrometeorological input and assessment of the representativeness of the sample.

Figures 2-10.3a,b depicts examples of Lower Zone Tension Water Storage (LZTWC) for the Sacramento Soil Moisture Accounting model (SAC-SMA) for mid-winter and early-summer for a high elevation watershed in the Sierra Mountains in southern California. Both plots show the datasets to be well-behaved and suggestive the sample sets are representative of soil moisture conditions for the time-of-year. In the case of the January 15th data, there is a about a 40% chance that soil will be fully wetted to field capacity. For the case of the June 30th data, the soil moisture states are all in the partially wetted range between fully dry and fully wet conditions.



Figures 2-10.3a,b – Probability-Plots of Seasonal State Variables for Subsurface Soil Moisture

2-10.8 Execution of a Resampling Approach for Hydrologic Soil Parameters and Snowpack

Standard Monte Carlo resampling is used for state variables for hydrologic soil, parameters and snowpack.

SEFM Operation – Selection of values of state variables for hydrologic soil parameters for setting initial watershed conditions proceeds as follows.

1. A mid-month or end-of-month date (month/day) would have been previously selected based on the seasonality of storms for the storm type/flood being analyzed;
2. A year is selected at random within the range of years for the state variables for hydrological soil properties. The date for the mid-month/year or end-of-month/year is used to set the state variables for the hydrological soil parameters and snowpack SWE for the various HRUs.
3. The antecedent precipitation at the key station for the chosen date is noted and will be used in selecting values of state variables for streamflows, river levels and reservoir levels. See Section 2-9.

Assumptions/Expectations – In application of SEFM, it is assumed that the sample sets of state variables for hydrological soil parameters are representative of the range and frequency of moisture conditions to be experienced in the watershed. The validity of this assumption increases as the length of the hydrometeorological time-series increases and there is a greater diversity in the seasonal distribution of daily, weekly, monthly and annual precipitation.

Guidance and Experience – Particular attention should be given to assessing the adequacy of the range and diversity of values of the state variables that can be chosen through resampling. An important aspect of stochastic flood simulations is to examine floods that occur for watershed conditions that are possible but have not been co-occurred with major storms in the historical record. The range and diversity of state variables is one of the sampling components that allows for simulation of unusual antecedent conditions. A shuffle resampling approach may be used (Section 2-9) to increase the diversity of the combinations of values of the state variables for flood simulations.

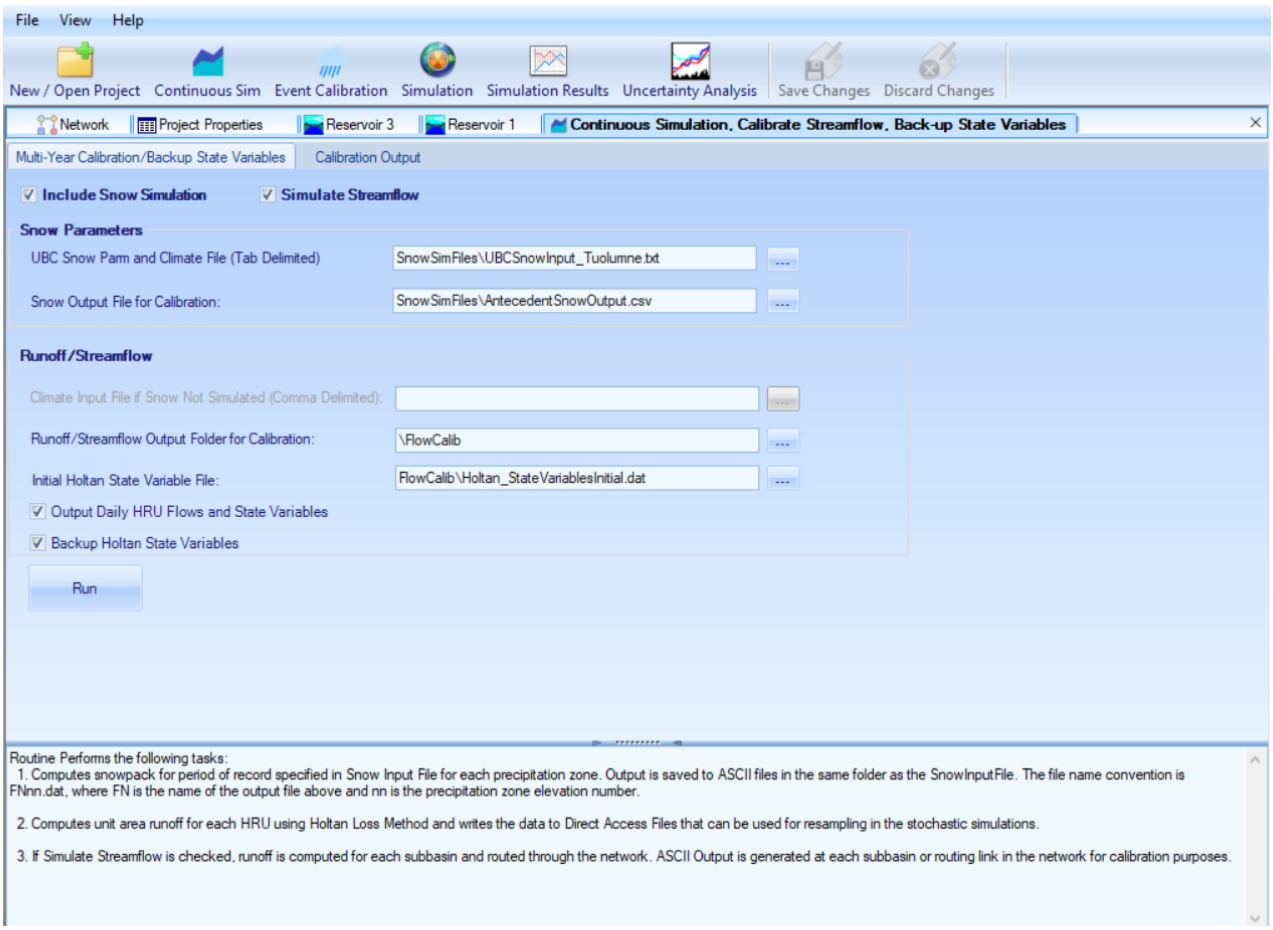
Augmenting Historical Data – In reviewing the probability-plots for a given watershed, it is possible that the available hydrometeorological time-series are too short, or insufficiently representative, to provide for an adequate sample set of the state variables. There are two options for expansion of the sample-set of values for the state variables.

The first option is to fit the historical data for each state variable for each mid-month and end-of-month by a 4-parameter Beta Distribution (Benjamin and Cornell[4]) or other suitable probability distribution to obtain values for selected non-exceedance probabilities. Correlation analyses would also be conducted between each of the state variables and antecedent precipitation for the key station to determine representative values of antecedent precipitation to be used for the additional values of the state variables.

If probabilistic analyses are used to augment the sample-set of state variables, the expanded sample-set would be comprised of two components. The first component is the observed historical values for a sample size equal to the number of years of record. The second component is a set of the values of state variables along with their non-exceedance probabilities. Algorithms within the SEFM stochastic engine would take care of resampling in a manner to provide for a representative sample for the mix of historical and expanded values for each state variable.

The second option is to use long time-series of precipitation and the other hydrometeorological time-series with continuous watershed modeling to compute additional values of hydrological soil parameters and snowpack SWE. One possible approach is to use boot-strap methods (Efron[103]) to create additional years of synthetic hydrometeorological time-series to produce a more representative set of values for the state variables. Care must be taken in generating the hydrometeorological time-series so the frequency of occurrence of unusual conditions is consistent with the length of the time-series (sample size). Unrepresentative hydrologic hazard curves can be produced if the frequency of rare conditions is over-represented in the sample sets of state variables.

Limitations, Adequate Record Length – In some cases, there may be an adequate length of hydrometeorological time-series record to calibrate the watershed model to streamflow volumes and obtain initial estimates of the hydrologic soil properties. However, the available record length may be insufficient to support augmentation of the hydrometeorological time-series for expanding the sample set of values for the state variables. When this occurs, the probabilistic analysis method (Section 2-11) should be used to develop the sample set of values of the state variables for hydrological soil parameters and snowpack.



Screen Shot 2-10.4 – Data Entry Format for Computation of Antecedent Snowpack and Streamflow for Resampling

2-11.2 SEFM Operation for Creation of Sample Set of State Variables

Sample sets of values of state variables for mid-month and end-of-month dates are created by Monte Carlo simulation as a feature of SEFM. Probabilistic analyses are conducted for antecedent precipitation and snowpack SWE for end-of-month dates. Mid-month values are obtained by interpolation between adjacent end-of-month values. Potential evapotranspiration (PET) values are determined for mid-month values. End-of-month PET values are obtained by interpolation for adjacent mid-month PET values.

The following procedures are used within SEFM for Monte Carlo simulation to create sample sets of state variables for hydrologic soil properties and snowpack SWE for mid-month and end-of-month dates. Separate analyses are conducted for each HRU using simulations with hydrometeorological data specific to a zone of mean annual precipitation, elevation and soil type.

For each HRU and mid-month and end-of-month date:

1. Select a sample size *(n*) for the size of the sample set of values of state variables to be created for use in resampling. A sample set of 50 is generally adequate to describe the range and diversity of values for resampling.

2. Use Latin-hypercube sampling to obtain *n* values of exceedance probability. Use the three-parameter Gamma distribution to generate *n* values of antecedent precipitation for the key precipitation station for the *n* values of exceedance probability for the end-of-month date. Distribution parameters for the three-parameter Gamma distribution for the key station are determined from a method-of-moments solution (within SEFM) for estimates of the population mean, coefficient of variation and coefficient of skewness provided by the user.

For each of the *n* values of exceedance probability for the selected mid-month or end-of-month:

3. Compute values of antecedent precipitation for the selected zone of mean annual precipitation for the start month through the month of interest using the user-supplied estimates of the population summary statistics for the selected zone of mean annual precipitation for the various end-of-months.
4. Use the correlation relationship between antecedent precipitation at the key precipitation station and snowpack SWE for the key snow station for the month of maximum accumulation to generate a value of snowpack SWE for the key station for the selected zone of mean annual precipitation and elevation zone for the end-of-month for the date of interest. The SWE values are generated in a manner which includes the unexplained variance in the correlation relationship which preserves the random scatter in the relationship. Compute the exceedance probability of the generated snowpack SWE value from the cumulative distribution function (CDF) of the mixed distribution for snowpack SWE.
5. Use the exceedance probability for snowpack SWE at the key snow station to compute snowpack SWE values for each end-of-month from the start date through the month of interest.
6. Compute twice-monthly values of antecedent precipitation and snowpack SWE by disaggregating the end-of-month antecedent precipitation and snowpack SWE values Monte Carlo procedures.

7. Further disaggregate the twice-monthly values of precipitation and snowpack into daily values using Monte Carlo methods for randomly generated number of storm events per 15-day period.
8. Obtain values of potential evapotranspiration (PET) from the PET analysis for all of the twice-monthly periods determined in Step 6.
9. The daily values of precipitation, PET and snowpack SWE are used along with the calibrated hydrologic soil properties and soil moisture accounting for the chosen watershed model to compute values of hydrologic soil parameters for the selected mid-month or end-of-month date. The collection of values of hydrologic soil parameters and SWE are stored together as a matched set. This preserves the natural dependencies that exist between the values of the state variables for a given set of climatic conditions.
10. Mean values of snow density for each elevation zone for the given date are obtained from analyses of snow density and are paired with the other values of the state variables in the matched set.
11. If floods produced by rain-on-frozen ground are a consideration, Latin-hypercube sampling is used to generate *n* values of antecedent 14-day mean daily air temperature for the given date, which are randomly assigned to the *n* samples created from Steps 3 through 10.

These procedures yield *n* paired samples of the state variables for hydrologic soil parameters, snowpack SWE and snow density for a given HRU. The *n* values of antecedent precipitation for the key precipitation station (Step 2) are linked with the values of the state variables in the matched sets. The values of antecedent precipitation will be used later in a Lookup Table for a separate linked database for selection of streamflows, river levels and reservoir levels via resampling (Section 2-9.4).

2-11 INITIAL WATERSHED CONDITIONS – PROBABILISTIC ANALYSES

Probabilistic analyses of antecedent precipitation, potential evapotranspiration and snowpack snow-water equivalent (SWE) can be used to develop sample sets of values of state variables for setting initial watershed conditions for stochastic flood simulations. This option is usually chosen when there are insufficient hydrometeorological time-series data specific to a watershed to support continuous watershed modeling.

The findings of the probabilistic analyses and Monte Carlo simulation are used along with soil moisture accounting methods to develop a sample set of state variables for setting initial watershed conditions for mid-month and end-of-month dates, which includes:

- Soil moisture conditions for all soil moisture storages for each HRU
- Snowpack, snow-water equivalent for each HRU (rain-on-snow floods)
- Snow density for each HRU (rain-on-snow floods)
- Average air temperature for prior 14-days for elevation zones (rain-on-frozen ground floods)

This is accomplished in an iterative process where hydrologic soil properties are first determined by calibration of the watershed model to historical floods (Figure 2-11.1). Monte Carlo sampling of the hydrometeorological inputs for precipitation and potential evapotranspiration are then used in conjunction with soil moisture accounting to create the sample set of values of the state variables. The similarity of this process to the process for continuous modeling (Figure 2-10.1) should be noted. The primary difference is that more event-specific and watershed-specific hydrometeorological data are available to support the continuous modeling approach. The additional data utilized in the continuous modeling approach allow for a more detailed analysis of state variables.

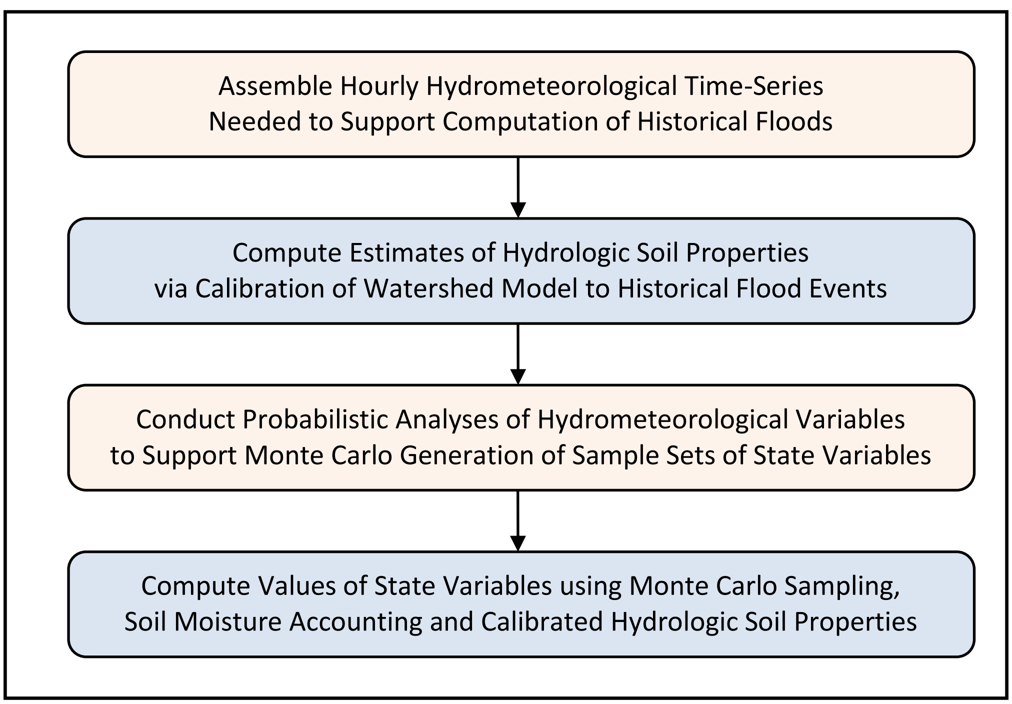


Figure 2-11.1 – Sequence of Tasks for Determining Values of State Variables for Initial Watershed Conditions for Hydrologic Soil Parameters Using the Probabilistic Analyses Method

Probabilistic analyses of antecedent precipitation and potential evapotranspiration are always needed for developing sample sets of values of the state variables for hydrological soil parameters. Additional probabilistic analyses are needed when rain-on-snow floods and/or floods produced by rain-on-frozen ground are a concern. A summary of probabilistic analyses that may be needed are listed below.

- Antecedent precipitation for zones of mean annual precipitation
- Potential evapotranspiration (PET) for zones of elevation
- Snowpack, snow-water equivalent (SWE) for zones of mean annual precipitation and elevation
- Correlation between snowpack SWE and antecedent precipitation for a key station
- Snow density for zones of elevation
- Average air temperature for prior 14-days for elevation zones (frozen ground cases)

Hybrid Probabilistic Approach – The situation commonly arises where there are sufficient hydrometeorological time-series data (say 6 to10-years) to support calibration of a continuous watershed model to obtain initial estimates of the hydrological soil properties. However, the length of the hydrometeorological time-series is insufficient for creation of an adequate sample size of values of state variables. In this case, a hybrid approach is taken where elements of both continuous modeling and probabilistic analyses are used to create the sample set of values of the state variables for resampling. The sequence of tasks for the hybrid approach is shown in Figure 2-11.2.

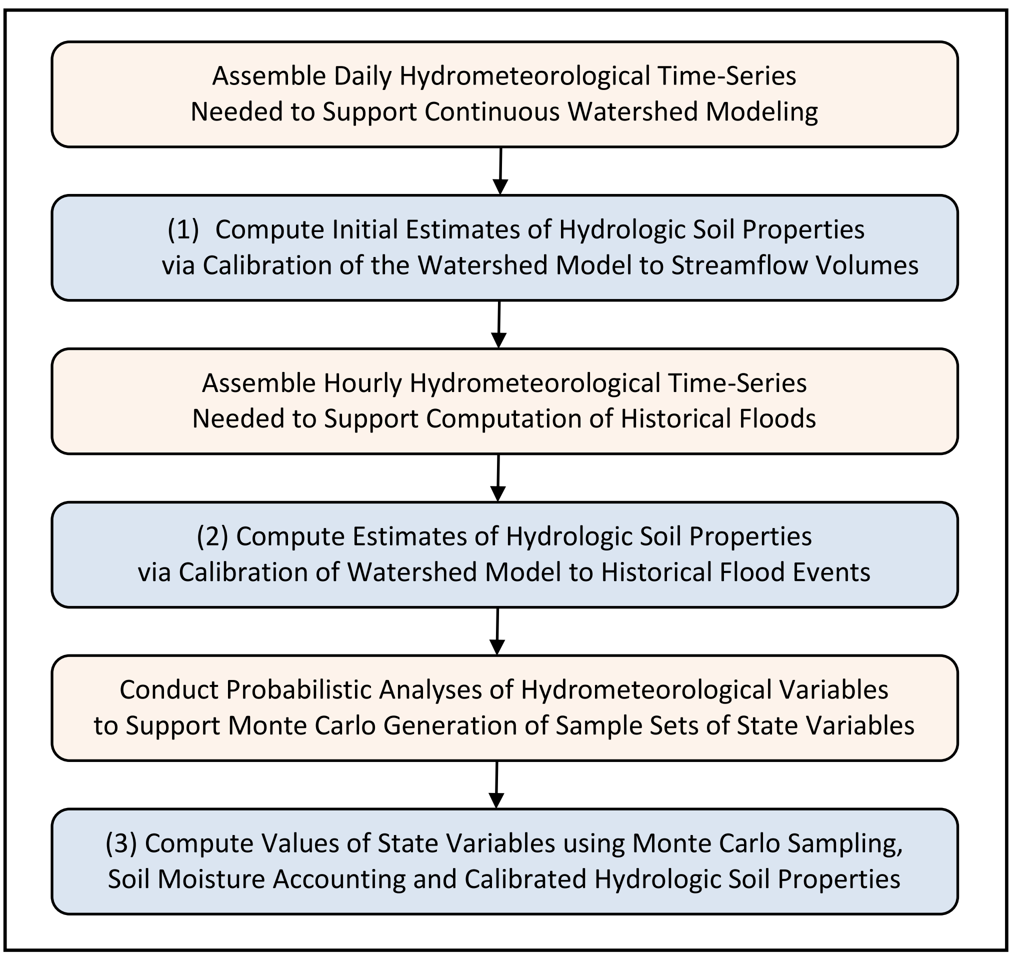


Figure 2-11.2 – Sequence of Tasks for Hybrid Probabilistic Analyses Approach

2-11.1 Use of Antecedent Precipitation for Linking State Variables

Values of antecedent precipitation at a key station for mid-month and end-of-month dates are used as a common link for the values of the state variables. Antecedent precipitation is defined as the cumulative precipitation from a specified start date and extends for a 12-month period. Ideally, the start date for antecedent precipitation is chosen at a time of the year that is hydrologically benign, where soil moistures are near the wilting point, storm activity is low and streamflows are low. See Section 2-9.3 for additional details on linked databases using antecedent precipitation.

In the probabilistic analyses method, there is not an actual date associated with mid-month and end-of-month values of state variables for hydrological soil parameters. Conversely, values of state variables for streamflows, river levels and reservoir levels do have actual dates. Therefore, it is necessary to assemble two databases for resampling of state variables that preserves the dependencies between state variables in each of the two databases.

The dependencies are preserved through use of values of antecedent precipitation at a key station within the watershed. One database is used for selecting state variables for hydrologic soil parameters, snowpack and antecedent air temperature for the various HRUs. The values of the state variables are associated with a common value of antecedent precipitation at the key station.

The second database is used for selecting streamflows, river levels and reservoir levels. The linked database of values of the state variables for the chosen date for streamflows, river levels and reservoir levels is sorted by magnitude of antecedent precipitation. This provides a look-up table of state variables for streamflows, river levels and reservoir levels corresponding to the value of antecedent precipitation in the first database for state variables for hydrologic soil parameters. See SEFM Operation in Section 2-9.4 for additional details on the resampling procedures.

2-11.2 SEFM Operation for Creation of Sample Set of State Variables

Sample sets of values of state variables for mid-month and end-of-month dates are created by Monte Carlo simulation as a feature of SEFM. Probabilistic analyses are conducted for antecedent precipitation and snowpack SWE for end-of-month dates. Mid-month values are obtained by interpolation between adjacent end-of-month values. Potential evapotranspiration (PET) values are determined for mid-month values. End-of-month PET values are obtained by interpolation for adjacent mid-month PET values.

The following procedures are used within SEFM for Monte Carlo simulation to create sample sets of state variables for hydrologic soil properties and snowpack SWE for mid-month and end-of-month dates. Separate analyses are conducted for each HRU using simulations with hydrometeorological data specific to a zone of mean annual precipitation, elevation and soil type.

1. Select a sample size *(n)* for the size of the sample set of values of state variables to be created for use in resampling. A sample set of 50 is generally adequate to describe the range and diversity of values for resampling.

For each zone of mean annual precipitation and elevation:

2. Latin-hypercube sampling methods are used to generate end-of-month values of antecedent precipitation using the three-parameter Gamma distribution for all zones of mean annual

precipitation and for the key precipitation station. Distribution parameters for the three-parameter Gamma distribution are determined from a method-of-moments solution (within SEFM) for estimates of the population mean, coefficient of variation and coefficient of skewness provided by the user.

3. The log-log regression relationship between antecedent precipitation and snowpack SWE for the key antecedent precipitation station and key snow station for the end-of-month of maximum snowpack accumulation is used to generate a value of snowpack SWE at the key snow station. The exceedance probability of the generated snowpack SWE value is computed from the cumulative distribution function (CDF) of the mixed distribution for snowpack SWE at the key snow station. This information is used to generate snowpack SWE values for all end-of-month periods in the snow season.
4. Monthly values of antecedent precipitation and snowpack SWE are disaggregated into daily values using Monte Carlo methods.
5. Daily values of potential evapotranspiration (PET) are obtained from the PET analysis by uniformly distributing the monthly values.
6. The daily values of precipitation, PET and snowpack SWE are used along with the calibrated hydrologic soil properties and soil moisture accounting for the chosen watershed model to compute values of hydrologic soil parameters for the selected mid-month or end-of-month date. The collection of values of hydrologic soil parameters and SWE are stored together as a matched set. This preserves the natural dependencies that exist between the values of the state variables for a given set of climatic conditions.
7. Mean values of snow density for each elevation zone for the given date are obtained from analyses of snow density and are paired with the other values of the state variables in the matched set.
8. If floods produced by rain-on-frozen ground are a consideration, Latin-hypercube sampling is used to generate *n* values of antecedent 14-day mean daily air temperature for the given date, which are randomly assigned to the *n* samples created from Steps 3 through 9.

These procedures yield *n* paired samples of the state variables for hydrologic soil parameters, snowpack SWE and snow density for a given HRU. The *n* values of antecedent precipitation for the key precipitation station (Step 2) are linked with the values of the state variables in the matched sets. The values of antecedent precipitation will be used later in a Lookup Table for a separate linked database for selection of streamflows, river levels and reservoir levels via resampling (Section 2-9.4).

