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Modeling, Mapping, and Consequences

Appendix 3.1.7

Snowmelt Model Development for Corps Water Management Systems

FY2023 Standard Operating Procedures for CWMS

March 2022

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CONTENTS

Executive Summary ... **1**

Section 1—Snowmelt Modeling Tasks in the Context of Rainfall Modeling Milestones ... **2**

1.1 Geospatial HEC-HMS Model Development (25 Percent Milestone) ... 3

1.2 Model Development (50 Percent Milestone) ... 3

1.3 Model Calibration (75 Percent Milestone) ... 3

1.4 Model Calibration and Control and Visualization Interface Integration (100 Percent Milestone) ... 4

Section 2—Snow Data Development ... **5**

2.1 Data Sources, Collection, and Development ... 5

2.1.1 Snow Water Equivalent and Other Snow Data ... 5

2.1.2 Precipitation ... 7

2.1.3 Temperature ... 7

2.1.4 Gridded Data Development ... 8

Section 3—Snow HEC-HMS Meteorologic Model Creation and Calibration ... **9**

3.1 Initial Snowmelt HEC-HMS Meteorological Parameters ... 9

3.1.1 Initial Conditions ... 9

3.1.2 Snow Model Parameters ... 11

3.2 Point Snowmelt and Accumulation Model ... 12

3.3 Gridded Basin Snowmelt and Accumulation Model ... 15

3.4 Antecedent Temperature Index-Meltrate Function Development ... 16

3.5 Interim Model Review (50 Percent Milestone Review) ... 19

3.6 Incorporate Review Comments ... 19

Section 4—Snowmelt Runoff Model Calibration and Verification ... **20**

4.1 Identify Snow Events of Interest ... 20

4.2 Calibration of HEC-HMS Model ... 20

4.2.1 Initial Basin Parameters ... 20

4.2.2 Creation of Optimization Trials ... 21

4.2.3 Parameter Search Method ... 21

4.2.4 Objective Function ... 21

4.2.5 Specify Parameters ... 21

4.2.6 Optimization Trial Simulation ... 21

4.3 Verification of hec-hms Model ... 21

4.4 Development of Final Suggested Parameter Set ... 22

4.5 Documentation of Calibrated/Validated hec-hms Model ... 22

4.6 Interim Model Review (75 Percent Milestone Review) ... 22

4.7 Incorporate Review Comments 22
Section 5—Model Testing and Control and Visualization Interface Integration....23
Section 6—Sources of Information 24
6.1 Miscellaneous Data Sources 24
6.2 Software Publications 24
6.3 United States Army Corps of Engineers Publications 25
6.4 Prospect Courses 25
6.5 Other Sources 25
List of Acronyms and Abbreviations 27
Glossary 29

LIST OF FIGURES

Figure 1-1. HEC-HMS Rainfall Runoff Milestones Workflow in Sequence with Snowmelt Modeling....3
Figure 2-1. Average Monthly Observed Temperatures by Elevation at Several Stations with a Watershed. 8
Figure 3-1. Sample Point Snowmelt and Accumulation Model 14
Figure 3-2. Modeled and Observed Snow Water Equivalent for 4 Years at a Snow Telemetry Station 14
Figure 3-3. Basin-averaged SWE Estimated from HEC-HMS and SNODAS for 2005 Melt Period 15
Figure 3-4. Basin-averaged SWE Estimated from HEC-HMS and SNODAS for 2008 Melt Period 16
Figure 3-5. Snow Water Equivalent vs Antecedent Temperature Index