Initial Values of Hydrologic Soil Parameters for Starting Month – The Monte Carlo procedures for soil moisture accounting require an initial value of each state variable for the hydrologic soil parameters for each HRU to start the computations at the beginning of the first month. These values typically have low sensitivity because the starting month is chosen at a hydrologically benign time of the year with soil moistures near the wilting point. The procedure is to conduct soil moisture accounting using the calibrated hydrologic soil properties to examine the soil moisture states for relatively dry, typical and relatively wet cases. This allows an assessment of the variability of the soil moisture states for a range of climatic conditions.

In many cases, several of the soil storages can be set to zero (empty) or at a fixed value for the beginning of the first month. Where variability exists for a hydrologic soil parameter, the minimum, median and maximum values of the soil moisture states are entered into SEFM for the start of the beginning month (Screen Shot 2-11.1). SEFM will fit a 4-parameter Beta distribution to generate *n* sample values for use in the Monte Carlo simulation procedure described above.

Radio buttons to set all HRUS to fixed value x for soil parameter P.

HRU	SOIL PARAMETER	MINIMUM	MEDIAN	MAXIMUM
010101	UZTWM	0.0	0.3	0.8

Screen Shot 2-11.1 – Example Data Entry Format for Soil Moisture States for Creation of Values of State Variables for Hydrological Soil Parameters

Assumptions/Expectations – It is assumed that there is a very high level of correlation between end-of-month antecedent precipitation values for each zone of mean annual precipitation. If the linear correlation coefficients are near unity and a common probability distribution is used for all zones of mean annual precipitation, then the exceedance probability would be very nearly the same for each value of antecedent precipitation for each zone of mean annual precipitation. Studies[47,62] have shown that correlation decays slowly with distance between locations for multi-month values of precipitation. Thus, it is reasonable to expect there would be a very high level of correlation for multi-month values of antecedent precipitation for locations that are physically near each other. This condition is easily satisfied for a watershed with a nominal area of several thousand square miles or less.

It is also expected that the three-parameter Gamma distribution[16,22,29,43,60] will be suitable for describing the historical antecedent precipitation data. Numerous studies[16,47,48,50] have found that monthly and multi-month precipitation are well-described by the three-parameter Gamma distribution. An example of a three-parameter Gamma distribution fitted to historical antecedent precipitation data is shown in Figure 2-11.3.

Guidance and Experience – One of the tasks during the analysis of antecedent precipitation is to choose a *key precipitation station*. The key precipitation station provides a common dataset for use in developing correlation relationships with snowpack SWE and for use with a linked dataset for resampling selection of streamflows, river levels and reservoir levels. Ideally, the key precipitation station should be a long-term station, centrally located within the watershed, and be in the mid-range of mean annual precipitation for the watershed. In the case where snowpack is a consideration, the best choice of the key station would be a location within the mid-range of elevations where snowpack accumulates. These criteria are intended to provide antecedent precipitation values that best represent the characteristics of the watershed.

Sample statistics for the coefficients of variation and skewness are subject to significant sampling variability in small datasets. Care should be taken to use a regional approach that considers the results from multiple sites to provide smoothed regional estimates of the coefficients of variation and skewness for the zones of mean annual precipitation and the key station. Two general trends are prevalent for the coefficients. Larger coefficients are associated with drier climates (zones of lower mean annual precipitation) and shorter durations (fewer number of months). Smaller coefficients occur in zones of higher mean annual precipitation and for durations of multiple-months. See Appendix A for additional details.

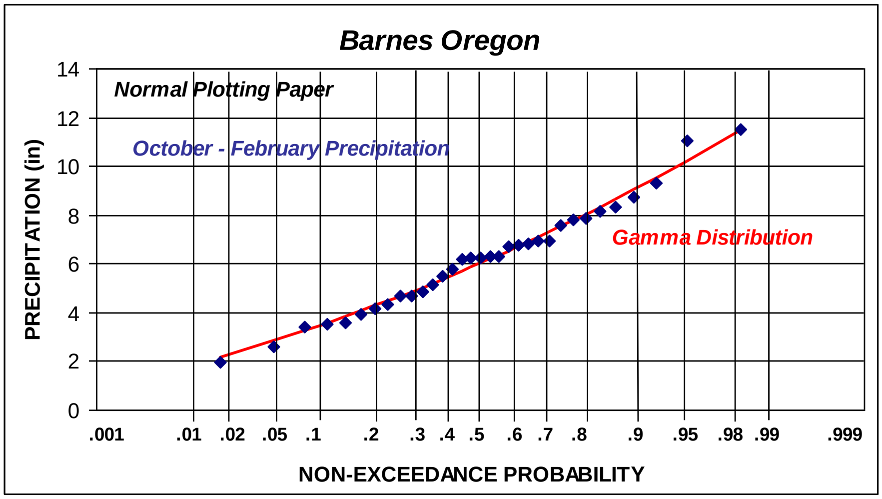


Figure 2-11.3 – Example Three-Parameter Gamma Distribution Fitted to Antecedent Precipitation for October 1st to the End-of-February for Barnes Oregon

2-11.3 Probabilistic Analyses of Antecedent Precipitation

Antecedent precipitation is used in the soil moisture water budget for determining initial soil moisture storages for a chosen storm date (Figures 2-11.1, 2-11.2, Section 2-11.2). Antecedent precipitation at a key station is also used as an explanatory variable in correlation analyses with snowpack and in the linked databases for hydrologic soil parameters, snowpack SWE, streamflows, river levels and reservoir levels. These relationships are later used in Monte Carlo simulations to allocate snowpack throughout the watershed, and to select values of state variables for hydrologic soil parameters, streamflows, river levels and reservoir levels.

***Work Products Needed from Probabilistic Analyses* –** Estimates of the population mean, coefficient of variation, and coefficient of skewness of antecedent precipitation are needed for each end-of-month for the each zone of mean annual precipitation. In most cases, precipitation stations will not be available at sites corresponding to the median of each zone of mean annual precipitation. Therefore, relationships must be developed with mean annual precipitation to allow estimation of population values for the various zones.

Datasets of antecedent precipitation are needed for the key station and for precipitation stations within and near the watershed of interest that are representative of the range of mean annual precipitation for the watershed under study. The dataset of antecedent precipitation at each station is assembled by computing the cumulative precipitation from the start of the chosen climatic year to the end of each subsequent month for each 12-month period of the record. Sample statistics are then computed for each precipitation station for each end-of-month. The procedures for conducting the probabilistic analyses are described in Appendix A.

***Data Entry Format* –** Antecedent precipitation is described for each mean annual precipitation zone for each month of the year. Data entry consists of estimates of the mean, coefficient of variation, and skewness coefficient for antecedent precipitation in each zone of mean annual precipitation for each end-of-month. In addition, estimated values of the mean, coefficient of variation, and skewness coefficient for end-of-month values of antecedent precipitation are entered for the *key precipitation station*. Inputs are entered on the *Ant_Precip* worksheet, and Screen Shot 2-11.2 depicts a partial listing of data entry.

Antecedent Precipitation Parameters

Antecedent Precipitation (in), 3-Parameter Gamma Distribution

	Key Station	Mean Annual Precipitation Zone						
		1	2	3	4	5	6	7
		75.00 in	85.00 in	95.00 in	105.00 in	115.00 in	0.00 in	0.00 in
October								
Mean	5.952	4.930	5.650	6.383	7.099	7.769		
Cv	0.556	0.606	0.572	0.538	0.505	0.478		
Skew	0.574	0.744	0.629	0.511	0.401	0.310		
November								
Mean	21.779	17.684	20.459	23.302	25.950	28.141		
Cv	0.406	0.439	0.417	0.394	0.373	0.355		
Skew	0.518	0.665	0.566	0.464	0.369	0.291		
December								
Mean	35.372	28.738	33.225	37.822	42.104	45.644		
Cv	0.338	0.363	0.346	0.328	0.312	0.298		
						0.280		

Precipitation Key Station Information
(Used for Reference, Not Read by Program)

Station Name	Stampede Pass
Station Number	45-8009
Elevation	3960 ft
Mean Annual Precip	90 in

Screen Shot 2-11.2 – Antecedent Precipitation Data Entry Format for Keechelus Watershed, Washington (Partial Listing)

2-11.4 Analyses of Monthly Potential Evapotranspiration (PET)

The magnitude of potential evapotranspiration is affected by several factors including solar radiation, duration/frequency/extent of cloud cover, air temperature, dewpoint, wind, atmospheric pressure, and ground cover[33,63,70]. Each of these factors varies both with the time of year and on a daily basis for a mountainous watershed. For example, while solar radiation is reasonably constant for a given time of year at a given latitude, cloud cover can restrict the effective solar energy that reaches the ground surface. Cloud cover is related to the number of rainy days each year and is therefore related to elevation and mean annual precipitation. Air temperature varies with time of year and elevation, and mean annual precipitation varies with elevation. The evaporation rate from soil surfaces is highly dependent upon the relative humidity, with higher rates of evaporation associated with low relative humidity and lower rates of evaporation associated with high relative humidity. For non-rainy days, the dewpoint temperature is largely governed by the existing air mass conditions, and air temperature decreases with elevation. This combination of conditions generally results in a reduction in the rate of evaporation from soils with increasing elevation.

Recognizing the complexity and interaction of the many factors, a practical model for evapotranspiration for use in the SEFM is attained by accounting for the variation of potential evapotranspiration by both time of year (end-of-month) and by elevation zone. The use of zones of elevation for describing the variability of evapotranspiration is based on the recognition that many of the factors discussed above vary with elevation. Use of elevation zones provides a practical approach to apportioning the variation of potential evapotranspiration throughout mountainous watersheds. In general, for a given time of year, lower evapotranspiration would be expected in zones of higher elevations that are associated with higher mean annual precipitation, greater cloud cover and higher relative humidity.

During winter periods when snowpack may cover the ground, the computation of evapotranspiration is more difficult. For HRUs covered by snow, potential evapotranspiration is reduced due to the lack of transpiration from low-lying vegetation. However, there is some evapotranspiration from those areas with coniferous forests. Fortunately, the relative proportion of wintertime evapotranspiration is small relative to that for the remainder of the year. Thus, the uncertainties in estimation of wintertime evapotranspiration typically do not have a significant influence on the magnitude of wintertime floods.

Sources of Evapotranspiration Data – Evapotranspiration data are not as widely available as other climatic data. Common data sources include NOAA monthly Climatological publications, , University agricultural research services, reservoir pan evaporation studies, and values that can be computed from Handbooks[33,63,70]. Information on evapotranspiration can also be developed from evapotranspiration estimation equations, such as Jensen-Haise[28] or Penman[46]. Estimation of evapotranspiration, particularly for high elevations, is more difficult due to the situation that many evaporation measurement sites only operate in the warm growing season. Thus less data are available for winter periods.

Daily time-series of potential evapotranspiration (PET) can be developed using a variety of methods. One option is to use seasonal precipitation and air temperature data, seasonal information on solar radiation and evapotranspiration estimation equations, such as Jensen-Haise[28] or Penman[46]to develop a twice-monthly values of PET. This approach may be used in combination with data from published sources such as NOAA monthly Climatological publications, University agricultural research services, reservoir pan evaporation studies, and values that can be computed from Handbooks[33,63,70]. Curve fitting methods can then be used to develop all-season predictor equations for estimation of daily PET. Figures 2-11.2a,b depicts examples of this procedure.

A second option is to use NOAA or NCAR reanalysis results presented in the form of daily gridded datasets for historical conditions for very large areas of the U.S.

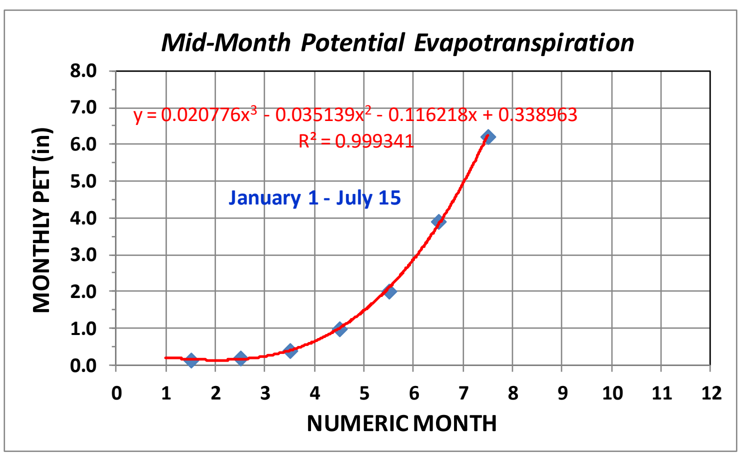


Figure 2-11.5a – Examples of Predictor Equations for Potential Evapotranspiration for January 1 through Mid-July

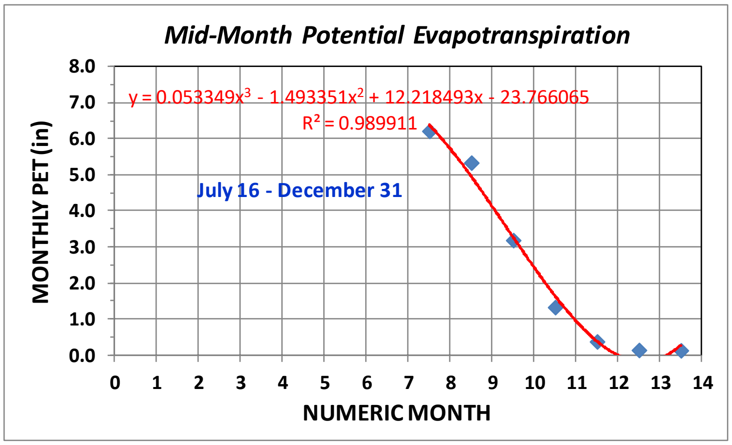


Figure 2-11.5b – Examples of Predictor Equations for Potential Evapotranspiration for Mid-July through December 31

Data Entry Format – Potential evapotranspiration is entered as mean annual values for each of the elevation zones. A separate table is used to enter the ratio of monthly to annual potential evapotranspiration for each month. Inputs are entered on the *Soil_Moisture* worksheet and an example is shown in Screen Shot 2-11.3.

Mean Annual Evapotranspiration (inches), for Each Elevation Zone							
Zone 1	Zone 2	Zone3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
3800 ft	4500 ft	5500 ft	6000 ft	0 ft	0 ft	0 ft	0 ft
29.00	28.00	25.00	22.00				

Ratio of Average Monthly Potential Evapotranspiration to Annual (Appled to Each Elevation Zone)

Month	Ratio to Annual
Oct	0.054
Nov	0.015
Dec	0.006
Jan	0.007
Feb	0.016
Mar	0.034
Apr	0.066
May	0.119
Jun	0.168
Jul	0.219
Aug	0.184
Sep	0.111
Total	1.000

Screen Shot 2-11.3 – Example Data Entry Format for Monthly Potential Evapotranspiration for A.R. Bowman Watershed, Oregon

2-11.5 Probabilistic Analyses of Snowpack

Snowpack magnitude in a mountainous watershed varies both temporally and spatially. Temporal variability includes seasonal variability as the snowpack accumulates in the late fall, reaches a maximum during the winter period, and melts out in the spring. It also includes variability produced by the year-to-year variation at a given site due to wet or dry climatic years. All other factors being equal, heavier snowpacks would be expected in wetter years and lighter snowpacks would be expected in drier years. Snowpack spatial variability arises primarily from differences in elevation, topographic orientation of hillside faces and wind-leeward effects between locations in the watershed which affects both temperatures and precipitation amounts.

Both temporal and spatial variability are addressed in the stochastic model. The temporal aspects are addressed by analyzing snowpack snow-water equivalent on a monthly basis (Figures 2-11.6 and 2-11.7 a,b). Also, snowpack is correlated with antecedent precipitation using a *key snowpack station* and *key precipitation station* that allows SEFM to account for the variability in the snowpack due to wet or dry climatic years. Both the deterministic and random components of the correlation relationship are preserved in the simulations.

The spatial aspects are addressed using regional analysis methods by analyzing snow-water equivalent (SWE) at multiple sites within the watershed and in climatologically similar areas representing locations with a range of elevation and mean annual precipitation. Sample statistics of snow-water equivalent from these sites are used to compute the frequency of snow-free ground (θ) and to estimate population means (μ) and standard deviations (σ) in natural log-space for snowpack snow-water equivalent. Regression relationships are developed for prediction of the three parameters (θ, μ, σ) using elevation as the explanatory variable along with a snowpack indexing procedure.

Magnitude-Frequency Relationships for Snowpack – The end-of-month snowpack magnitude-frequency relationship at each snow measurement site is described by a mixed distribution[14,47]. The mixed distribution is comprised of a mixing parameter (θ) that sets the frequency of time that the ground is snow-free (Figure 2-11.6), and a Log-Normal[16,29,43,60] distribution of snow-water equivalent values for the times when snow is on the ground (Figure 2-11.7a,b). Typical behavior for mountainous snow measurement sites is for the mixing parameter to be relatively large at the on-set of the winter season, to be zero or near zero during the winter period, and to increase in magnitude towards the spring of the year. A mixing parameter of 1.0 is set by the user for all warm season end-of-months when snow on the ground has never occurred or where snow on ground is determined to be extremely unlikely.

The mixed probability distribution model has the form:

$$F(x) = \theta + (1-\theta)\, G(x) \qquad (2\text{-}11.1)$$

where: $F(x)$ is the cumulative distribution function for snow-water equivalent, θ is the frequency of snow-free ground, $(1-\theta)$ is the frequency of snow-covered ground, and $G(x)$ is the cumulative distribution function for snow-water equivalent when the ground is snow-covered. The two-parameter Log-Normal distribution is used for describing the cumulative distribution function $G(x)$ when the ground is snow covered.

Snowpack Indexing – The snowpack indexing procedure was developed to both improve and simplify estimation of the parameters needed for spatial allocation of snow-water equivalent. Snowpack magnitude varies with both elevation and mean annual precipitation. Initially, this suggests that multiple regression techniques would be appropriate for estimation of the values of the mixing parameter (θ) and the log-normal distribution parameters (μ) and (σ) that are applicable for the various combinations of zones of elevation and mean annual precipitation. However, multiple regression methods are not well-suited to this situation because many projects will have a limited number of sites with snow measurements. The small sample sizes and natural variability of SWE data will limit the utility of multiple regression methods.

The snowpack indexing procedure allows regression analyses to be conducted using elevation as the explanatory variable by first indexing the means of the log-transformed SWE for the various sites to that expected at a site with a user-specified value of mean annual precipitation (the reference value of mean annual precipitation). The concept behind this approach is that snowpack magnitude at a given location for a given end-of-month can be considered to result from a combination of the magnitude of the moisture supply and the efficiency of the mechanism for producing snow.

The zone of mean annual precipitation can be viewed as an indicator of the magnitude of antecedent precipitation (moisture supply), with zones of higher mean annual precipitation having the potential to produce greater snowpacks. The elevation zone is an indicator of seasonal air temperatures and the efficiency of the mechanism for having precipitation occur in the form of snow. Higher elevations would be associated with lower temperatures and have higher efficiencies in producing larger snowpacks. For example, two separate sites in a given climatic region with similar elevation and mean annual precipitation would be expected to have similar snowpacks, all other factors being equal. Likewise, if two sites have the same elevation and one site has 20% greater annual precipitation, then the site with the greater annual precipitation would be expected to have about 20% higher SWE, all other factors being equal. This situation allows an indexing approach to be used that yields snowpack magnitude-frequency characteristics for a common value of mean annual precipitation for all sites.

Specifically, elevation is used as an explanatory variable in regression analyses for the mixing parameter (θ) and the standard deviation (natural log-space) of SWE when snow is on the ground. The mean (μ) of SWE (natural log-space) is indexed to a reference value of mean annual precipitation corresponding to a value representative of where the majority of snowpack accumulates in the watershed (Equation 2-11.2). This yields an indexed value of the mean of log-transformed SWE (μ_{ref}).

$$\mu_{ref} = \mu_i - LN(MAP_i) + LN(MAP_{ref}) \qquad (2\text{-}11.2)$$

where: μ_i is log-transformed mean value for the site of interest; MAP_i is the mean annual precipitation for the site of interest; and MAP_{ref} is the mean annual precipitation for the reference site.

The snowpack indexing procedure will be explained in detail in Appendix C.

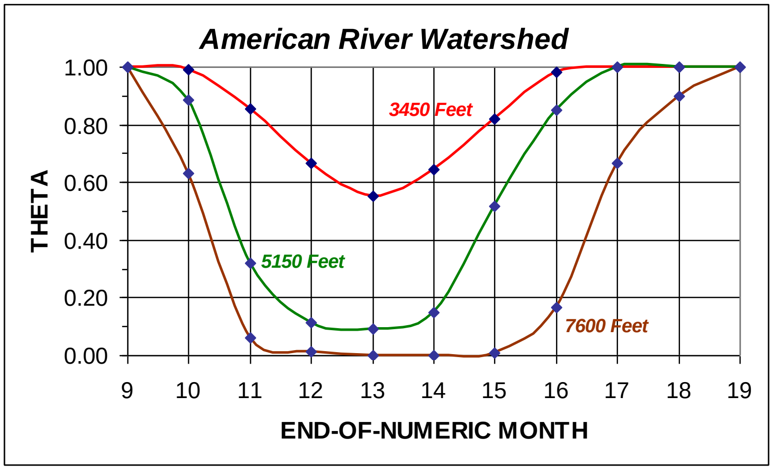


Figure 2-11.6 – Seasonal Variation of Mixing Parameter (θ) for Frequency of Snow-Free Ground Conditions at Various Elevations in the American River Watershed, California

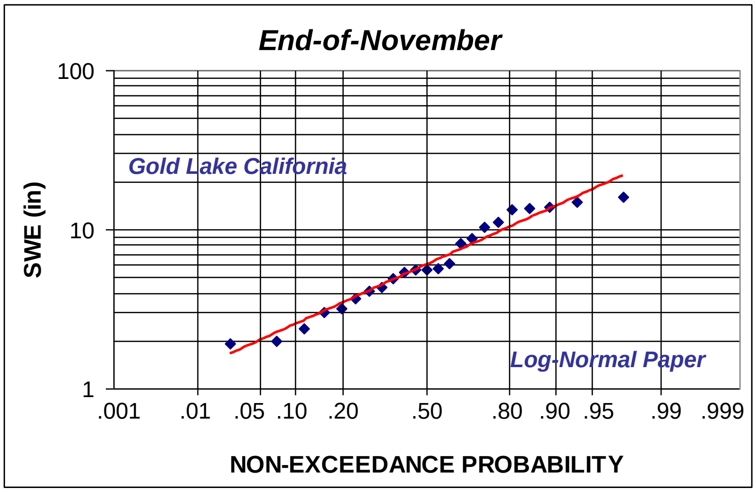


Figure 2-11.7a – Example Magnitude-Frequency Relationship for Snow-Water Equivalent (Log-Normal Distribution for Condition when Ground is Snow-Covered)

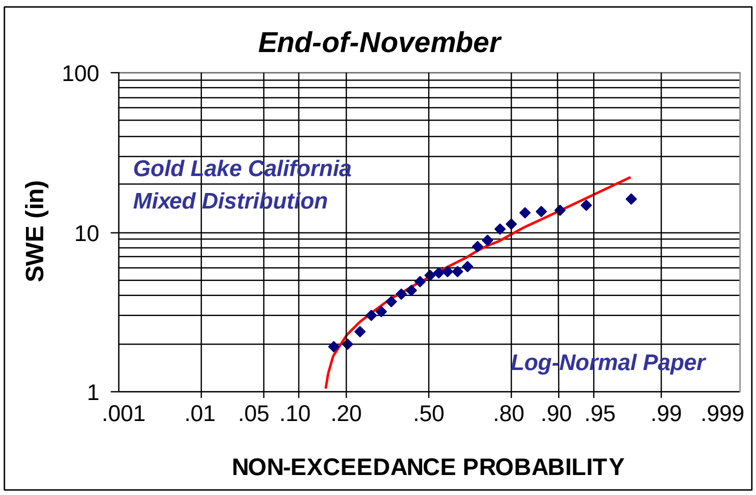


Figure 2-11.7b – Example Magnitude-Frequency Relationship for Snow-Water Equivalent Using a Mixed Distribution Model

Low-Elevation Intermittent Snow-on-Ground – A common occurrence in winter periods is for snow to accumulate at the lower elevations which persists for a few days to a few weeks and then melts out. This occurs from the chance events of below-average temperatures occurring with precipitation events and then followed by warmer near-normal temperatures at the low elevations. This intermittent snow-on-ground is an independent event relative to the wintertime buildup of snowpack at the higher elevations.

This situation is accounted for in SEFM by identifying which of the elevation zones typically have a seasonal snowpack develop, which elevation zones have the possibility of an intermittent snowpack and which elevations zones are snow-free. In simulations, snow-on-ground for the low elevation zones is simulated independent of the snowpack at the higher elevations. The elevation zones which are snow-free, have intermittent snowpack or have seasonal snowpack are identified in SEFM as shown in Screen Shot 2-11.4. Note that values of the mixing parameter theta (θ), that sets the frequency of time that the ground is snow-free are markedly higher for the elevation zones with intermittent snowpack.

SEFM Operation – For each simulation, a snowpack snow-water equivalent value is needed for each HRU within the watershed. This is accomplished in four steps. First, a value of snow-water equivalent for the *key snowpack station* is determined based upon the value of antecedent precipitation previously selected for the *key precipitation station* and the logarithmic correlation relationship between the two key stations:

$$LN\,(y) = \alpha + \beta\, LN\,(x) + \varepsilon \qquad (2\text{-}11.3a)$$

$$SWE = EXP\,[LN\,(y)] \qquad (2\text{-}11.3b)$$

where: y is the end-of-month snow-water equivalent; x is the end-of-month antecedent precipitation; alpha (α) and beta (β) are intercept and slope parameters; ε is a Normally distributed residual term that accounts for the unexplained variance; and *SWE* is the snow-water equivalent at the key snowpack station. An example correlation relationship is shown in Figure 2-11.8.

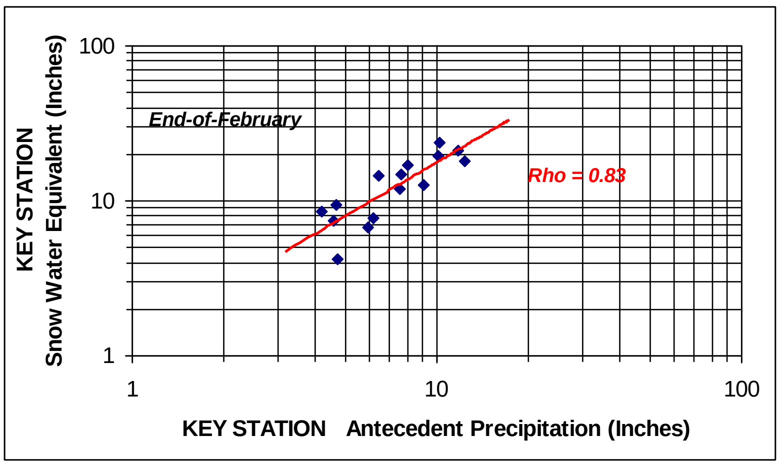


Figure 2-11.8 – Example Logarithmic Correlation Relationship Between Key Snowpack and Key Antecedent Precipitation Stations

Second, the exceedance probability of the value of snow-water equivalent is then computed for the *key snowpack station* based on a Log-Normal distribution and estimated values of the population mean and standard deviation for the *key snowpack station*.

Third, the value of the mixing parameter (θ) and Log-Normal distribution parameters (μ_{ref}, σ) are determined from the regression relationships with elevation for the elevation zone of interest (examples in Figures 2-5. 9a,b,c). And the mean (μ) of the Log-Normal distribution for the applicable zone of mean annual precipitation is obtained by reversing the snowpack indexing process for the previously computed (μ_{ref}) value (Equation 2-11.2).

$$\mu_i = \mu_{ref} + LN(MAP_i) - LN\,(MAP_{ref}) \qquad (2\text{-}11.4)$$

Lastly, the value of exceedance probability at the *key snowpack station* is used in conjunction with the snowpack parameters (θ, μ, σ) to allocate snowpack for the HRU of interest. This approach yields snowpacks with a common exceedance probability throughout the watershed and SWE that varies with elevation and mean annual precipitation. Figure 2-5.4 depicts the type of spatial distribution of snowpack that is produced by this approach.

Assumptions/Expectations – It is assumed that there is a high level of correlation between end-of-month snow-water equivalent values for sites in the watershed that accumulate snow. If the correlation coefficient (natural log-space) for a given end-of-month is unity, or near unity, and a common probability distribution is used, then the exceedance probability would be the same, or very nearly the same, for sites in the watershed that accumulate snow. It is reasonable to expect there would be a high level of correlation for snowpack values for locations that are physically near each other and that that correlation decays slowly with distance between locations for mountain snowpacks in the winter months. This is expected to be the typical situation for watershed, except for extremely large watersheds for major river systems that may span several climatological provinces.

Imposed Constraints – Small regional datasets comprised of several SNOTEL or snow-course stations with record lengths from 15 years to 30 years are typically available for analyses of snowpack. Given the typical size of these datasets, Monte Carlo sampling of snowpack snow-water equivalent is limited to exceedance probabilities in the range from 0.99 to 0.01. This allows simulation of uncommon values of snowpack but avoids excessive extrapolation of the frequency curves that are developed from the limited amount of snowpack data that are typically available. Since snowpack is derived from antecedent precipitation, snow-water equivalent cannot exceed antecedent precipitation for a given zone of mean annual precipitation. To avoid implausible situations, snowpack snow-water equivalent is limited to 95% of the value of antecedent precipitation. This constraint is not imposed often, but can come into play when unusually large (rare) snowpacks are simulated for zones of high elevation.

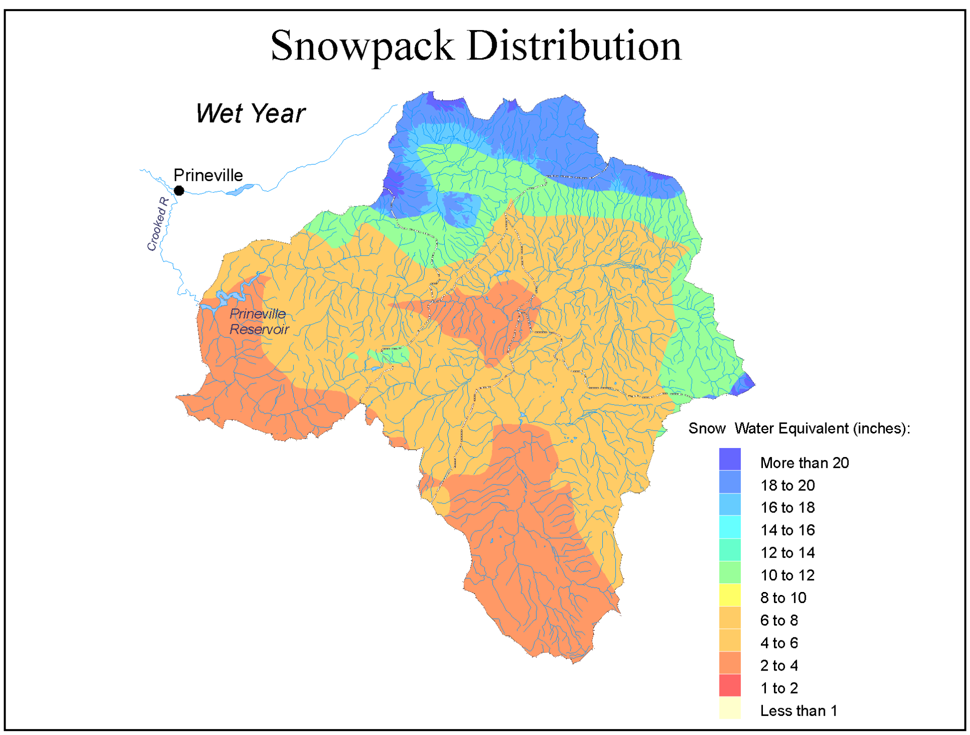


Figure 2-11.9 – Example Spatial Distribution of Snowpack for Crooked River Watershed, Oregon

Guidance and Experience – The magnitude of correlation between a *key snowpack station* and *key precipitation station* has been found[3,48,50] to vary by both time-of-year and elevation. Early in the winter season, air temperature is a major factor in determining whether precipitation falls in the liquid or solid phase. Late in the winter season, the magnitude of over-winter snowpack and the persistence of warm air temperatures determine how quickly the snowpack melts out. For both these situations, there is high variability in the amount of snow on the ground and lower correlation commonly exists between key precipitation and snowpack stations. Also, if the *key snowpack station* is at an elevation that commonly experiences precipitation in the liquid as well as the solid phase during storms, then there will be greater variability in snowfall and lower correlation will occur between the key precipitation and snowpack stations.

It should be noted that high correlation coefficients are not necessarily superior to low correlation coefficients, because the correlation relationship is not being used as a pure deterministic predictor. The goal is to replicate, to the greatest extent possible, the actual relationship between antecedent precipitation and snowpack that is observed in the watershed. The correlation relationship between the *key snowpack station* and *key precipitation station* is used to preserve both the deterministic (dependence) and random components of the relationship between snowpack and antecedent precipitation. This is needed to properly allocate the portion of antecedent precipitation that is held in the snowpack and to use the remainder for computing soil moisture budgets.

Data Entry Format – First, identify those months when snowpack is possible. A drop-down menu is used for each month to indicate whether snowpack is possible, or not possible (Screen Shot 2-5.1).

Next, snow-water equivalent magnitude-frequency curves are defined for each elevation zone in the watershed using the snowpack indexing procedure and for the key snowpack station. For each elevation zone for each end-of-month, data entry includes a mixing parameter (θ) for the frequency of snow-free conditions, and parameters μ_{ref} and σ for the mean and standard deviation of the Log-Normal distribution for the non-zero values of snow-water equivalent. The mean value μ_{ref} of log-transformed SWE is the expected value for a site with mean annual precipitation equal to the reference mean annual precipitation (indexing value). A θ parameter value of unity indicates a snow-free month.

Key precipitation and snowpack recording stations are used for determining the relationship between snow-water equivalent and antecedent precipitation. Data entry is required to describe the correlation relationship between the key stations for each month of the snowpack season. This includes parameters for the intercept, slope, and correlation coefficient. The distribution parameters for the key station are also needed for each month. This includes the θ parameter for the frequency of snow-free conditions, and parameters μ and σ for the mean and standard deviation of the Log-Normal distribution for the non-zero values of snow-water equivalent. Lastly, enter the value of mean annual precipitation used as the reference value in the snowpack indexing procedure.

All inputs are entered on the *Snow_Parms* worksheet and an example is shown in Screen Shot 2-11.3. Screen Shot 2-11.4 shows the data entry format for the reference value of mean annual precipitation.

Control

Snow Parameters

Snow on Ground is Possible in These Months	
Month	Snow Possible or Not Possible
Oct	No Snow
Nov	Snow Possible
Dec	Snow Possible
Jan	Snow Possible
Feb	Snow Possible
Mar	Snow Possible
Apr	Snow Possible
May	No Snow
Jun	No Snow
Jul	No Snow
Aug	No Snow
Sep	No Snow

Snowpack Key Station Information (Used for Reference, Not Read by Program)	
Station Name	Derr Snotel Site
Station Number	19E03S
Elevation	5670
Mean Annual Precip	30.6

Antecedent Snowpack Spatial Distribution Parameters

	Precip Zone 1	10.00 in		Precip Zone 2	13.00 in		Precip Zone 3
	Mixing Parameter, Frq of Snow Free	Log-Normal Distribution Parms		Mixing Parm, Snow Free	Log-Normal Dist Parms		Mixing Parm, Snow Free
Month	Ground (θ)	Mean (μ)	Stdev (σ)	Ground (θ)	Mean (μ)	Stdev (σ)	Ground (θ)
Oct	1.0000			1.0000			1.0000
Nov	0.4790	-1.4960	0.8600	0.3950	-1.1520	0.8380	0.3260
Dec	0.1610	-0.2030	0.9210	0.1160	0.0540	0.8890	0.0830
Jan	0.0500	0.2790	0.9360	0.0370	0.5550	0.8660	0.0280
Feb	0.1270	0.2600	0.9550	0.0810	0.5860	0.8810	0.0520
Mar	0.4690	-0.1960	0.8910	0.2900	0.2000	0.8430	0.1790
Apr	1.0000			0.8760	-0.2840	1.0680	0.7480
May	1.0000			1.0000			1.0000
Jun	1.0000			1.0000			1.0000
Jul	1.0000			1.0000			1.0000
Aug	1.0000			1.0000			1.0000
Sep	1.0000			1.0000			1.0000

Antecedent Snowpack Key-Station

	Log-Normal Distribution Parameters			Regression With Antecedent Precipitation Key Station		
Month	Mixing Parameter, Frq of Snow Free Ground (θ)	Location Parm (μ)	Dispersion Parm (σ)	Intercept (a)	Slope (b)	Corr Coeff (r)
Oct	1.000					
Nov	0.067	0.6750	0.8490	-0.2570	1.0170	0.5630
Dec	0.009	1.6280	0.7380	0.6500	0.7420	0.5320
Jan	0.009	2.1660	0.5260	0.9570	0.7200	0.5680
Feb	0.009	2.4590	0.4840	0.6900	0.9450	0.7330
Mar	0.009	2.5590	0.4630	0.6740	0.9530	0.7790
Apr	0.267	2.0500	0.7600	-1.1901	1.4786	0.7170
May	1.000					
Jun	1.000					
Jul	1.000					
Aug	1.000					
Sep	1.000					

Screen Shot 2-11.4 – Data Entry Format for Antecedent Snowpack (Partial Listing)

Reference Mean Annual Precipitation used in Scaling Snowpack (inches)	21.00

Screen Shot 2-11.5 – Data Entry Format for Snowpack Indexing Reference Value of Mean Annual Precipitation

2-11.6 Probabilistic Analyses of Antecedent 14-Day Mean Air Temperature

Antecedent temperature is used to determine whether a concrete frost exists in portions of the watershed at the onset of the extreme storm. A concrete frost is a type of frozen ground condition that can occur when there is sufficient soil moisture and the areal extent of freezing is sufficient to form a contiguous frozen layer that impedes surface infiltration.

Antecedent temperature is defined as the mean daily temperature averaged over the 14 days prior to the occurrence of the extreme storm (last two weeks of the month). The determination of the existence of frozen ground is made for each HRU based on the antecedent temperature, depth of snow cover, and soil moisture conditions for the HRU. If conditions are sufficient to support a concrete frost, then the surface infiltration rate is reduced to reflect the impedance to infiltration.

SEFM Operation – For each simulation, the antecedent temperature is selected for the *key temperature station* using a three-parameter Gamma distribution and standard Monte Carlo sampling procedures. Next, the antecedent temperature is determined for the mid-point of each elevation zone. This is accomplished by relating the antecedent temperature from the *key temperature station* to the mid-point of the various elevation zones using a user specified temperature lapse rate. Lastly, snow-depth and soil moisture conditions are checked, and a concrete frost is assumed to be present if the following conditions are satisfied:

1. Antecedent temperature is below freezing in the two-weeks prior to the storm event;
2. Snow-free ground or thin snowpack;
3. Sufficient moisture in the surface layer of the soil for frost to form.

Assumptions/Expectations – It is assumed that prolonged below freezing temperatures will produce a concrete frost when the upper layer of the soil is wet and there is limited insulating effect from snow cover. Concrete frosts have been observed to occur[57,58,59,74] when this combination of conditions has been present.

Guidance and Experience – Prior studies[57,59] have shown that a prolonged period of below-freezing temperatures is required for developing a concrete frost, and a duration of 14-days is suitable for determination of frozen ground conditions. Analysis of average 14-day temperatures[48,50] has shown the data to have minor to moderate skewness. The three-parameter Gamma distribution[4,16,29,60] is well-suited to describe air temperature data with minor to moderate skewness (Figure 2-11.10).

Sample statistics for the variance and coefficient of skewness are subject to significant sampling variability in small datasets. Smoothing of the sample statistics across the 12 months is recommended to provide improved end-of-month estimates and reasonable month-to-month variation.

Temperature lapse rates should be selected consistent with the general conditions expected over a two-week period. This would correspond to temperature lapse rates between the wet pseudo-adiabatic rate of about -2.7°F/1000 feet, associated with rainy periods, and the dry adiabatic rate of about -5.4°F/1000 feet, commonly associated with precipitation-free periods and clear skies. An average value of –4.0°F/1000 feet, representing a mixture of the two lapse rates, is a reasonable choice.

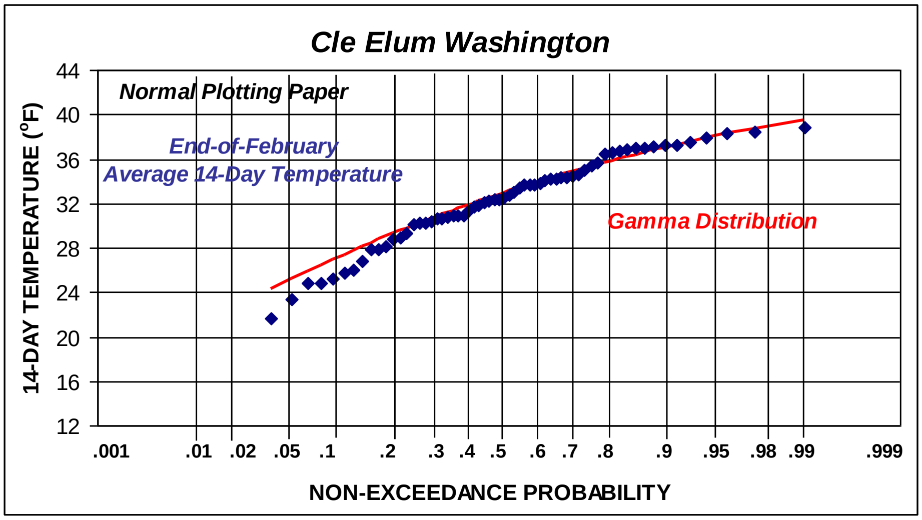


Figure 2-11.10.1 – Probability-Plot of Average End-of-February 14-Day Temperature

Experience in mountainous watersheds[58,65] has shown that it is unusual to produce the combination of conditions necessary for forming a concrete frost over large portions of a watershed. Experience has also shown that frozen ground conditions rarely occur in heavily forested watersheds with thick litter layers and are rarely seen where free-draining sandy soils are present. When frozen ground conditions do occur in the western US, they are most often seen in watersheds with fine-grained soils, at lower elevations in semi-arid climates where thin snowpacks are common.

Rule-of-Thumb Criteria – General rule-of-thumb criteria for formation of a concrete frost[58,59] includes:

- antecedent mean daily 14-day air temperature below freezing:
- snowpack depth less than 6-inches (snow-water equivalent of about 1.0 inches); and
- soil moisture content of 2-inches or more in a fine-textured (non-porous) soil.

Limited data and studies are available for determining the reduction in surface infiltration rate for frozen ground conditions. A surface infiltration rate of 0.10 inch/hour, or one-third of the minimum surface infiltration rate, whichever is smaller, is commonly used. The elapsed time for melting of the frozen ground is dependent upon the temperature of the rain during the storm and the depth of frost penetration. Durations of 12-hours to 72-hours are commonly used for melting of the concrete frost.

Selecting Key Temperature Station – Ideally, the *key temperature station* should be a long-term station centrally located within the watershed at an elevation where conditions are most conducive to the formation of a concrete frost. The *key temperature station* can be co-located with the key precipitation and key snow pack stations if desired.

Data Entry Format for Antecedent Temperature **–** The model input consists of estimates of the mean, standard deviation, and coefficient of skewness of the mean daily temperature averaged over the last 14 days of each month for the key temperature station. Temperature differences are also entered that relate the temperature at the key station to the mid-point of each elevation zone. Inputs are entered on the *Ant_Temp* worksheet and an example is shown in Screen Shot 2-6.1.

Data Entry Format for Frozen Ground Conditions – Criteria for formation of a concrete frost are entered on the *Snow_Parms* worksheet. Data entry includes the maximum allowable depth of snowpack expressed as a snow-water equivalent, and the minimum required soil moisture content.

Data entry is also required for the surface infiltration characteristics after the concrete frost occurs. Input parameters include the surface infiltration rate (inch/hour) after the concrete frost forms, and the elapsed time for melting of frozen ground and the surface infiltration rate to return to unfrozen conditions (Screen Shot 2-11.6).

If it is determined that conditions for forming a concrete frost are not physically plausible at any time of the year, the data entry screen can be left empty, and the box on the *Control* worksheet (Screen Shot 2-11.7) can be checked (✓) for a fixed temperature with the temperature set above freezing.

Control

Antecedent Temperature

Used in Frozen Ground Calculations

Temp Difference Between Elevation Zones and Key Temperature Station	
Elevation Zone	(Deg F)
1 (3800 ft)	1.9
2 (4500 ft)	0.0
3 (5500 ft)	-2.7
4 (6100 ft)	-5.4
5 (0 ft)	
6 (0 ft)	
7 (0 ft)	

(Note: This lapse rate is used to set frozen ground conditions. The lapse rate on the Snow_Parm page sets the temperatures during the event)

Antecedent Temperature Key Station Gamma Distribution Parameters			
Last 2 Weeks of:	Mean	Std Dev	Skew
Oct	44.20	3.85	0.00
Nov	32.40	4.55	-0.40
Dec	27.40	5.60	-0.80
Jan	29.10	6.25	-1.00
Feb	35.30	4.75	-0.80
Mar	38.90	3.75	-0.30
Apr	43.50	3.55	0.20
May	52.10	3.45	0.50
Jun	59.70	3.30	0.50
Jul	66.50	3.15	0.50
Aug	62.30	3.25	0.40
Sep	54.00	3.45	0.30

Station Name	Barns Station
Station Number	35-0501
Elevation	3970 feet
Mean Annual Precip	12.9 inches

Antecedent Temperature (if Constant)	
Elevation Zone	Temp, Deg F
1	
2	
3	
4	
5	
6	
7	

Frozen Ground Criteria	
(These Values Are Entered on the Snow_Parms Sheet	
Min Soil Moisture (in)	2.00
Max Snow Water Equivalent (inches)	1.00
Frozen Surface Infilt Rate (in/hr)	0.10
Time Required to Melt Frozen Ground (hrs)	72

Screen Shot 2-11.6 – Example Data Entry Format for Antecedent Temperature and Criteria for Frozen Ground Conditions

PART III – WATERSHED MODELS

3-0 CHOICE OF WATERSHED MODELS

SEFM is currently configured to be used with the following watershed models:

- SEFM watershed model, modified Holtan method, single event and continuous modeling
- SEFM watershed model, Sacramento Soil Moisture Accounting method, continuous modeling
- HEC-1 watershed model, modified Holtan method, single event and continuous modeling
- HEC-1 watershed model, Sacramento Soil Moisture Accounting method, continuous modeling
- HEC-HMS watershed models with sub-basin configuration, backward compatible to HEC-1
- UBC watershed model, continuous modeling

Each of these watershed models have many similarities because they are all modeling the rainfall-runoff and snowmelt processes, generating streamflow hydrographs and routing the hydrographs through a stream network to a location of interest. With regard to stochastic flood simulations, the primary differences between the models are how the hydrologic soil processes are modeled, and the procedures for transforming quickflow and interflow runoff into streamflow hydrographs. Details about these processes and use of the SEFM engine with these watershed models is presented in later sections in Chapter 3.

3-0.1 Terminology for Hydrologic Runoff Responses for Watershed Modeling

The following terms are used for hydrologic runoff responses in the SEFM User's Manual and are presented here to provide a common framework in discussion of the various watershed models. A generalized depiction of the various contributors to a flood hydrograph is shown in Figure 3-0.1. Details about modeling of the hydrologic processes for these runoff responses are discussed in the sections for each of the watershed models.

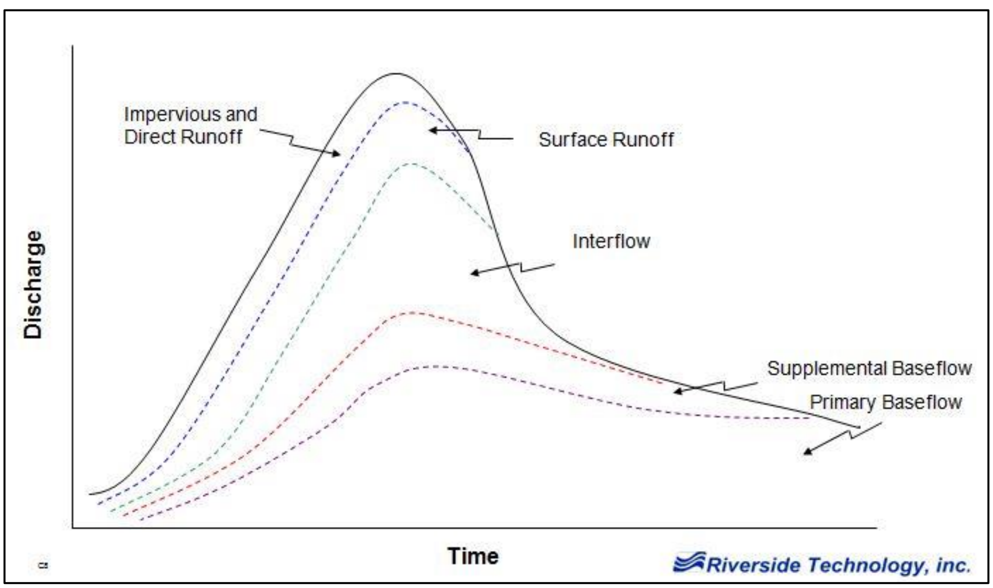


Figure 3-0.1 – Generalized Depiction of Runoff Components for Flood Hydrographs Graphic Courtesy of Riverside Technology, Inc.

Direct Runoff – Direct runoff refers to runoff/streamflow generated by precipitation which falls on reservoirs, natural lakes, marshes, wetlands and other water bodies directly connected to the stream network.

Quickflow Runoff – Quickflow runoff is the generic term given to runoff that occurs relatively soon following precipitation input. This would include surface runoff, saturated overland flow, flow through macro-pores in the upper soil horizon and any other mechanism that allows a relatively quick runoff response. Many watershed models use standard unit-hydrograph procedures to transform quickflow runoff to a streamflow hydrograph. Quickflow, when it occurs, is a primary contributor to floodflows.

Interflow Runoff – Interflow can be loosely defined as subsurface runoff via a variety of paths whose response time is intermediate between that of quickflow runoff and the groundwater response. Interflow runoff is generally described as water that infiltrates the soil surface and moves laterally through the surficial soil mantle or at shallow depths in fractured bedrock under both saturated and unsaturated conditions until it enters a stream channel or causes displacement of subsurface water into a stream channel.

Interflow runoff is a common occurrence for those areas of the watershed that receive low to moderate precipitation intensities. Simulation of the interflow component begins after the surficial soil moisture deficit and subsurface storage deficits are satisfied. Interflow runoff is typically transformed to a streamflow hydrograph using linear reservoir routing procedures. Interflow is often a major component of floodflows, particularly for floods generated by synoptic-scale mid-latitude cyclones that produce intermediate and long duration storms and may include snowmelt.

Supplemental Baseflow – Supplemental baseflow is a groundwater term used in the Sacramento Soil Moisture Accounting method (SAC-SMA, Burnash and Ferral[100]) and is adopted in SEFM. It applies to a delayed streamflow response to an individual precipitation event or seasonal wet period with a response time of several days to several weeks. The response time is intermediate between that of interflow and primary baseflow. Supplemental baseflow is typically a minor contributor to floodflows in response to a major storm event. The exception is very large watersheds where supplemental baseflow from areas near the outlet of the watershed may join with quickflow or interflow runoff generated in the headwaters of the watershed.

Primary Baseflow – Primary baseflow is another groundwater term used in SAC-SMA and is adopted in SEFM. It is generally described as dry-weather streamflow that occurs as groundwater discharge. It has a very-delayed response to an individual precipitation event or seasonal wet period with a response time in the range of several weeks to several months. Primary baseflow is not a contributor to floodflows in response to a major storm event.

Deep Recharge – Deep recharge is the term given to groundwater generated in a watershed which emerges downstream of the point of interest, such as the outlet of the watershed or a at streamflow gage where streamflow measurements are available. The loss of groundwater to areas outside the watershed, which were generated by precipitation occurring within the watershed, must be accounted for in water-budget computations in calibration of the watershed model.

3-0.2 Storm Type Considerations for Modeling Rainfall-Runoff Processes

The four storm types (Section 2-4) produce a wide range of precipitation-intensity characteristics.

- Synoptic-Scale Mid-Latitude Cyclones
- Synoptic-Scale Tropical Storms and Tropical Storm Remnants
- Mesoscale Storms with Embedded Convection
- Local Storms

For the cases of the mesoscale and synoptic scale storm types, low to moderate precipitation intensities are likely to occur over much of the watershed. These lower intensities are of a magnitude which commonly produces interflow runoff with a somewhat delayed streamflow response. In contrast, convective storm cells in local storms and mesoscale storms with embedded convection can produce locally high precipitation intensities that can produce a significant quickflow response over limited areas.

Recognizing this situation, SEFM utilizes hydrologic soils modules for describing the rainfall-runoff process that compute both quickflow and interflow runoff. In particular, the hydrologic soils modules are configured to provide for soil moisture accounting where the soil moisture content is used in computing infiltration rates which govern the proportioning of quickflow, interflow and contributions to groundwater. Groundwater discharge (baseflow) may also be computed although it often has little contribution to the flood response for a storm event. Modeling of the groundwater contribution is used in calibration of the watershed model which facilitates estimation of the surficial and subsurface soil moisture storage capacities. Continuous hydrologic modeling is also used to develop seasonal soil moisture states for use in resampling for stochastic generation of antecedent conditions.

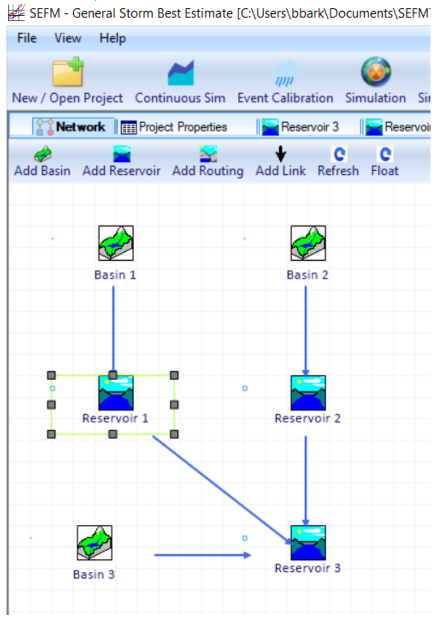
3-1 SEFM WATERSHED MODEL – WATERSHED LAYOUT

The SEFM watershed model is a basic hydrologic model which computes runoff, generates streamflow hydrographs and routes the hydrographs to a downstream location. The SEFM watershed model has the following features:

- Sub-basin configuration within a stream network, including dams and reservoir operations
- Distributed inputs for precipitation, evapotranspiration, snowpack and hydrologic soil parameters
- Computes runoff using either a modified Holtan procedure for soil moisture accounting or the Sacramento Soil Moisture Accounting method (SAC-SMA)
- Computes snowmelt using an energy-budget method and the USBR snow-compaction method
- Computes runoff on a distributed basis for land segments, Hydrologic Runoff Units (HRUs)
- Computes quickflow runoff for each sub-basin and transforms to a streamflow hydrograph using a unit-hydrograph
- Computes interflow runoff for each sub-basin and uses linear reservoir routing procedures to generate a streamflow hydrograph
- Computes supplemental baseflow and primary baseflow using the Sacramento Soil Moisture Accounting methodology
- Uses hydrologic routing methods for routing hydrographs through the stream network

3-1.1 Description of Sub-Basins and the Stream Network

Watersheds are described using sub-basins connected to a stream network which may include dams upstream of the point of interest. A drag-and-drop graphical interface is included for defining the watershed layout (Screen Shot 3-1.1)



Screen Shot 3-1.1 – Drag and Drop Graphical Interface for Defining Watershed Layout

3-1.2 SEFM Operation for Hydrologic Soil Processes

Details of the hydrologic soil processes are described in Section 3-2 for the modified Holtan method and in Section 3-3 for the Sacramento Soil Moisture Accounting method.

3-1.3 Quickflow Hydrographs

When the unit hydrograph was first proposed in the 1932, surface runoff was considered to be overland flow, defined as water that travels over the ground surface to the stream channel. As more flood studies and scientific investigations have been conducted over the years, the term surface runoff has generally been replaced by *quickflow* which encompasses runoff via a variety of paths.

As used in SEFM, quickflow runoff is the term given to runoff that occurs relatively soon following precipitation input relative to the slower travel time of interflow and the groundwater response. This would include surface runoff, saturated overland flow, flow through macro-pores in the upper soil horizon and any other mechanism that allows a relatively quick runoff response.

SEFM Operation – Quickflow runoff is transformed to a streamflow hydrograph using standard unit-hydrograph procedures.

The primary descriptors of the quickflow runoff unit hydrograph[33] are the lag time ($LagTime_{peak}$), unit duration (D) of runoff generated by precipitation, period of rise (Pr), peak discharge (Qp), and the shape of the unit hydrograph (Figure 3-1.4).

$LagTime_{peak}$ is defined as the elapsed time from the centroid of precipitation that produces runoff to the occurrence of the flood peak. Alternative measures of lag-time have also been used by various investigators. The most common alternative definition of lag-time is the elapsed time from the centroid of precipitation excess (precipitation that produces runoff) to the center of mass of the flood hydrograph. This latter definition is used by the US Bureau of Reclamation and the difference between that definition and the definition used here in the SEFM should be noted.

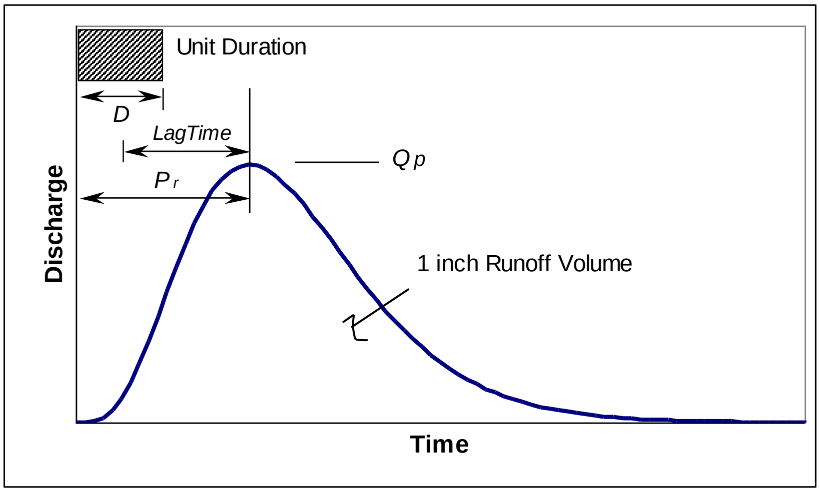


Figure 3-1.4 – Characteristics of Unit Hydrographs

The relationship between the period of rise, unit duration and lag time is defined by:

$$P_r = D/2 + LagTime_{peak} \qquad (3\text{-}1.3)$$

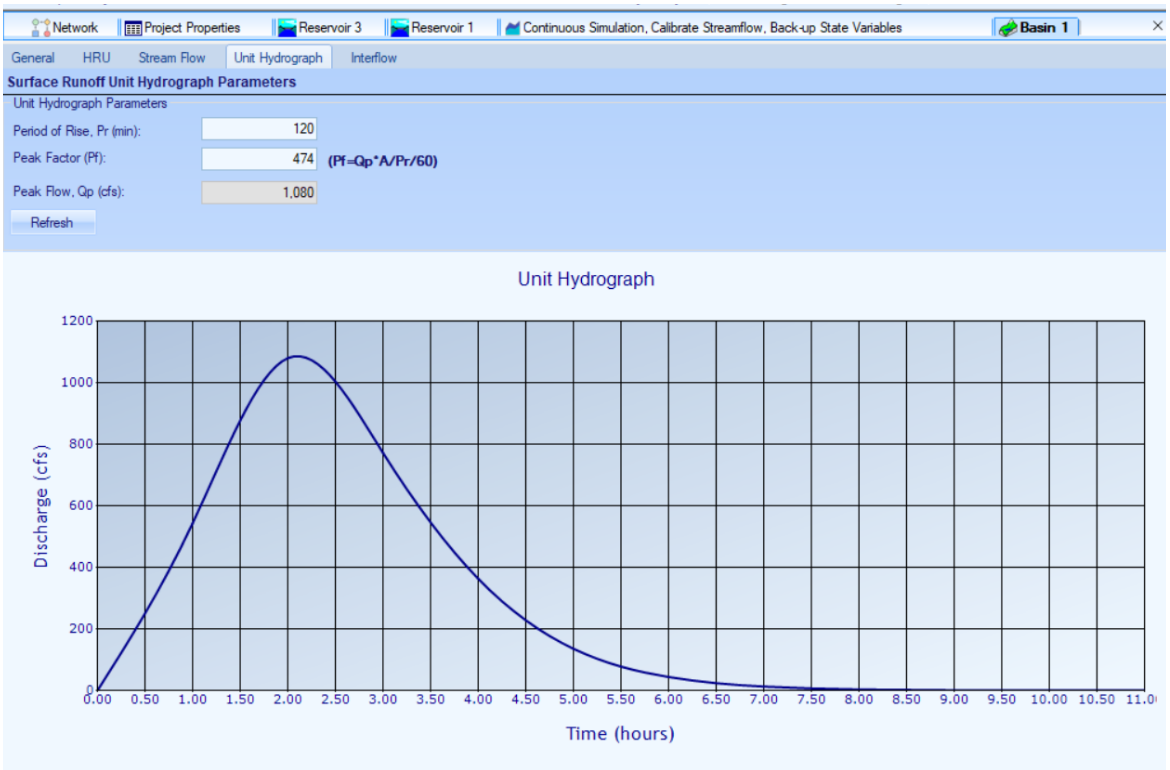
The peak flow (cfs) of the unit hydrograph is determined as a function of the watershed area (A) in square miles, the period of rise in hours, and a peaking factor (Cp):

$$Q_p = \frac{C_p A}{P_r} \qquad (3\text{-}1.4)$$

A brief summary of peaking coefficients obtained by various methods and for various geographical areas in the US are listed in Table 3-1.1.

Table 3-1.1 – Comparison of Peaking Factors for Various Methods/Regions

APPLICATION	*Cp*
Soil Conservation Service Method – Small Watersheds	484
Original Snyder Unit Hydrograph – Appalachian Mountains	360 to 442
USBR - Great Plains	517
USBR - Rocky Mountains – General Storm	387
USBR - Rocky Mountains – Thunderstorm	648
USBR - Southwest Desert, Great Basin, Colorado Plateau	622
USBR - Sierra Nevada, Coast and Cascade Ranges	474
Seattle COE – Western Washington Mountains	542
Schaefer – Thunderstorm Floods Missouri Ozarks	620



Screen Shot 3-1.3 – Example Data Entry Format for Quickflow Runoff Unit Hydrographs

3-1.4 Interflow Runoff Hydrographs

Interflow is water that infiltrates the soil surface and moves laterally through the soil layers or at shallow depths in fractured bedrock under saturated conditions until it enters a stream channel or causes displacement of sub-surface water into a stream channel. Interflow can also be more loosely defined as subsurface runoff via a variety of paths whose response time is intermediate between that of quickflow runoff and the groundwater response.

Generally, watersheds with relatively shallow and/or porous soils over an impermeable layer, such as bedrock, or glacial till, can produce significant quantities of interflow. Because interflow travels subsurface, the travel time is longer, and the response is much more attenuated than that for quickflow runoff.

SEFM Operation – Interflow runoff hydrographs are computed in SEFM using linear reservoir routing procedures. The computational procedures for the modified Holtan method are described in Section 3-2 and the procedures for the Sacramento Soil Moisture Accounting method are described in Section 3-3.

3-1.5 Snowmelt Computations for Flood Simulations

Snowmelt computations can be very complicated when considering the full range of hydrometeorological conditions and energy considerations for snowpack accumulation and ablation over the winter months. However, it is possible to use more simplified procedures for snowmelt computation in SEFM because the flood simulations are for a more restrictive set of hydrometeorological conditions and a short time-frame. Specifically, the conditions of interest are rain-on-snow events and the short period of time during and immediately following a storm event.

Snowmelt is computed using the Corps of Engineers Energy Budget Equation[64,65,87]. Precipitation is assumed to fall as snow if the air temperature for the mid-point in a given elevation zone is less than the freezing temperature plus two degrees Fahrenheit. Snowfall is added to the snowpack and is available for melt later in the simulation. Air temperatures for each HRU are based on the air temperature temporal patterns for the selected prototype storm (Section 2-7).

The USBR snow compaction procedure[85] is used for tracking the snow density, snow depth and snow-water equivalent in each HRU. Snowmelt and liquid precipitation are released from the snowpack after the snow compaction process results in a snow density of 0.40.

SEFM Operation – Snowmelt and snow compaction computations are conducted for each HRU. Snowmelt computations are based on the areal extent of forest coverage for each HRU as indicated by the forest coverage for the associated elevation zone. If the air temperature is greater than the freezing temperature plus 2°F, then snowmelt is computed by Equations 3-1.9 and 3-1-10, and added to the precipitation amount for the given time-step. The snowmelt amount and remaining snowpack snow-water equivalent are tracked separately for each HRU as part of the snow compaction and snowmelt processes.

For Rainy Periods in Open Areas or Partly Forested Areas:

$$Melt = [0.029\,(\Delta_t/24) + 0.0084\,kv\,(\Delta_t/24) + 0.007P]\,(T_a - Freeze) + 0.09(\Delta_t/24) \qquad (3\text{-}1.9)$$

For Rainy Periods in Heavily Forested Areas:

$$Melt = [0.074\,(\Delta_t/24) + 0.007P]\,(T_a - Freeze) + 0.05(\Delta_t/24) \qquad (3\text{-}1.10)$$

where:

Melt – is the snow-water equivalent melted (inches per time-step),
k – is a convection melt coefficient that is dependent upon the extent of forest coverage for the HRU,
v – is the wind speed at 50 feet above the snow surface (miles/hour) and taken to be a nominal 18 mph, which provides consistency of Equations 3-1.9 and 3-1.10 for heavily forested areas
P – is the precipitation during the current time-step (inches),
T_a – is the air temperature during the current time-step (°F) and air temperature is taken to be equal to the dewpoint temperature during rainy periods,
Freeze – is the freezing temperature (°F), which has been set to 32°F, and
Δ_t – is the computational time-step (hours).

The convection melt coefficient (k) in Equation 3-1.9 varies from 0.30 to 1.00 and reflects the exposure of the basin to wind and to snowmelt via convection. The melt coefficient varies with forest cover having a value of 0.30 for heavily forested areas with reduced exposure to wind, to a value of 1.00 for open rangelands with full exposure to the wind. Table 3-1.2 shows the convection melt coefficients for various ranges of forest coverage.

Table 3-1.2 – Convection Melt Coefficients for Various Ranges of Forest Coverage

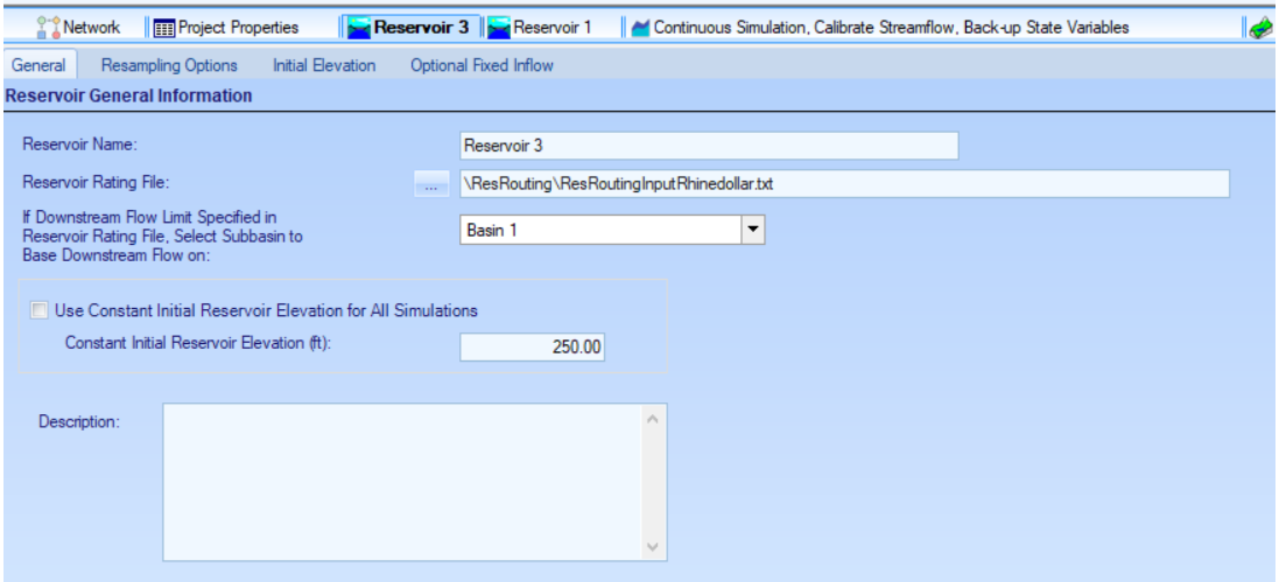
FOREST COVERAGE	FOREST COVERAGE DESCRIPTION	CONVECTION MELT COEFFICIENT (*k*)
0 % - 10%	Open	1.00
10% - 60%	Partly Forested	0.75
60% - 80%	Forested	0.55
80% - 100%	Heavily Forested	0.30

Data Entry Format – Data entry consists of the parameters for snowmelt and includes the freezing temperature in degrees °F, where the freezing temperature is normally taken to be 32°F. The percentage of forest cover in each elevation zone is used to set the convection melt coefficients (Table 3-1.2). The percentage forest coverage is specified on the elevation zone input screen (Screen Shot 3-1.6). Snow water equivalent and snow density are resampled from the antecedent snow time series computed using the UBC snow routine.

Screen Shot 3-1.6 – Example Data Entry for Forest Coverage in Elevation Zones

3-1.6 Reservoir Routing and Dam Operations

Reservoir operations are simulated consistent with standard operating procedures for the project under study. The USCOE Modified Puls level pool routing routine has been modified to accommodate complex operational rule-curves for low-level outlets, gated spillways and open channel spillways. Screen Shot 3-1.8 shows an example of data entry for a complex reservoir operating procedure employed during flood events. Reservoir operation input is performed using a tab-delimited input file. A separate file is specified for each reservoir in the project. Parameters in the reservoir input file are defined in the next section.



Screen Shot 3-1.8 – Example of Data Entry for Reservoir Routing

3-2.0 Reservoir Routing Input File

The reservoir routing parameter file includes input for specifying the elevation/volume relationship for the reservoir, reservoir outlets (low level outlets, gates, spillways, etc.) and settings for simulating gate failure scenarios. The file is tab delimited ASCII formatted and is created using an Excel workbook template (SEFMRoutingInputStrathcona.xls) included with SEFM in the ExcelFiles folder. Each of the data inputs in the reservoir routing input file are described in the following sections.

3-2.1 Reservoir Name, Comments, Number of Outlets, Reservoir Rating

Reservoir Name and Comments – These fields provide information on the reservoir and routing information in the file. These fields are informational only and are not read by the routing routine (Figure 3-2.1).

No Outlets – This field defines the number of hydraulic outlets. Parameter sets for the number of hydraulic outlets specified must be included in the input file. An outlet is defined as either a *Gate* or a *Downstream Flow Limit*. Gates and Downstream Flow Limits are described in Section 3-2.3.

Variable Gate Opening Time (Minutes) – Represents the time to make one gate adjustment for spillways with adjustable gates. A gate adjustment is the time to open (or close) a gate from one setting to the next. The program divides the computational time step by the gate adjustment time and sets the maximum number of gate opening changes in one computational time step to this number. This limit only comes into play when the reservoir is rising quickly and the gates are being opened rapidly to maintain a constant reservoir level.

Hold Outflow=Inflow – Boolean value if true, then the outflow from the reservoir is set equal to the inflow at the start of routing if the initial reservoir discharge is greater than the inflow. The outflow is held equal to the inflow until the inflow matches the initial reservoir discharge. This prevents drafting of the reservoir prior to the arrival of the main part of the flood.

<u>Monthly Gate Open/Close Elevation Table</u> – Gated spillways include parameters that define the elevation when the gate begins to open on the rising hydrograph limb and another elevation that defines when the gate begins to close on the falling hydrograph limb. The open and close elevations can be varied by month to reflect seasonal reservoir operations. The Monthly Gate Open/Close Elevation Table defines the seasonal open and close elevations if these elevations vary throughout the year. If the parameter *Use Monthly Gate Open/Close Table* in the parameters for an individual gate is set to true, then the values in this table are used to define the seasonally varying gate open and close elevations.

<u>Reservoir Rating</u> – Defines the reservoir elevation/volume relationship. Rows is the number of entries in the rating table. Elevation is expressed as meters and volume is expressed as cubic meters. Note that the maximum elevation specified for the reservoir rating must be the same as the maximum elevation specified in the elevation/discharge rating of each outlet.

	A	B	C	D	E	F
1	SEFM RESERVOIR ROUTING INPUT (SAVE AS TAB DELIMITED FILE)					
2	RESERVOIR NAME:	STRATHCONA (INCLUDES GATE OPEN FAILURE OPERATIONS)				
3	COMMENTS:	OUTLETS INCLUDE GATE 2, GATES 1+3, DAM CREST, DOWNSTREAM LIMIT WHEN RESERVOIR IS BETWEEN 220 AND				
4	NO OUTLETS:	7				
5	VARIABLE GATE OPENING TIME (MIN):	5	Time between gate adjustments to keep inflow=outflow			
6	HOLD OUTFLOW=INFLOW	TRUE	Prevents drafting of reservoir at start if rating table discharge at start is			
7	MONTHLY GATE OPEN/CLOSE ELEVATION TABLE					
8	Month	Open	Close			
9	1	220.0	215.0			
10	2	220.0	215.0			
11	3	220.0	215.0			
12	4	220.0	215.0			
13	5	220.0	215.0			
14	6	220.0	215.0			
15	7	220.0	215.0			
16	8	220.0	215.0			
17	9	220.0	215.0			
18	10	220.0	215.0			
19	11	220.0	215.0			
20	12	220.0	215.0			
21						
22	RESERVOIR RATING					
23	Rows:	59				
24	ELEV	VOLUME				
25	195.07	85630144.				
26	195.68	95416446.				
27	196.29	105202748.				
28	196.90	114989051.				
29	197.51	124775353.				
30	198.12	134561655.				
31	198.73	146794533.				
32	199.34	159027410.				
33	199.95	171260288.				
34	200.56	183493166.				
35	201.17	195726044.				
36	201.78	207958921.				
37	202.39	220191799.				
38	203.00	232424677.				

Figure 3-2.1 – SEFM Routing Input File, Reservoir Name, Comments, Number of Outlets, Reservoir Rating

3-8.2 Gate Failure Simulation

Complex gate failure scenarios can be simulated with SEFM by specifying the parameters in the Gate Failure Simulation section (Figures 3-2.2a and 3-2.2b). Failure is defined as the gate not being operational and the gate discharge is set to zero when failed. It does not include the simulation of an uncontrolled release through the gate opening due to a catastrophic structural failure of the gate. Gate failures can encompass one or more gates and the failure may occur for the entire simulation or for a specified period. The input parameters for gate failure simulation are described in the sections below.

Enable Gate Operation Failure – Boolean value that defines whether gate failure simulations are to be included in the simulation. If the value is set to false, then the gate failure parameters in the table below are read but get failures are not simulated. If true, then the parameters are used to simulate gate failure scenarios.

Number of Conditions – Is the number of gate failure conditions entered in the gate failure scenario table.

Description – Is a user defined description for the gate failure, for example one gate unavailable for 12 hours.

Condition Number – Each condition is numbered sequentially beginning at 1.

Dependent Condition No – Defines a condition number that must already be true if the current condition number is to be true. For example, in Figure 3-2.2a, Condition Number 2, which is two gates failed for 12 hours only occurs when Condition 1 is also true. Thus, Condition Number 2 has 1 entered in the dependent condition column.

Conditional Probability – Is the probability of the current condition occurring after any prerequisite conditions have occurred. For example, the probability of Condition Number 2 being true is 0.4553 but Condition 1 must also be true.

Total Probability – Is the probability of each condition being true. Data in this column is for informational purposes only and is not used in the failure computation. The development of the failure probability information in Figures 3-2.2a and 3-2.2b was derived from the failure probability tree diagram shown in Figure 3-2.3 and Table 3-2.1.

Reservoir Elevation when Gate Fails – Is the reservoir elevation when the program begins applying the gate failure probability. This elevation should be set a small amount above the gate open elevation. For example, the typical gate open elevation for Gate 1 is 220.0 m and the failure elevation was set to 220.05 m.

Operation Failure Duration – Is the number of hours that the gate remains out of operation once the gate fails. This parameter allows for the simulation of gate repairs to be accounted for in the simulation. Once the operation failure time has been reached, the gate discharge capacity is restored and it functions normally for the rest of the simulation. To simulate a gate failure with no gate repairs, then the Operation Failure Duration is set to a large number, typically 999.0.

Gate Operation Failure for Each Gate – A Boolean value entered for each gate for each failure condition. Marking this value as True will result in the gate being inactive when the failure condition is true. For example, if failure condition 2 is true then Gate number 2 will be inactive for 12 hours.

	A	B	C	D	E	F	G
84							
85	ENABLE GATE OPERATION FAILURE	TRUE					
86	NUMBER OF CONDITIONS	6					
87			DEPENDENT	CONDITIONAL	TOTAL	RESERVOIR ELEV	OPERATION FAILURE
88	DESCRIPTION	CONDITION NUMBER	CONDITION NO	PROBABILITY	PROBABILITY	WHEN GATES FAIL	DURATION (HRS)
89	One gate unavailable for 12 hours:	1	0	0.0459	0.0150	220.05	12
90	Two gates unavailable for 12 hours:	2	1	0.4553	0.0100	220.05	12
91	All Three gates unavailable for 12 hours:	3	2	0.4737	0.0090	220.05	12
92	One gate unavailable throughout flood:	4	1	0.2179	0.0100	220.05	999
93	Two gates unavailable throughout flood:	5	2	0.0478	0.0010	220.05	999
94	All Three gates unavailable throughout flood:	6	3	0.0909	0.0009	220.05	999
95							

Figure 3-2.2a – SEFM Routing Input File Template, Gate Failure Simulation Parameters

CONDITIONAL	TOTAL	RESERVOIR ELEV	OPERATION FAILURE	ENTER TRUE IF GATE OPERATION FAILURE OCCURS (1 ENTRY FOR EACH GATE)					
PROBABILITY	PROBABILITY	WHEN GATES FAIL	DURATION (HRS)	GATE 1	GATE 2	GATE 3	GATE 4	GATE 5	GATE 6
0.0459	0.0150	220.05	12.	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
0.4553	0.0100	220.05	12.	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE
0.4737	0.0090	220.05	12.	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE
0.2179	0.0100	220.05	999.	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
0.0478	0.0010	220.05	999.	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE
0.0909	0.0009	220.05	999.	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE

Figure 3-2.2b – SEFM Routing Input File Template, Gate Failure Simulation Parameters (Continued)

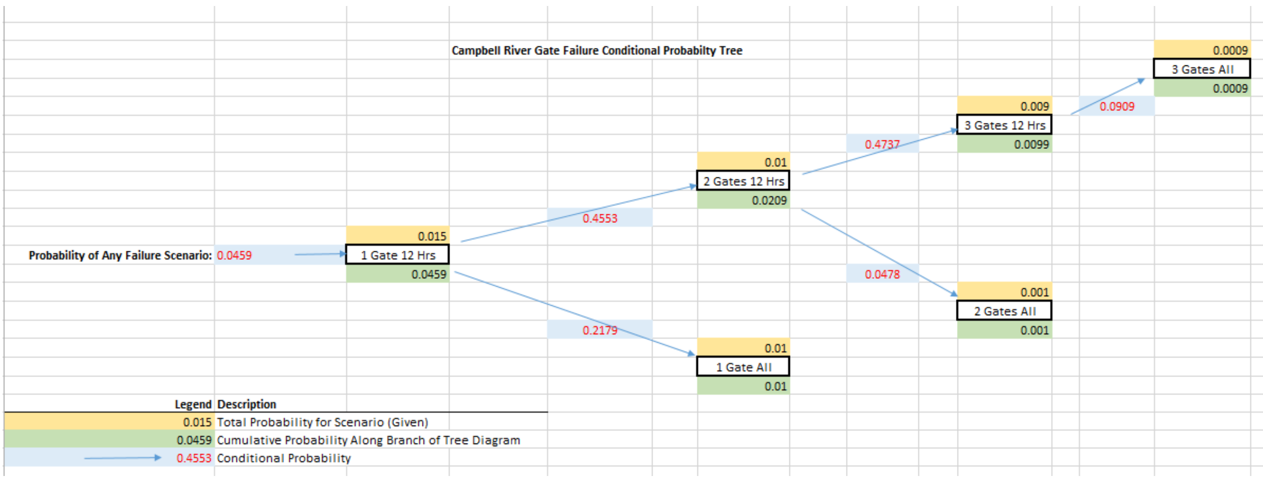


Figure 3-2.3 – Gate Failure Probability Tree Diagram for Input Shown in Figures 3-2.2a and 3-2.2b

Table 3-2.1 – Gate Failure Scenarios with Total Probability and Conditional Probability

Campbell River Gate Failure Scenarios				
June 27, 2014				Conditional
		Desired Total	Depends on	Probability from
Scenarios	Graphic Item	Probability	Scenario No.	Tree Diagram
1. One gate unavailable for 12 hours:	1 Gate 12 Hrs	0.0150	None	0.0459
2. Two gates unavailable for 12 hours:	2 Gates 12 Hrs	0.0100	1	0.4553
3. All Three gates unavailable for 12 hours:	3 Gates 12 Hrs	0.0090	2	0.4737
4. One gate unavailable throughout flood:	1 Gate All	0.0100	1	0.2179
5. Two gates unavailable throughout flood:	2 Gates All	0.0010	2	0.0478
6. All Three gates unavailable throughout flood:	3 Gates All	0.0009	3	0.0909

3-2.3 Gate Outlets

Following the Gate Failure Simulation section, the remainder of the input file is devoted to parameters describing each hydraulic outlet. The number of outlets (No Outlets) is defined near the beginning of the input file. The total number of *Gate Outlets* plus *Downstream Flow Limit Outlets* must equal the value specified for the *No Outlets* parameter.

Gate Outlets are the most common type of outlet and can represent low level outlets, gated or ungated spillways, and dam overtopping. An elevation/discharge relationship is used to define the hydraulics for each gate. Additional parameters define the open/close behavior if the outlet is controlled and whether the gate operation is a function of the exceedance probability of the current storm. The parameters for each gate simulated are shown in Figure 3-2.4 and are described below. *Downstream Flow Limit Outlets* are described in Section 3-2.4.

Outlet Type – Defines whether the outlet is a *Gate* or a *Downstream Flow Limit*. Enter GATE to define a Gate outlet or DS LIMIT to define a downstream flow limit. Information on downstream flow limits is presented in Section 3-8.4.

No of This Type – Is the number of this type of outlet. The numbering begins at 1 and proceeds to the number of gate outlets in the input file.

Outlet Name – Is a user-defined name for the outlet. This is for information purposes and is not used by the program.

Control Elevation – Is the lowest reservoir elevation at which discharge can occur through this structure. It should be set equal to the lowest elevation in the elevation/discharge rating for the structure.

Discharge to Primary Stream – Is a Boolean value indicating whether the discharge from this outlet contributes to flow in the principal river system downstream of the dam. A value of True indicates that the discharge contributes to flow in the principal river system. A False value indicates that flows bypass the downstream system and contribute to flows in a different watershed. This feature can be used when there are saddle dams or other outlets that discharge to adjacent watersheds.

Outlet Type – A value of *FIXED* or *VARIABLE* is specified for this parameter. A Fixed outlet type is represented by a single elevation discharge relationship. An example of this type of outlet would be an overflow spillway without gates or dam crest overtopping. An example of a Variable gate would be a gated spillway where the discharge rate for a given reservoir elevation can be adjusted by changing the gate opening setting. A Variable gate is represented by an elevation/discharge matrix, where the first column is the reservoir water surface elevation and each subsequent column represents the discharge for a higher gate opening.

Variable Outlet Data – Includes a series of parameters that define when the outlet is opened and closed. These parameters are only used if the Outlet Type field is set to Variable.

- Use Monthly Gate Open/Close Table – Is a Boolean value that defines whether the open and close elevations are to be varied by season. If this value is set to True, then the Open and Close Elevations specified in the *Monthly Gate Open/Close Elevation Table* near the beginning of the data file are used to define the reservoir elevations where the gate begins to open and close. If this value is False, then the fixed open and close elevations specified for the gate below are used regardless of the season when the flood occurs.

- Initially Open – Is a Boolean value that defines whether the gate is open at the beginning of the simulation. A True value sets the gate to open at the start and False sets the gate initially closed at the start of the simulation.

- If Open Discharge Column – Is an integer value that defines the discharge column if the gate is open at the beginning of the simulation. This parameter is only used if *Initially Open* is set to True.

- Open Elevation – Is the reservoir water surface elevation that defines when the current gate begins to open.

- After Outlet No. – If the current gate is to be opened after another gate is opened first, then the gate number of the dependent gate is entered in this field. The gate number is defined in the *No of This Type* field. If the current gate does not depend on any other gate being opened, then a value of zero is entered.

- Is Open at Col – Is the discharge column for the dependent gate to be opened before the current gate starts to open.

- Close Elevation – Is the reservoir water surface elevation that defines when the current gate begins to close. Note that gates will close in the same order and conditions as they were opened.

- Gate Open Tolerance – Defines the amount the reservoir must rise above the Open Elevation before the gate is opened. For example, if the Open Elevation is 220.0 m and the Gate Open Tolerance is 0.10 m, then the gate will begin to open when the reservoir water surface elevation reaches 220.1 m.

- Close Gate Based on Storm Magnitude – This feature allows gates to be closed at a specified storm exceedance probability to simulate project operations during large floods. Enter True to enable this feature.

- Precip AEP to Close Gate – If the Annual Exceedance Probability (AEP) of the storm key duration is less than the specified AEP, then the gate is closed the specified hours prior to the beginning of the maximum 48-hour precipitation.

- Hrs Before Start Of 48-Hr Max To Limit Discharge – If the annual exceedance probability of the storm key duration is less than the specified AEP, then the gate is closed for the hours specified in this input field prior to the beginning of the maximum 48-hour precipitation. The time from the beginning of the storm to the beginning of the maximum 48-hour precipitation is included in each storm template file.

No Discharge Columns – Is an integer value defining the number of discharge columns (not counting the elevation column) in the Elevation/Discharge rating matrix for the gage. If the gate is defined as fixed, then a value of 1 is entered and one discharge value is entered with each elevation entry in the Elevation/Discharge rating matrix.

No Discharge Rows – Is an integer value defining the number of discharge rows in the Elevation/Discharge rating matrix for the gage.

104	OUTLET TYPE:	GATE					
105	NO OF THIS TYPE:	1					
106	OUTLET NAME:	GATE 2					
107	CONTROL ELEVATION:	214.88					
108	DISCHARGE TO PRIMARY STREAM:	TRUE					
109	OUTLET TYPE:	VARIABLE					
110	VARIABLE OUTLET DATA						
111	USE MONTHLY GATE OPEN/CLOSE TABLE	FALSE					
112	INITIALLY OPEN	FALSE					
113	IF OPEN DISCHARGE COLUMN	1					
114	OPEN CONDITIONS						
115	OPEN ELEVATION:	220.00					
116	AFTER OUTLET NO:	0					
117	IS OPEN AT COL:	0					
118	AND SPECIFIED OUTLET OPERATION HAS FAILED	FALSE					
119	OR OPEN IF ANY OUTLET OPERATION HAS FAILED	FALSE					
120	CLOSE ELEVATION:	215.00					
121	GATE OPEN TOLERANCE (m):	0.000					
122	CLOSE GATE BASED ON STORM MAGNITUDE	FALSE					
123	PRECIP AEP TO CLOSE GATE	0.0000E+00					
124	HRS BEFORE START OF 48-HR MAX TO LIMIT DISC	0					
125	NO DISCHARGE COLUMNS:	20					
126	NO DISCHARGE ROWS:	32					
127	**Elev.**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**
128	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**
129	214.88	0.0	0.0	0.0	0.0	0.0	0
130	215.0	0.6	0.6	0.6	0.6	0.6	0
131	215.5	6.2	6.7	6.7	6.7	6.7	6
132	216.0	9.5	15.6	16.2	16.2	16.2	16
133	216.5	11.8	21.2	27.3	27.8	27.8	27
134	217.0	13.6	25.2	34.4	40.3	40.9	40
135	217.5	15.1	28.5	40.0	49.1	54.9	55
136	218.0	16.8	32.0	45.5	57.1	66.3	72
137	218.5	18.3	35.2	50.5	64.2	75.8	85
138	219.0	19.7	38.1	55.1	70.5	84.2	95
139	219.5	21.0	40.7	59.2	76.2	91.6	105
140	220.0	22.2	43.2	63.0	81.4	98.5	113

Figure 3-2.4 – Gate Outlet Parameter Input

3-2.4 Downstream Flow Limit Outlet

A *Downstream Flow Limit Outlet* is used to set the discharge rate from the project so that a specified flow rate is not exceeded downstream of the project. This is commonly used to reduce the likelihood flooding based on a prescribed flow limit at a downstream location.

This type of outlet requires a discharge time series that represents the flow at the downstream location without the discharge from the project. The program sets the discharge from the project as the difference between the allowable discharge and the downstream flow time series. The program evaluates the allowable discharge and changes the discharge from the project at each time step during the routing. The downstream flow limit overrides the discharge from any open gates to regulate flow to meet the downstream flow condition.

The downstream flow time series is computed by SEFM from one of the Basins in the project. The basin to use for the downstream flow limit is defined on the General tab for the reservoir (Figure 3-2.5). Parameters for the Downstream Flow Limit Outlet are shown in Figure 3-2.6 and are described below.

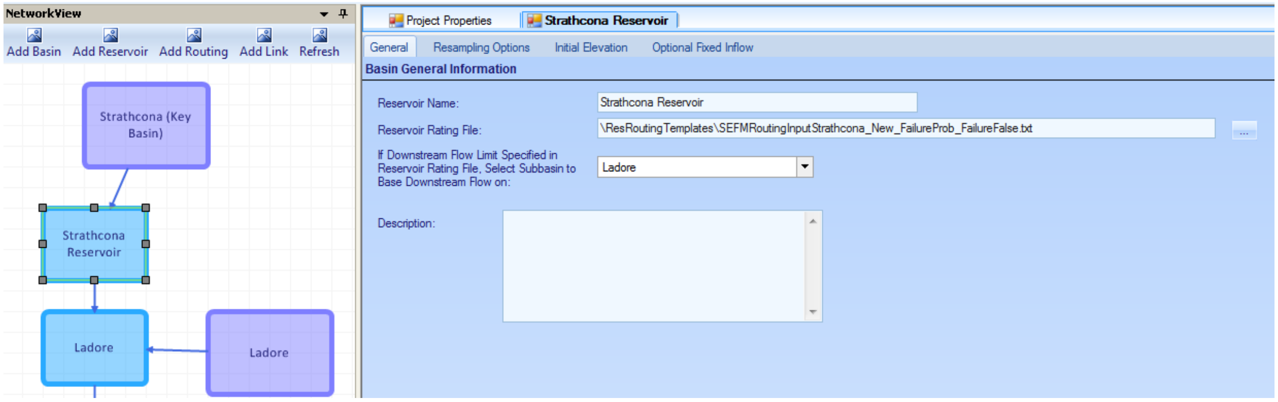


Figure 3-2.5 – General Tab for Reservoir Input showing Subbasin used to Define the Downstream Flow Limit

<u>Outlet Type</u> – Defines whether the outlet is a *Gate* or a *Downstream Flow Limit*. Enter "DS LIMIT" to define a Downstream Limit outlet.

<u>No of This Type</u> – Is the number of this type of outlet. The numbering begins at 1 and proceeds to the number of downstream flow limit outlets in the input file.

<u>Min Elevation</u> – Is the lower bound of the reservoir water surface elevation where the downstream limit operates. When the reservoir water surface elevation is lower than this value, then the downstream limit constraint is not imposed.

<u>Max Elevation</u> – Is the upper bound of the reservoir water surface elevation where the downstream limit operates. When the reservoir water surface elevation is higher than this value, then the downstream limit constraint is not imposed.

<u>Discharge Limit</u> – Is the maximum allowable discharge rate at the downstream location.

<u>DS Hydrograph File Scale Factor</u> – Each hydrograph value from the time series used to represent the flows at the downstream location are scaled by this factor. This feature allows for adjustments to be made to the flows computed by the source basin to better represent the flow conditions at the downstream location.

<u>DS Hydrograph Lag (Hours)</u> – The hydrograph used to represent the flows at the downstream location can be lagged by a user specified number of hours. This feature is useful for accounting for the travel time to the downstream location.

	A	B	C	D	E
95					
96	OUTLET TYPE:	DS LIMIT			
97	NO OF THIS TYPE:	1			
98	MIN ELEVATION	220.00			
99	MAX ELEVATION	222.00			
100	DISCHARGE LIMIT	280.0	Limit is 700, set at 40% to account for Inflow at Ladore		
101	DS HYDROGRAPH FILE SCALE FACTOR	0.80	Use Ladore Inflow Hydrograph Scaled by 0.80 Downstram Flow		
102	DS HYDROGRAH LAG (HOURS)	0			

Figure 3-2.6 – Downstream Flow Limit Outlet Input Parameters

3-2 SEFM WATERSHED MODEL – MODIFIED HOLTAN

One of the options in the SEFM watershed model is the use of a modified Holtan method for computing runoff and generating streamflow hydrographs. The modified Holtan version of the SEFM watershed model has the following features:

- Sub-basin configuration within a stream network, including dams and reservoir operations
- Distributed inputs for precipitation, evapotranspiration, snowpack and hydrologic soil parameters
- Computes runoff using a modified Holtan procedure using soil moisture accounting methods
- Computes snowmelt using an energy-budget method and the USBR snow-compaction method
- Computes runoff on a distributed basis for land segments, Hydrologic Runoff Units (HRUs)
- Computes quickflow runoff for each sub-basin and transforms to a streamflow hydrograph using a unit-hydrograph
- Computes interflow runoff for each sub-basin and uses a two-stage linear reservoir routing procedure to generate a streamflow hydrograph
- Optional computation of supplemental baseflow and primary baseflow using procedures in Sacramento Soil Moisture Accounting model (SAC-SMA)
- Uses hydrologic routing methods for routing hydrographs through the stream network

3-2.1 Single-Event and Continuous Modeling Versions

The modified Holtan model can be executed in either the single-event or continuous modes depending on the availability of historical data for model calibration. The continuous modeling option is strongly preferred because it can provide better estimates of hydrologic soil properties and can be used to provide a diverse sample-set of seasonal hydrologic conditions for use in a Monte Carlo resampling scheme.

An initial calibration of the watershed model for hydrologic soil properties is obtained via a water-budget approach using either daily or sub-daily hydrometeorological time-series. This initial calibration accounts for quickflow and interflow runoff volumes produced by individual storm events and baseflows produced by individual storm events and seasonal periods of low intensity precipitation. A second round of calibration of the watershed model is obtained by calibration to historical floods where the focus is on fine-tuning the estimates of the hydrologic soil properties and determining timing parameters for quickflow and interflow flood hydrographs.

The single-event version of the modified Holtan approach is an alternative which may be needed in data sparse areas. In this approach, calibration of the watershed model is obtained by calibration to historical floods where the focus is on quickflow and interflow runoff. This approach generally requires a greater number of probabilistic analyses (Section 2-x) to assemble the sample-sets of hydrometeorological inputs for stochastic flood modeling.

3-2.2 Modeling of Hydrologic Processes

A hydrologic processes module is used for describing the rainfall-runoff processes. In particular, the hydrologic soils module is configured to provide for soils moisture accounting where the soil moisture content is used to set the surface infiltration rate. Specifically, the Holtan Loss Equation[19,20,64] (Equation 3-1.1) is modified to allow for computation of quickflow and interflow runoff and for supplemental and primary baseflow. Many elements of the Sacramento Soil Moisture Accounting method (SAC-SMA) have been implemented which provide for continuous modeling and for computation of baseflows (Tables 3-2.1a,b,c).

Modeling of the groundwater contribution as supplemental and primary baseflows is used in initial calibration of the watershed model which facilitates estimation of the surficial and subsurface soil moisture storage capacities. Continuous hydrologic modeling is also used to develop seasonal soil moisture states for use in resampling for stochastic generation of floods.

The hydrologic processes module has the following features for soil moisture accounting and modeling the rainfall-runoff processes.

Impervious Areas

- Runoff from water bodies directly connected to the stream network
- Runoff from impervious land areas such as rock outcrops and pavement in urban areas
- Surface depression storage

Pervious Areas

- Interception storage
- Surficial soil moisture storage capacity
- Maximum surface infiltration rate
- Minimum surface infiltration rate
- Frozen ground surface infiltration rate
- Subsurface soil moisture storage capacity
- Leakage from surficial soil to subsurface free water storage
- Deep percolation rate
- Subsurface free water storage capacity for Supplemental baseflow
- Subsurface free water storage capacity for Primary baseflow
- Deep recharge

Water Bodies Directly Connected to the Stream Network – Reservoirs, lakes, marshes, wetlands and other water bodies that are directly connected to the stream network are treated as impervious areas. These areas are subject to liquid precipitation inputs and evaporation. High elevation lakes which freeze over in the winter and which can accumulate snowpack are treated as impervious land areas.

Impervious Land Areas – Land areas such as pavement and high-density development in urban areas, and rock outcrops in mountainous terrain are treated as impervious areas.

Surface Depression Storage – is the depth of storage for scattered depressions on impervious surfaces where rainfall or snowmelt accumulates and does not contribute to quickflow from impervious surfaces. Surface depression storage is most commonly associated with rock outcrops and paved areas in urban settings. Surface depression storage may also be used in a mixed pervious and impervious soil "zone" such as found in high alpine areas in the mountains to account for large closed depressions and scattered alpine lakes that are remnants of glaciation. These closed depressions can be significant sources of storage that are not contributors to quickflow and interflow runoff in response to a storm event.

Interception **–** is the depth of precipitation which is retained in the canopy of trees and by vegetation on the ground. It is applicable to rainfall-runoff modeling of pervious land areas.

Surficial Soil Moisture Storage Capacity **–** is the moisture holding capacity of the soil column to the depth that can be affected by evapotranspiration in the normal rooting zone. This corresponds to the soil moisture content between the wilting point and field capacity.

Maximum Surface Infiltration Rate **–** is the maximum rate at which the soil can accept water at the soil surface for a specified soils zone. This occurs when the soil is at the wilting point having been desiccated by evapotranspiration.

Minimum Surface Infiltration Rate **–** is the limiting rate at which the soil can accept water at the soil surface for a specified soils zone. This occurs when the surficial soil is fully wetted and soil moisture is at field capacity or higher.

Frozen Ground Surface Infiltration Rate – If frozen ground conditions are present, then the surface infiltration is reduced to a user-defined rate that simulates the impedance of infiltration due to ice within the surficial layers of the soil. The reduced surface infiltration rate for frozen ground persists until air temperatures are above freezing for a time period greater than a user-specified melt time. After this time, the surface infiltration rate reverts back to that determined by the modified Holtan equation.

Subsurface Storage Capacity – is the depth of storage for deep soils below the normal rooting zone and is accessed by deep rooting trees and shrubs, particularly in arid and semi-arid climates. It also accounts for subsurface depression storage in hollows, depressions and fractures in the surficial bedrock surface where moisture is stored and is primarily removed through evapotranspiration by deep-rooted trees and other deep-rooted vegetation. The existence of subsurface depression storage is common in mountainous terrain. In the western US, moisture is extracted from the subsurface depression zone by evapotranspiration during the warm season and the storage is refilled at the start of the rainy season in the fall of the year.

The existence of subsurface depression storage is evidenced by streamflow responses significantly lagging the cumulative precipitation at the start of the rainy season following a prolonged dry warm period. This situation can often be assessed by constructing a plot of cumulative precipitation and cumulative streamflow (less baseflow) beginning at the start of the rainy period following a prolonged warm and dry period.

A classic example is the storm of October 1962 on the 1,860-mi^2 American River watershed in central California. A basin-average precipitation of over 14-inches fell in 72-hours and yielded less than 2-inches of runoff. Initially, this would seem impossible because large areas of the American River watershed have very shallow soils overlying granite with very little soil moisture storage capacity. The vast majority of the storm event went to refill subsurface hollows and fractures in the surficial bedrock. Once the subsurface storage was filled, the runoff characteristics were as expected for shallow soils overlying granite. The situation of subsurface depression storage is more easily seen in mountain areas in the western US where the fall rainy season follows a dry summer period. Moisture from the first storms of the season replenish soil moisture and refill subsurface storage.

Leakage from Surficial Soil to Subsurface Free Water Storage **–** accounts for non-uniformity of the hydrologic soil characteristics for the surficial and subsurface soil zones where areas of coarse soils and other anomalies allow precipitation input to migrate downward to the free water storages that support baseflows. This parameter is found through calibration of the watershed model using historical hydrometeorological inputs and historical streamflow volumes. This leakage has the effect of reducing interflow and increasing baseflow.

Deep Percolation Rate **–** is the limiting rate that a soil layer, hardpan within the soil column, or underlying bedrock can accept water that has infiltrated the surface of the soil for a specified soils zone. Water that passes through this limiting soil layer, hardpan, or bedrock contributes to groundwater and appears in the stream as supplemental and primary baseflow.

Subsurface Free Water Storage Capacity for Supplemental Baseflow **–** is a groundwater response with a lag time greater than interflow runoff and less than primary baseflow. Moisture supply for supplemental and primary baseflow is provided by deep percolation after the soil moisture capacities for the surficial soil and subsurface storage are satisfied. The terms supplemental baseflow and primary baseflow correspond to the terminology and procedures used in SAC-SMA.

Subsurface Free Water Storage Capacity for Primary Baseflow **–** is a very delayed groundwater response which sustains streamflow during dry weather periods. It has a very long response time, greater than supplemental baseflow.

Deep Recharge **–** is the portion of baseflow that occurs as streamflow at a location downstream of the point of interest for watershed modeling. Deep recharge is of interest in watershed model calibration in balancing the water budget for a watershed. Deep recharge has the effect of reducing baseflow magnitudes that appear in the stream relative to what would have been available due to moisture inputs to groundwater.

Evapotranspiration **–** is the evapotranspiration for a specified elevation zone for a given time of year.

A schematic of quickflow, interflow and baseflow for pervious land areas is shown in Figure 3-1.1a. This formulation was chosen because of the ability to account for the soil moisture deficit and the initial and minimum surface infiltration rates. This approach provides for the surface infiltration rate at the start of the storm to be dependent upon soil moisture conditions. As precipitation continues during the storm, the soil column is further wetted and surface infiltration decays to a minimum value of Fc as the soil moisture deficit decreases to zero (Figure 3-1.1b).

$$F = (GIA)\, SMD^{IEXP} + Fc \qquad (3\text{-}1.1)$$

$$GIA = (F_{max} - Fc)/SMD_{max}^{IEXP} \qquad (3\text{-}1.2)$$

where:
- F – is the surface infiltration rate (in/hr, mm/hr);
- GIA – is a soil zone specific constant that yields the maximum surface infiltration rate when the soil moisture content is equal to the wilting point;
- SMD – is the soil moisture deficit (in, mm);
- SMD_{max} – is the maximum soil moisture deficit, which equals the soil moisture storage capacity (in, mm);
- $IEXP$ – is the infiltration exponent, default value is 1.4;
- Fc – is the minimum surface infiltration rate for the soil zone (in/hr, mm/hr); and,
- F_{max} – is the maximum surface infiltration rate for the soil zone (in/hr, mm/hr).

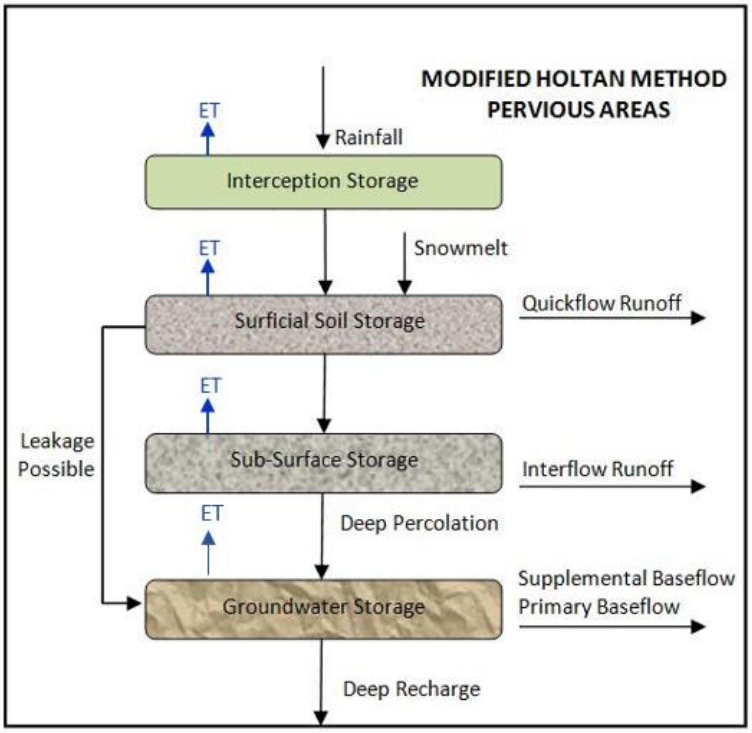


Figure 3-1.1a – Schematic of Soil Moisture and Runoff Processes for Modified Holtan Method for Pervious Land Areas Used in the SEFM Watershed Model and HEC-1 Watershed Model

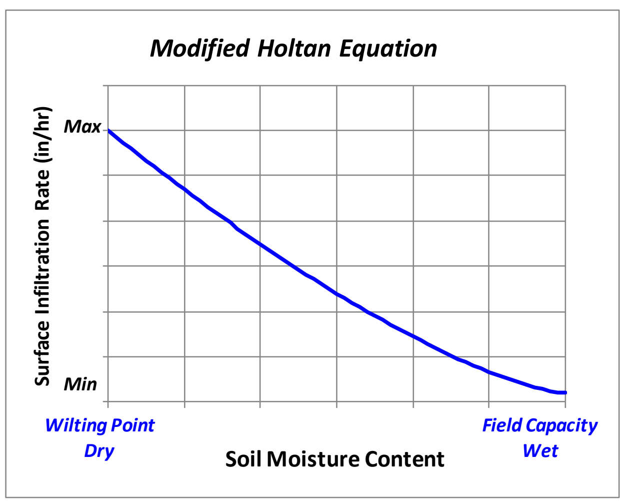


Figure 3-1.1b – Example of Variation of Surface Infiltration Rate with Soil Moisture Content for Modified Holtan Approach

A schematic of quickflow runoff and depression storage for impervious land areas is shown in Figure 3-1.2. Note that depression storage is used for impervious land areas (Figure 3-1.2) but not for pervious land areas (Figure 3-1.1a). This formulation was chosen because water temporarily stored in surface depressions in pervious land areas often transmits water to the surficial soil during intermittent long-duration storm events and has the potential to generate interflow runoff. In those cases where surface depression storage is considered an issue for pervious areas, a mixed soil "zone" can be utilized comprised of impervious and pervious areas.

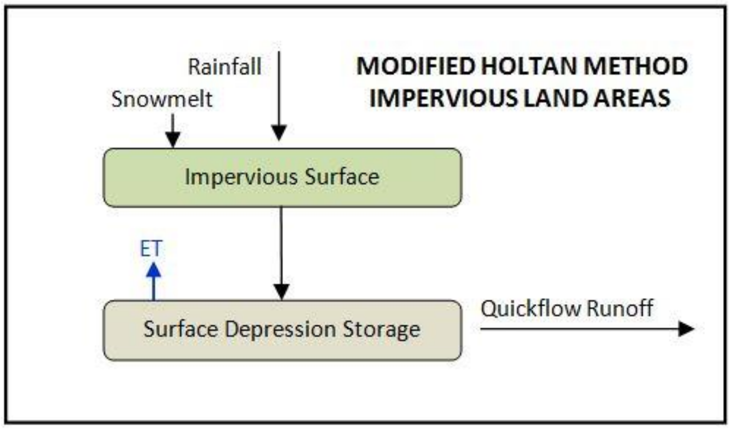


Figure 3-1.2 – Schematic of Soil Moisture and Runoff Processes for Modified Holtan Method for Impervious Land Areas Used in the SEFM Watershed Model and HEC-1 Watershed Model

3-1.3 Quickflow Hydrographs

Standard unit-hydrograph approaches are used to transform quickflow runoff to a streamflow hydrograph. Details on development of quickflow unit-hydrographs are described in Section 3-2 for the SEFM watershed model.

3-1.4 Interflow Runoff Hydrographs

Interflow runoff is water that infiltrates the soil surface and moves laterally through the surficial soil mantle or at shallow depths in fractured bedrock under both saturated and unsaturated conditions until it enters a stream channel or causes displacement of subsurface water into a stream channel. Interflow can also be more loosely defined as subsurface runoff via a variety of paths whose response time is intermediate between that of quickflow runoff and the groundwater response. Simulation of the interflow component begins after the surficial soil moisture deficit and subsurface storage deficits are satisfied. Interflow runoff is typically transformed to a streamflow hydrograph using linear reservoir routing procedures.

SEFM Operation – Interflow runoff hydrographs are computed in SEFM using a two-stage linear reservoir routing procedure. Conceptually, this may be viewed as a two component interflow response where two conceptual reservoirs are in series and each has a separate storage constant (k). A third parameter is used to set the proportion of interflow runoff that discharges directly to the stream system from the upper reservoir, with the remainder being routed through the lower reservoir. This approach allows a high level of flexibility in modeling the interflow response and in mimicking the shape of the recession limb of historical flood hydrographs.

Using linear reservoir concepts, the volume of storage in the conceptual reservoir is taken to be a linear function of discharge from the reservoir (Equation 3-1.3). Linear reservoir routing is a type of hydrologic routing that uses the principle of conservation of mass (Equation 3-1.4), which may be written in finite difference form as shown in Equation 3-1.5.

$$S = KO^m \quad \textit{(for linear reservoir, m=1)} \qquad (3\text{-}1.3)$$

$$I - O = dS/dt \qquad (3\text{-}1.4)$$

$$(I_1 + I_2)/2 \; - \; (O_1 + O_2)/2 = (S_2 - S_1)/\Delta t \qquad (3\text{-}1.5)$$

where: I_1 *and* I_2 are inflows to the conceptual reservoir; O_1 and O_2 are outflows from the conceptual reservoir; and S_1 and S_2 are storage within the conceptual reservoir. The subscripts *1* and *2* represent values at the start and end of a computational time-step, respectively.

Rearranging Equation 3-1.5 and substituting Equation 3-1.3 results in the working form of the linear reservoir routing equation (Equation 3-1.6a).

$$O_2 = O_1 + w\,[\,I_1 + I_2 - 2O_1\,] \qquad (3\text{-}1.6a)$$

$$w = \Delta t/(2K + \Delta t) \qquad (3\text{-}1.6b)$$

where: K is the storage constant, which has units of time and can be viewed as a type of lag-time measurement; and Δt is the computational time-step in hours.

For the case of interflow modeling, inflows to the upper conceptual reservoir (cfs) are obtained as the product of the interflow runoff volume per time-step and the sub-basin area being considered.

Figures 3-2.3a and 3-2.3b depict two examples of the two-stage reservoir response to a single pulse of 1-inch of interflow runoff generated over a 1-hour time-step for a 1-square mile watershed. The first example has upper and lower reservoir constants of 12-hours and a proportioning parameter where 40% of the outflow from the upper storage zone is discharged directly to the receiving stream and the remaining 60% is routed through the lower conceptual reservoir. The second example has an upper reservoir lag of 12-hours, a lower reservoir lag of 24-hours and a proportioning parameter where 5% of the outflow from the upper storage zone is discharged directly to the receiving stream and the remaining 95% is routed through the lower conceptual reservoir. These examples provide insight into the flexibility of the two-stage linear reservoir routing approach to mimicking an interflow response.

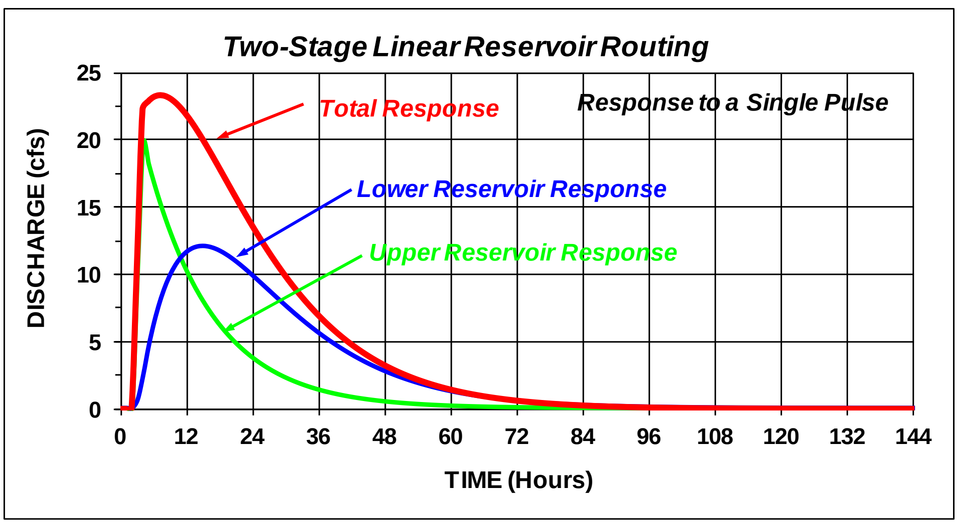


Figure 3-2.3a – Example 1 of Two-Stage Linear Reservoir Routing for Interflow Runoff

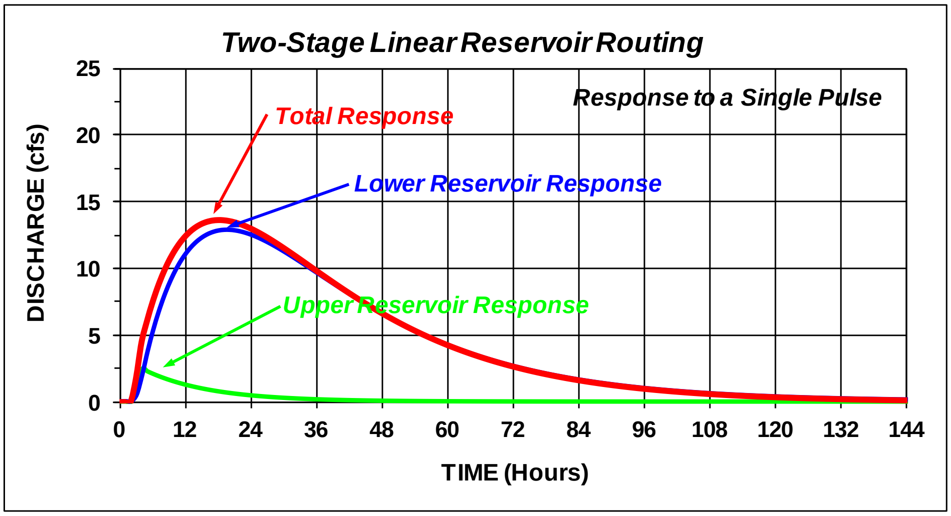


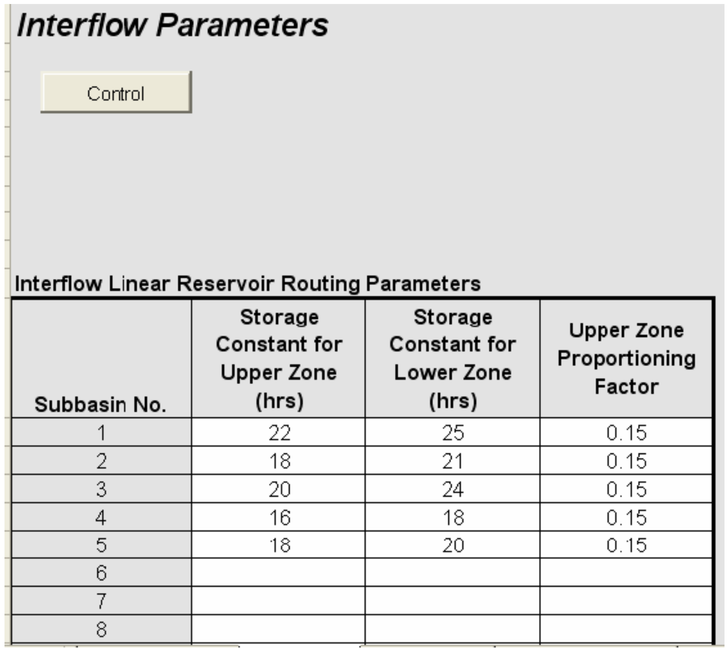
Figure 3-2.3b – Example 2 of Two-Stage Linear Reservoir Routing for Interflow Runoff

Guidance and Experience – An initial estimate of the storage constant for the upper storage zone for a particular sub-basin may be taken by adding from 4-hours to 24-hours to the time-lag for surface runoff. Smaller storage constants (shorter lag-times) for upper storage zones are generally associated with steeper slopes and shallow soils over impermeable layers. Longer lag-times in both the upper and lower storage zones are generally associated with flatter slopes and deep soils. Sub-basins with relatively high drainage densities in the first and second order streams are associated with shorter interflow lag-times. Conversely, low drainage densities may be an indicator of long interflow lag-times. Storage constants can be refined through calibration to historical floods, with particular attention paid to the recession limb of the flood hydrograph.

The upper zone proportioning parameter is used to control the flashiness of the upper zone response. The value is restricted to the range between zero and unity with larger values producing flashier interflow responses and smaller values yielding more attenuated interflow hydrographs.

In calibration to historical floods, it will be common to encounter situations where the available streamflow records represent the discharge from multiple sub-basins. In these cases, it may be difficult, or impossible, to separate out the upper and lower zone storage constants for the individual sub-basins. The watershed should be treated as a lumped system and common upper and lower zone storage constants (k) and upper proportioning parameter should be applied to all sub-basins. Where one or more sub-basins have unique sub-surface characteristics, additional iterations can be attempted to better replicate the interflow response from these sub-basins while preserving the overall interflow response from the collection of sub-basins.

Data Entry Format – Data entry consists of inputting the storage constants (k) for the upper and lower storage zones and the upper zone proportioning parameter for each sub-basin (Screen Shot 3-2.1). A test routine is contained on the *Interflow* worksheet which allows direct viewing of the effect of changes to the storage constants and proportioning parameter for each sub-basin (Screen Shot 3-2.2).



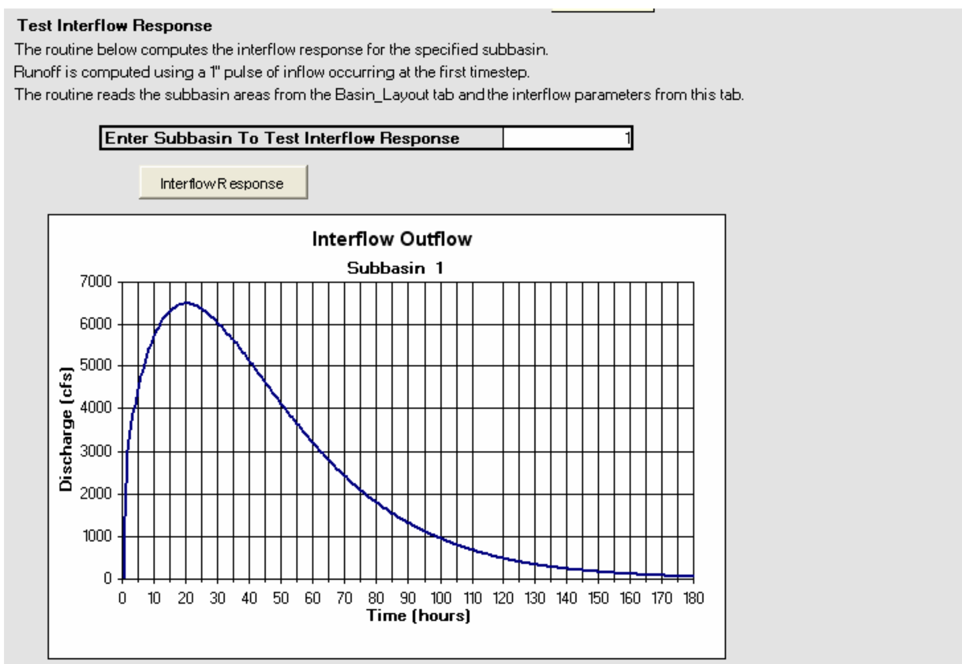
Interflow Parameters

Control

Interflow Linear Reservoir Routing Parameters

Subbasin No.	Storage Constant for Upper Zone (hrs)	Storage Constant for Lower Zone (hrs)	Upper Zone Proportioning Factor
1	22	25	0.15
2	18	21	0.15
3	20	24	0.15
4	16	18	0.15
5	18	20	0.15
6			
7			
8			

Screen Shot 3-2.1 – Example Data Entry Format for Two-Stage Interflow Linear Reservoir Routing



Screen Shot 3-2.2 – Example Test Plot for Interflow Runoff Hydrograph

3-2.5 Comparison with Sacramento Soil Moisture Accounting Method

As discussed previously, the procedures for use of the Holtan Loss Equation have been modified substantially by incorporating components from the SAC-SMA. This allows the modified Holtan method to be operated on a continuous basis and to account for baseflows. Tables 3-2.1a,b,c list parameters in the modified Holtan method that match the SAC-SMA method.

Table 3-2.1a – SAC-SMA Hydrologic Soil Property Parameters Used in Modified Holtan Method

SAC-SMA PARAMETER	DESCRIPTION	MODIFIED HOLTAN ASSOCIATION
UZTWM	Upper Zone Tension Water Capacity (in, mm)	Surficial Soil
LZTWM	Lower Zone Tension Water Capacity (in, mm)	Subsurface Soil
LZFSM	Lower Zone Free Water Supplemental Baseflow Capacity (in, mm)	Supplemental Baseflow
LZFPM	Lower Zone Free Water Primary Baseflow Capacity (in, mm)	Primary Baseflow

Table 3-2.1b – SAC-SMA Hydrologic Soil State Parameters Used in Modified Holtan Method

SAC-SMA PARAMETER	DESCRIPTION	MODIFIED HOLTAN ASSOCIATION
UZTWC	Upper Zone Tension Water Content (in, mm)	Surficial Soil
LZTWC	Lower Zone Tension Water Content (in, mm)	Subsurface Soil
LZFSC	Lower Zone Free Water Supplemental Baseflow Content (in, mm)	Supplemental Baseflow
LZFPC	Lower Zone Free Water Primary Baseflow Content (in, mm)	Primary Baseflow

Table 3-2.1c – SAC-SMA Hydrologic Soil Process Parameters Used in Modified Holtan Method

SAC-SMA PARAMETER	DESCRIPTION	MODIFIED HOLTAN ASSOCIATION
LZSK	Lateral drainage rate of supplemental free water (fraction contents/day)	Supplemental Baseflow
LZPK	Lateral drainage rate of primary free water (fraction contents/day)	Primary Baseflow
PFREE	Leakage from Upper Zone to Lower Zone Free Water	Leakage to Subsurface
RSERV	Lower zone free water not removable by evapotranspiration	Baseflows
SIDE	Fraction of baseflow that goes to deep recharge	Deep Recharge

3-2.6 SEFM Operation for Hydrologic Soil Processes

Runoff calculations for quickflow and interflow are performed for each time-step by a simple accounting process utilizing the precipitation amount, soil moisture deficit, surface infiltration rate, deep percolation rate, and modified Holtan equation. Separate rainfall-runoff computations are conducted for each HRU to reflect the site-specific climatic and soil conditions. Runoff from each HRU is aggregated to the sub-basin level. A quickflow unit-hydrograph is used to convert the quickflow runoff volume for each sub-basin into a flood hydrograph. A two-stage linear reservoir routing procedure is used to convert the interflow runoff volume from each sub-basin into an interflow hydrograph.

***Data Entry Format* –** Data entry consists of entering hydrologic soil properties for each soil zone. This includes values for: interception storage; surficial soil moisture storage capacity; maximum surface infiltration rate; minimum surface infiltration rate; Holtan infiltration exponent; subsurface soil moisture capacity; deep percolation rate; and supplemental and primary baseflow. An example of data entry is shown in Screen Shot 3-1.1.

Also see Section 2-1.1, *Watershed Layout*, for further discussion of soil zones.

Number of Soil Zones	5

Soil Zone Definition					
Zone Number	Infiltration Exponent	Maximum Surface Infiltration Rate (in/hr)	Minimum Surface Infiltration Rate (in/hr)	Maximum Soil Moisture Storage (in)	Deep Percolation Rate (in/hr)
1	1.4	2.00	0.60	4.00	0.060
2	1.4	2.00	0.60	6.00	0.060
3	1.4	2.00	0.60	6.00	0.080
4	1.4	0.00	0.00	0.00	0.000
5	1.4	10.00	10.00	4.00	0.060
6					
7					

Comments
Soil Zone 1 is SCS Hydrologic Soil Type C
Soil Zone 2 is SCS Hydrologic Soil Type B
Soil Zone 3 is SCS Hydrologic Soil Type A
Soil Zone 4 is water (lake surfaces)
Soil Zone 5 is used for all soils in Subbasin 4 which has no surface connection to Keechelus Lake.

Screen Shot 3-2.3 – Example Data Entry Format for Soils Characteristics at Keechelus Watershed, Washington

Guidance and Experience for Hydrologic Soil Parameters – The modified Holtan approach has been used in watersheds representing a wide range of soil properties and climatic conditions. In particular, the minimum surface infiltration rate and deep percolation rate are important factors in determining the hydrologic response of the watershed. The magnitude of the deep percolation rate is a critical factor in determining the runoff volume of the flood. The magnitude of the minimum surface infiltration rate relative to the magnitude of the precipitation intensities is a critical factor in determining the quickflow runoff response, and therefore the "flashiness" of the flood hydrograph. Initial estimates of these rates can be obtained from STATSGO and SSURGO[66] databases and other soils mapping information. Final values for use in flood modeling should be determined by calibration to observed floods.

Table 3-2.2 lists typical ranges of hydrologic soil parameters for the modified Holtan method that have been found for calibrated watershed models. Parameter values outside these ranges are clearly possible. However, values within these ranges provide a good starting point for Monte Carlo calibration methods (Section 4-x). The ranges for parameters common to SAC-SMA were obtained from National Weather Service guidance and experience with SCA-SMA (Anderson[97]).

Table 3-2.2 – Typical Ranges of Hydrologic Soil Parameters for Modified Holtan Method

SOILS PARAMETER	TYPICAL PARAMETER RANGE		COMMENTS
	LOWER	UPPER	
Surficial Soil Storage Capacity	1.00 in	4.00 in	
Maximum Surface Infiltration Rate (F_{max})	1.00 in/hr	3.00 in/hr	
Minimum Surface Infiltration Rate (F_C)	0.10 in/hr	0.40 in/hr	
Holtan Exponent (IEXP)	1.4	1.4	Default value, unless site-specific studies
Subsurface Soil Storage Capacity	2.00 in	8.00 in	Larger values associated with storage in hollows and fractures in surficial bedrock in mountainous watersheds
Deep Percolation Rate	0.02 in/hr	0.10 in/hr	
Lower Zone Free Water Storage Supplemental Baseflow	0.60 in	12.0 in	LZFSM, from NWS
Supplemental Baseflow Daily Depletion Rate	0.03 contents/day	0.20 contents/day	LZSK, (fraction storage contents/day)
Lower Zone Free Water Storage Primary Baseflow	1.50 in	24.0 in	LZFPM, from NWS
Primary Baseflow Daily Depletion Rate	0.001 contents/day	0.015 contents/day	LZPK, (fraction storage contents/day)

Guidance and Experience, Frozen Ground Conditions –Antecedent temperature is used to determine whether a concrete frost exists in portions of the watershed at the onset of the extreme storm. A concrete frost is a type of frozen ground condition that can occur when there is sufficient soil moisture and the areal extent of freezing is sufficient to form a contiguous frozen layer that impedes surface infiltration.

Antecedent temperature is defined as the mean daily temperature averaged over the 14 days prior to the occurrence of the storm at the start of flood simulations. The determination of the existence of frozen ground is made for each HRU based on the antecedent temperature, depth of snow cover, and soil moisture conditions for the HRU. If conditions are sufficient to support a concrete frost, then the surface infiltration rate is reduced to reflect the impedance to infiltration.

Prior studies[57,59] have shown that a prolonged period of below-freezing temperatures is required for developing a concrete frost, and a duration of 14-days is suitable for determination of frozen ground conditions. Figure 3-1.3 depicts an example of the behavior of 14-day average temperature for a location in the Cascade Mountains in Washington.

Experience in mountainous watersheds[58,65] has shown that it is unusual to produce the combination of conditions necessary for forming a concrete frost over large portions of a watershed. Experience has also shown that frozen ground conditions rarely occur in heavily forested watersheds with thick litter layers and are rarely seen where free-draining sandy soils are present. When frozen ground conditions do occur in the western US, they are most often seen in watersheds with fine-grained soils, at lower elevations in semi-arid climates where thin snowpacks are common. General rule-of-thumb criteria for formation of a concrete frost[58,59] includes: snowpack depth less than 6-inches (snow-water equivalent of about 1.0 inches); and soil moisture content of 2 inches or more.

Limited data and studies are available for determining the reduction in surface infiltration rate for frozen ground conditions. A surface infiltration rate of 0.10 inch/hour, or one-third of the minimum surface infiltration rate, whichever is smaller, is commonly used. The elapsed time for melting of the frozen ground is dependent upon the temperature of the rain during the storm and the depth of frost penetration. Durations of 12-hours to 72-hours are commonly used for melting of the concrete frost.

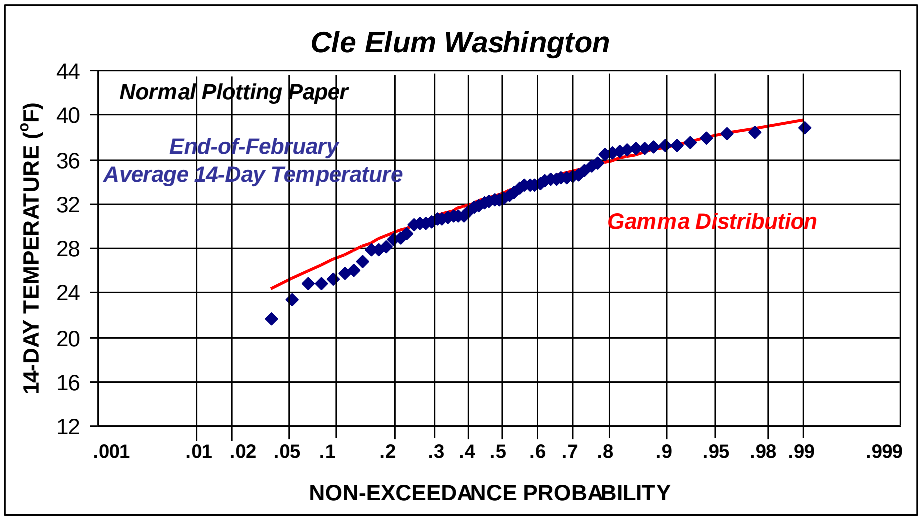


Figure 3-2.5 – Probability-Plot of Average End-of-February 14-Day Temperature

Assumptions and Expectations, Frozen Ground Conditions – It is assumed that prolonged below freezing temperatures will produce a concrete frost when the upper layer of the soil is wet and there is limited insulating effect from snow cover. Concrete frosts have been observed to occur[57,58,59,74] when this combination of conditions has been present.

Data Entry Format for Frozen Ground – The data entry for frozen ground criteria is shown in Screen Shot 3-1.2.

Frozen Ground Criteria	
Min Soil Moisture (in)	2.00
Max Snow Water Equivalent (inches)	1.00
Frozen Surface Infilt Rate (in/hr)	0.10
Time Required to Melt Frozen Ground (hrs)	72

Screen Shot 3-1.2 – Example Data Entry Format for Frozen Ground Conditions

3-3 SEFM WATERSHED MODEL – SACRAMENTO SOIL MOISTURE ACCOUNTING

A second option for the SEFM watershed model is to use the Sacramento Soil Moisture Accounting model (SAC-SMA, Burnash and Ferral[x]) for computing runoff and generating streamflow hydrographs. The SAC-SMA version of the SEFM watershed model has the following features:

- Sub-basin configuration within a stream network, including dams and reservoir operations
- Distributed inputs for precipitation, evapotranspiration, snowpack and hydrologic soil parameters
- Computes runoff using SAC-SMA using soil moisture accounting methods
- Computes snowmelt using an energy-budget method and the USBR snow-compaction method
- Computes runoff on a distributed basis for land segments, Hydrologic Runoff Units (HRUs)
- Computes quickflow runoff for each sub-basin and transforms to a streamflow hydrograph using a unit-hydrograph
- Computes interflow runoff for each sub-basin and uses a linear reservoir routing methods to generate a streamflow hydrograph
- Computes groundwater inputs and generates supplemental baseflow and primary baseflow using linear reservoir routing methods
- Uses hydrologic routing methods for routing hydrographs through the stream network

3-3.1 Single-Event and Continuous Modeling Versions

SAC-SMA was originally developed for use in continuous modeling but can be operated in either single-event or continuous modes for application of SEFM. The choice of single-event versus continuous modeling would be made based on the availability of historical hydrometeorological time-series data for model calibration. The continuous modeling option is strongly preferred because it can provide better estimates of hydrologic soil properties and can be used to provide a diverse sample-set of seasonal hydrologic conditions for use in a Monte Carlo resampling scheme.

An initial calibration of the watershed model for hydrologic soil properties is obtained via a water-budget approach using either daily or sub-daily hydrometeorological time-series. This initial calibration accounts for quickflow and interflow runoff volumes produced by individual storm events and baseflows produced by individual storm events and seasonal periods of low intensity precipitation. A second round of calibration of the watershed model is obtained by calibration to historical floods. A short computational time-step is used which is compatible with the runoff and hydrologic response time of the sub-basins and watershed under study. The focus of this second level of calibration is on fine-tuning the estimates of the hydrologic soil properties and determining timing parameters for quickflow and interflow flood hydrographs.

The single-event version of SAC-SMA is an alternative which may be needed in data sparse areas. In this approach, calibration of the watershed model is obtained by calibration to historical floods where the focus is on quickflow and interflow runoff. This approach generally requires a greater number of probabilistic analyses (Section 2-x) to assemble the sample-sets of hydrometeorological inputs for stochastic flood modeling.

3-3.2 External Calibration of the SAC-SMA Model

The option for use of the SAC-SMA model with the SEFM stochastic engine is provided as a convenience to the analyst who has a preference for SAC-SMA. No tools or utilities are provided with SEFM for calibration of SAC-SMA models. The analyst is responsible for calibration of SAC-SMA outside of SEFM, which then allows use of the calibrated model parameters within SEFM.

3-3.3 Modeling of SAC-SMA Hydrologic Processes

Numerous technical articles and guidance documents have been written about operation and calibration of SAC-SMA (Burnash and Ferral[x], Anderson[x,x], and Koren et al[x,x]) . A brief summary of SAC-SMA is presented here and the reader may refer to technical publications for more detailed descriptions and information.

Basic operation of SAC-SMA is depicted in Figure 3-3.1a. The hydrologic soil properties, soil states and hydrologic process parameters are listed below and Figure 3-3.1b provides a flowchart of the interconnections between the soil storages and hydrological processes.

Land Use Descriptors – Three parameters are used to describe land use characteristics (Table 3-3.1). Two parameters are used to define the land area occupied by impervious surfaces. One parameter is for impervious areas that are permanent and the second parameter is dynamic in that it tracks land areas that respond like impervious areas when the soil mantle becomes wetter, which is consistent with the variable source area and saturated overland flow concepts. A third parameter identifies areas of riparian vegetation adjacent to the stream network. All other areas are considered to be pervious areas with a soil mantle.

Table 3-3.1 –Land Use Descriptors used by SAC-SMA

PARAMETER DESCRIPTION	SAC-SMA PARAMETER	COMMENT
Impervious Area	PCTIM	Fraction of land area occupied by permanent impervious areas
Additional Impervious Area	ADIMP	Additional impervious area (fraction of land area) which achieves impervious characteristics as the soil mantle becomes wetter
Riparian Vegetation Area	RIVA	Fraction of land area occupied by riparian vegetation areas adjacent to the stream network

Moisture Storages – Five moisture storages are used by SAC-SMA for modeling of the soil moisture and runoff processes (Table 3-3.2). Each of these moisture storages has a capacity and the state condition varies continuously with rainfall and snowmelt input, reduction by evapotranspiration, moisture transfers between storages and output as streamflows.

Table 3-3.2 – Moisture Storages used by SAC-SMA

PARAMETER DESCRIPTION	SAC-SMA PARAMETERS	
	CAPACITY	STATE CONDITION
Upper Zone Tension Water Storage	UZTWM	UZTWC
Upper Zone Free Water Storage	UZFWM	UZFWC
Lower Zone Tension Water Storage	LZTWM	LZTWC
Lower Zone Free Water Storage for Supplemental Baseflow	LZFSM	LZFSC
Lower Zone Free Water Storage for Primary Baseflow	LZFPM	LZFPC

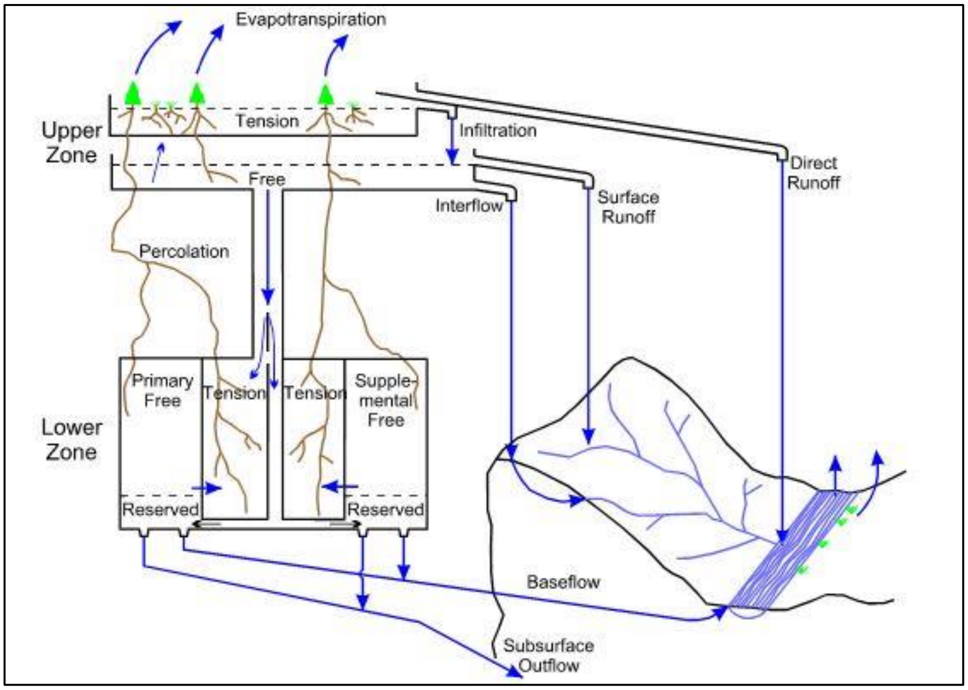


Figure 3-3.1a – Schematic of Soil Moisture and Runoff Processes for Sacramento Soil Moisture Accounting Method Used in the SEFM Watershed Model and HEC-1 Watershed Model

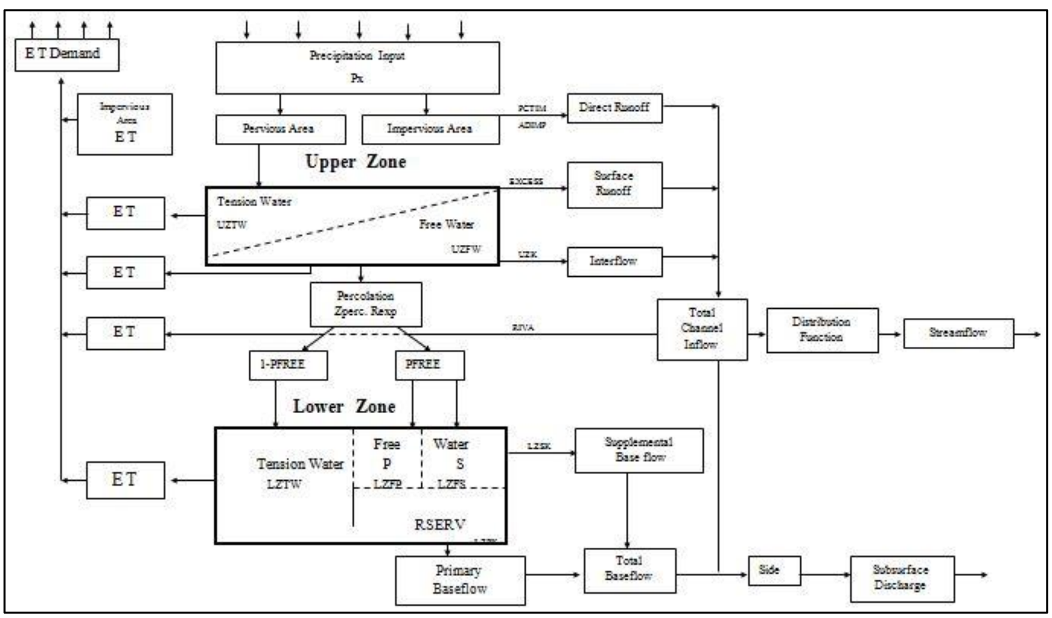


Figure 3-3.1b – Flowchart of Hydrological Processes for SAC-SMA and Interconnections between Soil Storages

Hydrologic Process Parameters – Five parameters are associated with the infiltration and percolation processes (Table 3-3.3) which transfer moisture between storages. The percolation rate is a complex relationship between soil moisture states and capacities in the upper and lower zone free water storages.

The minimum percolation rate (*PBASE*) occurs when the lower zone storages are filled, where *PBASE* (mm/day) is computed as:

$$Min\ Percolation\ Rate = PBASE = LZFSM*LZSK + LZFPM*LZPK \quad \text{3-3.1a}$$

The maximum percolation rate (mm/day) occurs when the lower zone storages are empty and is computed as:

$$Max\ Percolation\ Rate = PBASE*(1 + ZPERC) \quad \text{3-3.1b}$$

The percolation rate at any given time is dependent upon the product of the percolation demand and the relative supply of moisture from the upper zone free water. The percolation demand is a function of the deficit in lower zone free water ($Deficit_{LZFW}$) such that:

$$Deficit_{LZFW} = [(LZFSM-LZFSC) + (LZFPM-LZFPC)] / (LZFSM + LZFPM) \quad \text{3-3.2a}$$

$$Percolation\ Demand = PBASE*(1 + ZPERC*\ Deficit_{LZFW}^{REXP}) \quad \text{3-3.2b}$$

$$Percolation\ Rate = Percolation\ Demand *(UZFWC/UZFWM) \quad \text{3-3.2c}$$

Table 3-3.3 – Hydrologic Process Parameters for Transfer of Soil Moisture

PARAMETER DESCRIPTION	SAC-SMA PARAMETER	COMMENT
Multiplicative Factor of PBASE to Set Maximum Percolation Rate	ZPERC	
Exponent on Percolation Equation	REXP	
Upper Zone Free Water Passes Directly to Lower Zone Free Water	PFREE	Fraction of Moisture Input; reduces interflow and increases baseflow
Lower Zone Free Water Not Subject to Evapotranspiration	RSRV	Below root zone
Fraction of Supplemental and Primary Baseflow that is lost to Deep Recharge	SIDE	

Parameters for Transforming Runoff to Streamflow – Three parameters are used for transforming runoff volumes for a given time-step to streamflows using linear reservoir routing procedures.

Table 3-3.4 –Parameters for Transforming Runoff Volume to Streamflow

PARAMETER DESCRIPTION	SAC-SMA PARAMETER	COMMENT
Interflow Storage Depletion Rate	UZK	Fraction of UZFWC per day
Lower Zone Free Water Supplemental Storage Depletion Rate	LZSK	Fraction of LZFSC per day
Lower Zone Free Water Primary Storage Depletion Rate	LZPK	Fraction of LZFPC per day

Guidance and Experience for Hydrologic Soil Parameters –Table 3-3.5 lists typical ranges of hydrologic soil parameters for SAC-SMA based on extensive experience at the National Weather Service (Anderson[x]) in use of SAC-SMA throughout the U.S. Parameter values outside these ranges are possible. However, values within these ranges provide a good starting point for calibration of watershed models.

Table 3-3.5 – Typical Ranges of Hydrologic Soil Parameters for SAC-SMA

SAC-SMA PARAMETER	TYPICAL PARAMETER RANGE		DESCRIPTION AND COMMENTS
	LOWER	UPPER	
PCTIM	0.00	0.05	Permanent Impervious Land Use (fraction of land area)
ADIMP	0.00	0.20	Additional Impervious Land Use (fraction of land area)
RIVA	0.00	0.20	Riparian Vegetation Area (fraction of land area)
UZTWM	25	125	Upper Zone Tension Water Storage Capacity (mm)
UZFWM	10	75	Upper Zone Free Water Storage Capacity (mm)
UZK	0.20	0.50	Upper Zone Interflow Daily Depletion Rate (fraction contents/day)
LZTWM	25	125	Lower Zone Tension Water Storage Capacity (mm)
LZFSM	15	300	Lower Zone Free Water Storage Supplemental Baseflow (mm)
LZSK	0.03	0.20	Supplemental Baseflow Daily Depletion Rate (fraction contents/day)
LZFPM	40	600	Lower Zone Free Water Storage Primary Baseflow (mm)
LZPK	0.001	0.015	Primary Baseflow Daily Depletion Rate (fraction contents/day)
ZPERC	20	300	Multiplicative Factor to set Maximum Percolation Rate
REXP	1.4	3.5	Exponent in percolation demand equation
PFREE	0.00	0.50	Leakage Upper to Lower Zone Free Water (fraction moisture input)

3-3.4 SEFM Operation for Hydrologic Soil Processes

START HERE FOR UPDATING

Runoff calculations for quickflow and interflow are performed for each time-step by a simple accounting process utilizing the precipitation amount, soil moisture deficit, surface infiltration rate, deep percolation rate, and modified Holtan equation. Separate rainfall-runoff computations are conducted for each HRU to reflect the site-specific climatic and soil conditions. Runoff from each HRU is aggregated to the sub-basin level. A quickflow unit-hydrograph is used to convert the quickflow runoff volume for each sub-basin into a flood hydrograph. A two-stage linear reservoir routing procedure is used to convert the interflow runoff volume from each sub-basin into an interflow hydrograph.

Data Entry Format **–** Data entry consists of entering hydrologic soil properties for each soil zone. This includes values for: interception storage; surficial soil moisture storage capacity; maximum surface infiltration rate; minimum surface infiltration rate; Holtan infiltration exponent; subsurface soil moisture capacity; deep percolation rate; and supplemental and primary baseflow. An example of data entry is shown in Screen Shot 3-1.1.

Also see Section 2-1.1, *Watershed Layout*, for further discussion of soil zones.

Number of Soil Zones	5

Soil Zone Definition

Zone Number	Infiltration Exponent	Maximum Surface Infiltration Rate (in/hr)	Minimum Surface Infiltration Rate (in/hr)	Maximum Soil Moisture Storage (in)	Deep Percolation Rate (in/hr)
1	1.4	2.00	0.60	4.00	0.060
2	1.4	2.00	0.60	6.00	0.060
3	1.4	2.00	0.60	6.00	0.080
4	1.4	0.00	0.00	0.00	0.000
5	1.4	10.00	10.00	4.00	0.060
6					
7					

Comments

Soil Zone 1 is SCS Hydrologic Soil Type C
Soil Zone 2 is SCS Hydrologic Soil Type B
Soil Zone 3 is SCS Hydrologic Soil Type A
Soil Zone 4 is water (lake surfaces)
Soil Zone 5 is used for all soils in Subbasin 4 which has no surface connection to Keechelus Lake.

Screen Shot 3-1.1 – Example Data Entry Format for Soils Characteristics at Keechelus Watershed, Washington

Guidance and Experience, Surface Infiltration and Deep Percolation Rates – The magnitude of the minimum surface infiltration rate and deep percolation rate are important factors in determining the hydrologic response of the watershed. The magnitude of the deep percolation rate is a critical factor in determining the runoff volume of the flood. The magnitude of the minimum surface infiltration rate relative to the magnitude of the precipitation intensities is a critical factor in determining the quickflow runoff response, and therefore the "flashiness" of the flood hydrograph. Initial estimates of these rates can be obtained from STATSGO[66] databases and other soils mapping information. Final values for use in flood modeling should be determined by calibration to observed floods.

The exponent (*IEXP*) on the infiltration equation (Equation 2-13.1) was determined by Holtan[12] to have a value of 1.4. This value should be used as the default unless site-specific information is available that indicates a different value is appropriate.

Guidance and Experience, Frozen Ground Conditions –Antecedent temperature is used to determine whether a concrete frost exists in portions of the watershed at the onset of the extreme storm. A concrete frost is a type of frozen ground condition that can occur when there is sufficient soil moisture and the areal extent of freezing is sufficient to form a contiguous frozen layer that impedes surface infiltration.

Antecedent temperature is defined as the mean daily temperature averaged over the 14 days prior to the occurrence of the storm at the start of flood simulations. The determination of the existence of frozen ground is made for each HRU based on the antecedent temperature, depth of snow cover, and soil moisture conditions for the HRU. If conditions are sufficient to support a concrete frost, then the surface infiltration rate is reduced to reflect the impedance to infiltration.

Prior studies[57,59] have shown that a prolonged period of below-freezing temperatures is required for developing a concrete frost, and a duration of 14-days is suitable for determination of frozen ground conditions. Figure 3-1.3 depicts an example of the behavior of 14-day average temperature for a location in the Cascade Mountains in Washington.

Experience in mountainous watersheds[58,65] has shown that it is unusual to produce the combination of conditions necessary for forming a concrete frost over large portions of a watershed. Experience has also shown that frozen ground conditions rarely occur in heavily forested watersheds with thick litter layers and are rarely seen where free-draining sandy soils are present. When frozen ground conditions do occur in the western US, they are most often seen in watersheds with fine-grained soils, at lower elevations in semi-arid climates where thin snowpacks are common. General rule-of-thumb criteria for formation of a concrete frost[58,59] includes: snowpack depth less than 6-inches (snow-water equivalent of about 1.0 inches); and soil moisture content of 2 inches or more.

Limited data and studies are available for determining the reduction in surface infiltration rate for frozen ground conditions. A surface infiltration rate of 0.10 inch/hour, or one-third of the minimum surface infiltration rate, whichever is smaller, is commonly used. The elapsed time for melting of the frozen ground is dependent upon the temperature of the rain during the storm and the depth of frost penetration. Durations of 12-hours to 72-hours are commonly used for melting of the concrete frost.

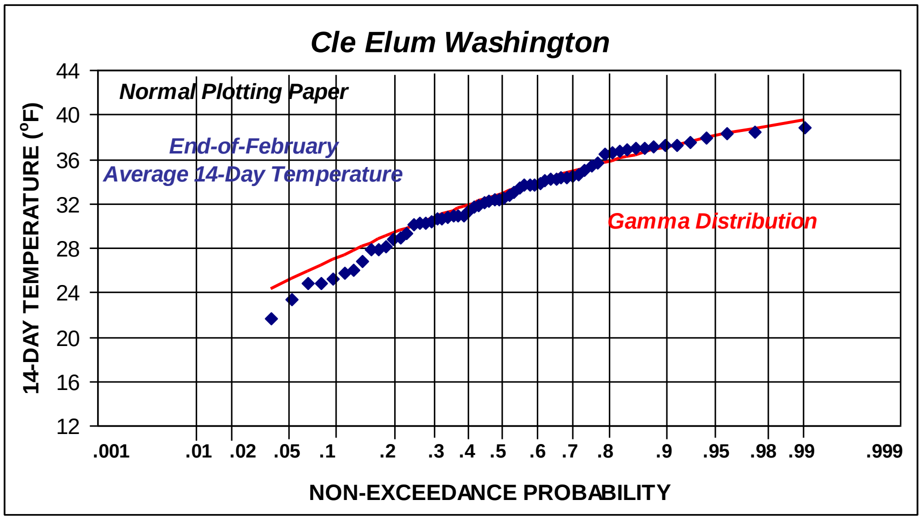


Figure 3-2.5 – Probability-Plot of Average End-of-February 14-Day Temperature

Assumptions and Expectations, Frozen Ground Conditions – It is assumed that prolonged below freezing temperatures will produce a concrete frost when the upper layer of the soil is wet and there is limited insulating effect from snow cover. Concrete frosts have been observed to occur[57,58,59,74] when this combination of conditions has been present.

Data Entry Format for Frozen Ground – The data entry for frozen ground criteria is shown in Screen Shot 3-1.2.

Frozen Ground Criteria	
Min Soil Moisture (in)	2.00
Max Snow Water Equivalent (inches)	1.00
Frozen Surface Infilt Rate (in/hr)	0.10
Time Required to Melt Frozen Ground (hrs)	72

Screen Shot 3-2.4 – Example Data Entry Format for Frozen Ground Conditions

3-4 HEC-1 WATERSHED MODEL

The HEC-1 watershed model has been modified for use with the SEFM stochastic engine. Most of the standard features of HEC-1 version 4.0 are intact, although HEC-1 is primarily used for routing of hydrographs through the stream network. The majority of computations for the hydrologic processes are performed within the SEFM stochastic engine. The SEFM/HEC-1 watershed model includes the following features for stochastic flood modeling:

- Sub-basin configuration within a stream network, including dams and reservoir operations
- Distributed inputs for precipitation, evapotranspiration, snowpack and hydrologic soil parameters
- Computes runoff using a modified Holtan procedure using soil moisture accounting methods or the Sacramento Soil Moisture Accounting method (SAC-SMA)
- Computes snowmelt using an energy-budget method and the USBR snow-compaction method
- Computes runoff on a distributed basis for land segments, Hydrologic Runoff Units (HRUs)
- Computes quickflow runoff for each sub-basin and transforms to a streamflow hydrograph using a unit-hydrograph
- Computes interflow runoff for each sub-basin and uses linear reservoir routing procedures to generate an interflow streamflow hydrograph
- Optional computation of supplemental baseflow and primary baseflow using procedures in SAC-SMA
- Uses hydrologic routing methods for routing hydrographs through the stream network

3-4.1 Modeling of Hydrologic Soil Processes

The hydrologic soil processes are modeled using either a modified Holtan method or the Sacramento Soil Moisture Accounting method (SAC-SMA). Details on the modified Holtan method are described in Section 3-2 and details about SAC-SMA are described in Section 3-3.

3-4.2 HEC-1 Executed in Batch Mode

The HEC-1 watershed model is executed in batch mode to allow multi-thousand flood simulations to be conducted without user interaction. This is accomplished by first creating multi-thousand HEC-1 input files containing the stochastic inputs. The HEC-1 input files are then executed in batch mode to generate multi-thousand flood hydrographs which are processed by the SEFM post-processor.

The HEC-1 input files are variations of the HEC-1 Template File which is the master file describing the essential features of the sub-basins and watershed.

3-4.3 HEC-1 Template File

The standard 80 column punch card ASCII Text format[64] utilized by HEC-1 for data input has been modified to work with the SEFM stochastic engine. This is accomplished by replacing specific data input "cards" with a card identifier that indicates Monte Carlo data input is to be used. These data input "cards" are replaced with Monte Carlo generated data for execution by HEC-1.

This template file is similar to a standard HEC-1 input file however it is much shorter, since the precipitation and runoff calculations are being performed by the SEFM engine. Table 3-4.1 lists the HEC-1 Monte Carlo cards that are read and replaced during the simulation. An example template file and corresponding HEC-1 input file produced by the SEFM program are shown in Section 3-4.4.

Table 3-4.1 – Monte Carlo Cards for HEC-1 Template File

ORIGINAL HEC-1 CARD	MONTE CARLO CARD	PURPOSE
IT	MCIT	HEC-1 Simulation Duration and Time-step
ID	MCID	Run Title
BA	MCBA	Surface and Interflow Components
BF	MCBF	Initial Streamflow for continuous modeling
		Initial Streamflow with Baseflow Recession Applied for single event modeling
RS	MCRS	Initial Reservoir Elevation
SE SV SQ	MCRT	Allows for simulation of time varying reservoir operations by inserting different reservoir rating tables for each simulation month

Monte Carlo Card Replacement for Production Runs
The following section describes how the Monte Carlo cards are replaced and input data inserted for production runs of SEFM.

MCIT – This card is replaced by a HEC-1 *IT* card that contains the computational time-step, simulation run length and simulation start date.

MCID – This card is replaced by a HEC-1 *ID* card that contains the run title.

MCBA – This card represents the runoff for each sub-basin. It is replaced by two sets of HEC-1 cards that contain the surface runoff and interflow runoff.

The quickflow runoff (precipitation less the infiltrated moisture) is represented by HEC-1 ***PI*** cards. These are followed by ***UI*** cards, which is the quickflow runoff unit hydrograph. Since the SEFM engine is performing the soil moisture calculations, a HEC-1 uniform loss rate card ***LU*** is added with the loss rate set to zero.

A ***KK*** card denotes the beginning of the interflow component with the sub-basin number followed by an "I". The interflow is entered into HEC-1 on ***QI*** cards since the interflow streamflow computations are applied by the SEFM engine.

Another HEC-1 card ***HC*** is added that combines the two runoff hydrograph components together.

MCBF – This card is replaced by ***QI*** cards that represent the initial baseflow upstream of the reservoir at the onset of the storm event. This card is placed immediately upstream of the reservoir card in the template file. An additional HEC-1 hydrograph combine ***HC*** card is added to combine the baseflow with the simulated flood flows.

MCRS – This card is replaced by an ***RS*** card that has the initial reservoir elevation at the onset of the storm event.

MCRT – This card is used to simulate time varying reservoir operations. A different set of reservoir elevation (***SE***) reservoir volume (***SV***) and reservoir discharge (***SQ***) cards may be specified for each month. The set of cards corresponding to the month when the storm occurs are inserted into the input file in place of the ***MCRT*** card.

3-4.4 Hydrograph Output File

The SEFM post-processor reads a standard HEC-1 punch file that is created for each simulation performed by HEC-1. For each output hydrograph desired (usually the reservoir inflow and outflow) a ***KO*** and a ***KF*** card must be included to create the punch file. The ***KO*** card must include parameters defining that a punch file is to be used and the output time-step should be set equal to the computation time-step. The ***KF*** card formats the punch file output so that it can be read by the post-processor. The format must be a valid *Fortran* format that saves the hydrograph output in a single column. The following shows an example of valid ***KO*** and ***KF*** cards for Monte Carlo simulation:

```
KO                             7                              TS
KF   YES(2X,F10.1)
```

where TS is the time-step in hours. These cards are not automatically added by the SEFM program but must be added by the user, which provides the flexibility of defining any number of hydrographs to analyze from the watershed.

It is recommended that one input file be created and tested using HEC-1 before performing multiple simulations to ensure that the watershed layout is correct and the desired results are being saved from the model. Before running multiple simulations, it is recommended that the template file contain the following two lines to minimize the size of the output files:

```
*NOLIST
IO      5
```

3-4.5 Example HEC-1 Template File and Batch Files

The following "card" file shows an example of an HEC-1 template file set up for use with SEFM. This example is for a simple 2 sub-basin watershed with a dam at the outlet of the watershed. The standard HEC-1 cards have been replaced by the user with card identifiers (red) indicating these inputs will be changed to have data input from Monte Carlo data generation procedures.

User Supplied HEC-1 Template File Modified for Use by SEFM

```
*NOLIST
ID       MONTE-CARLO SIMULATION RUN
MCID
MCIT
IO      5       0       0
KK      1   SUBBASIN 1
MCBA    1                                    MONTE CARLO SURFACE AND INTERFLOW, BASIN 1
KK      2   SUBBASIN 2
MCBA    2                                    MONTE CARLO SURFACE AND INTERFLOW, BASIN 2
KK     2C Combine SUBBASIN 1 and 2
HC      2
KK     5R ROUTE COMBINED FLOWS TO NEXT SUBBASIN
RM      4     2.0      .1
MCBF                                         MONTE CARLO BASE FLOW
KK     5C COMBINE BASE FLOW WITH MAINSTEM FLOW, WRITE TO PUNCH FILE
KO                             7                             .50
KF    YES(2X,F10.1)
HC      2
KKDAM    RESERVOIR ROUTE
KO                             7                             .50
KF    YES(2X,F10.1)
MCRS
SV20000.   92808  112599  125130  138736  153423  160063  169117  185592  193992
SV203092  221757  233146  243389  261811  289443  335497  395832  789976
SE3150.0 3211.17 3220.00 3224.00 3230.00 3234.80 3237.00 3240.00 3245.00 3247.24
SE3250.0 3255.00 3257.90 3260.00 3264.00 3270.00 3280.00 3290.00 3354.00
SQ 100.0   100.0   100.0   100.0   100.0   100.0  1327.0  3000.0  3000.0  3000.0
SQ4150.0  6500.0  8120.0  9252.1 11540.2 15274.0 22225.2 29994.8 80000.0
ZZ
```

Example HEC-1 File Created by SEFM using Template File Above

```
*NOLIST
ID       MONTE-CARLO SIMULATION RUN
ID SEFM Simulation
IT     30 01JAN99     0000      200
IO      5       0       0
KK      1   SUBBASIN 1
*    First Surface Runoff (PI Cards) Then Interflow (QI Cards)
BA   632.
PB      0
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0396  0.0396  0.0425  0.0425  0.0611  0.0611  0.1392  0.1283
PI0.0585  0.0585  0.0006  0.0006  0.0003  0.0003  0.0003  0.0003  0.0003  0.0003
PI0.0003  0.0003  0.0003  0.0003  0.0003  0.0003  0.0001  0.0001  0.0001  0.0001
PI0.0001  0.0001  0.0001  0.0001  0.0001  0.0001  0.0001  0.0001  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
```

```
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
UI    4.    50.2   198.9   506.5  1012.5  1736.6  2679.9  3828.0  5154.3  6624.2
UI 8198.  9835.6 11495.4 13139.7 14733.8 16247.5 17655.7 18938.2 20079.7 21069.6
UI21902. 22573.8 23086.7 23444.2 23652.7 23720.1 23656.1 23471.0 23176.2 22783.2
UI22304. 21749.2 21130.9 20459.6 19745.4 18997.9 18225.8 17437.3 16639.6 15839.2
UI15042. 14253.2 13477.0 12717.2 11977.1 11259.1 10565.5  9897.7  9257.1  8644.4
UI 8060.  7504.6  6977.6  6479.0  6008.2  5564.8  5148.0  4756.8  4390.5  4048.0
UI 3728.  3430.5  3153.4  2895.9  2657.0  2435.6  2230.8  2041.5  1866.7  1705.6
UI 1557.  1420.6  1295.1  1179.8  1074.0   977.1   888.4   807.2   732.9   665.1
UI  603.   546.8   495.4   448.5   405.9   367.1   331.9   299.9   270.9   244.5
UI  221.   199.0   179.4   161.6   145.6   131.1   118.0   106.1    95.4    85.8
UI   77.    69.3    62.2    55.8    50.1    44.9    40.3    36.1    32.4    29.0
UI   26.    23.2    20.8    18.6    16.7    14.9    13.3    11.9    10.6     9.5
UI    8.     7.6     6.8     6.0     5.4     4.8     4.3     3.8     3.4     3.0
UI    3.     2.4     2.1     1.9     1.7     1.5     1.3     1.2     1.1     0.9
UI    1.     0.7     0.7     0.6     0.5     0.5     0.4     0.4     0.3     0.3
UI    0.     0.2     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
LU    0.    0.00      0.
KK     1I
KM       INTERFLOW FROM SUBBASIN  1
BA  0.00
QI   0.      0.1     0.2     0.4     0.6     0.8     1.0     1.3     1.6     2.0
QI   2.      6.3    14.5    26.7    43.0    63.0    86.7   114.0   144.7   178.7
QI  216.   256.0   294.8   332.3   368.4   403.1   436.3   468.2   498.8   528.0
QI  556.   582.6   608.0   632.3   655.4   677.4   698.3   718.1   736.9   754.7
QI  772.   787.5   802.5   816.6   829.8   842.3   853.9   864.8   874.9   884.3
QI  893.   900.9   908.2   914.9   920.9   926.4   931.3   935.6   939.4   942.6
QI  945.   947.5   949.3   950.5   951.3   951.7   951.7   951.2   950.4   949.2
QI  948.   945.8   943.6   941.1   938.3   935.2   931.8   928.2   924.4   920.3
QI  916.   911.5   906.8   901.9   896.8   891.5   886.1   880.5   874.8   868.9
QI  863.   856.8   850.6   844.2   837.8   831.2   824.6   817.9   811.1   804.3
QI  797.   790.4   783.4   776.3   769.2   762.0   754.8   747.6   740.4   733.1
QI  726.   718.5   711.2   703.9   696.6   689.3   682.0   674.7   667.4   660.2
QI  653.   645.7   638.4   631.2   624.1   616.9   609.8   602.7   595.7   588.6
QI  582.   574.7   567.8   560.9   554.1   547.3   540.5   533.8   527.2   520.6
QI  514.   507.5   501.0   494.6   488.2   481.9   475.6   469.4   463.3   457.2
QI  451.   445.1   439.2   433.3   427.5   421.7   416.0   410.3   404.7   399.1
QI  394.   388.2   382.8   377.5   372.2   367.0   361.9   356.8   351.7   346.7
QI  342.   336.9   332.1   327.3   322.6   317.9   313.3   308.8   304.3   299.8
QI  295.   291.1   286.8   282.6   278.4   274.3   270.2   266.2   262.2   258.3
QI  254.   250.6   246.8   243.1   239.4   235.7   232.2   228.6   225.1   221.7
KK     1C
KM       COMBINE SURFACE AND INTERFLOW FROM SUBBASIN  1
HC      2
KK      2  SUBBASIN 2
*     First Surface Runoff (PI Cards) Then Interflow (QI Cards)
BA  513.
PB      0
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0379  0.0379  0.0393  0.0393  0.0534  0.0534  0.1131  0.1039
PI0.0488  0.0488  0.0108  0.0106  0.0061  0.0061  0.0061  0.0061  0.0061  0.0061
PI0.0063  0.0063  0.0063  0.0063  0.0062  0.0062  0.0015  0.0015  0.0015  0.0015
PI0.0015  0.0015  0.0015  0.0015  0.0015  0.0015  0.0015  0.0015  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
PI0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
UI    2.    40.1   189.0   536.5  1153.5  2080.2  3322.6  4855.8  6631.2  8583.7
UI10640. 12726.4 14771.4 16712.1 18495.7 20080.6 21436.8 22545.4 23397.6 23993.7
UI24341. 24452.9 24347.5 24045.7 23570.6 22946.0 22196.0 21343.8 20411.9 19420.8
UI18390. 17335.2 16272.6 15214.8 14172.8 13155.9 12171.3 11225.0 10321.5  9463.8
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UI 8654.  7893.4  7182.0  6519.5  5904.9  5336.9  4813.7  4333.4  3893.7  3492.3
UI 3127.  2795.2  2494.6  2222.9  1978.0  1757.4  1559.4  1381.8  1222.9  1080.9
UI  954.   841.5   741.2   652.2   573.2   503.3   441.5   386.9   338.7   296.3
UI  259.   226.1   197.3   172.0   149.8   130.4   113.4    98.6    85.6    74.3
UI   64.    55.9    48.4    41.9    36.3    31.3    27.1    23.4    20.2    17.4
UI   15.    12.9    11.1     9.6     8.3     7.1     6.1     5.2     4.5     3.9
UI    3.     2.8     2.4     2.1     1.8     1.5     1.3     1.1     1.0     0.8
UI    1.     0.6     0.5     0.4     0.4     0.3     0.3     0.2     0.0     0.0
LU    0.    0.00      0.
KK    2I
KM      INTERFLOW FROM SUBBASIN  2
BA  0.00
QI    2.     7.4    14.8    24.4    36.3    50.3    66.3    84.2   103.9   125.4
QI  149.   180.1   220.3   269.0   325.8   390.3   462.2   541.1   626.7   718.6
QI  817.   920.1  1022.0  1121.8  1219.5  1315.1  1408.5  1499.8  1589.0  1676.2
QI 1761.  1844.4  1925.6  2004.8  2082.1  2157.6  2231.2  2303.1  2373.2  2441.7
QI 2508.  2573.6  2637.1  2699.1  2759.5  2818.5  2876.0  2932.1  2986.6  3039.5
QI 3091.  3140.6  3189.0  3235.9  3281.4  3325.5  3368.3  3409.9  3450.1  3486.8
QI 3520.  3549.7  3576.0  3599.2  3619.3  3636.4  3650.7  3662.2  3671.2  3677.6
QI 3682.  3684.3  3685.6  3685.8  3684.8  3682.7  3679.6  3675.5  3670.5  3664.7
QI 3658.  3650.5  3641.4  3630.7  3618.4  3604.7  3589.6  3573.2  3555.5  3536.6
QI 3517.  3495.5  3473.4  3450.4  3426.4  3401.7  3376.2  3349.9  3322.9  3295.4
QI 3267.  3238.5  3209.2  3179.5  3149.4  3118.9  3088.0  3056.9  3025.4  2993.7
QI 2962.  2929.6  2897.3  2864.8  2832.2  2799.6  2766.8  2734.0  2701.2  2668.4
QI 2636.  2602.9  2570.1  2537.5  2504.9  2472.4  2440.0  2407.8  2375.7  2343.7
QI 2312.  2280.3  2248.8  2217.6  2186.5  2155.6  2125.0  2094.6  2064.4  2034.4
QI 2005.  1975.3  1946.1  1917.1  1888.4  1860.0  1831.9  1804.0  1776.4  1749.1
QI 1722.  1695.3  1668.8  1642.7  1616.8  1591.2  1565.9  1540.9  1516.2  1491.8
QI 1468.  1443.8  1420.3  1397.0  1374.1  1351.4  1329.1  1307.0  1285.2  1263.7
QI 1243.  1221.6  1201.0  1180.6  1160.6  1140.8  1121.3  1102.0  1083.1  1064.4
QI 1046.  1027.8  1010.0   992.3   975.0   957.9   941.0   924.5   908.1   892.0
QI  876.   860.6   845.2   830.1   815.2   800.6   786.2   772.0   758.0   744.3
KK    2C
KM      COMBINE SURFACE AND INTERFLOW FROM SUBBASIN  2
HC     2
KK    2C Combine SUBBASIN 1 and 2
HC     2
KK    5R ROUTE COMBINED FLOWS TO NEXT SUBBASIN
RM     4     2.0      .1
KK    BF BASE FLOW
BA  0.00
IN    60
QI 1243.  1223.4  1203.9  1184.7  1165.8  1147.2  1128.9  1110.9  1093.2  1075.8
QI 1059.  1041.8  1025.2  1008.8   992.7   988.4   984.1   979.8   975.5   971.2
QI  967.   962.7   958.5   954.3   950.1   945.9   941.8   937.7   933.6   929.5
QI  925.   921.4   917.3   913.3   909.3   905.3   901.3   897.4   893.5   889.6
QI  886.   881.8   877.9   874.1   870.2   866.4   862.6   858.9   855.1   851.3
QI  848.   843.9   840.2   836.5   832.9   829.2   825.6   822.0   818.4   814.8
QI  811.   807.7   804.1   800.6   797.1   793.6   790.1   786.7   783.2   779.8
QI  776.   773.0   769.6   766.2   762.9   759.5   756.2   752.9   749.6   746.3
QI  743.   739.8   736.5   733.3   730.1   726.9   723.7   720.5   717.4   714.2
QI  711.   708.0   704.9   701.8   698.7   695.7   692.6   689.6   686.6   683.6
KK    5C COMBINE BASE FLOW WITH MAINSTEM FLOW, WRITE WRITE TO PUNCH FILE
KO                           7                             .50
KF   YES(2X,F10.1)
HC     2
KKDAM   RESERVOIR ROUTE
KO                           7                             .50
KF   YES(2X,F10.1)
RS     1    ELEV 3225.47
SV20000.   92808  112599  125130  138736  153423  160063  169117  185592  193992
SV203092  221757  233146  243389  261811  289443  335497  395832  789976
SE3150.0 3211.17 3220.00 3224.00 3230.00 3234.80 3237.00 3240.00 3245.00 3247.24
SE3250.0 3255.00 3257.90 3260.00 3264.00 3270.00 3280.00 3290.00 3354.00
SQ 100.0   100.0   100.0   100.0   100.0   100.0  1327.0  3000.0  3000.0  3000.0
SQ4150.0  6500.0  8120.0  9252.1 11540.2 15274.0 22225.2 29994.8 80000.0
ZZ
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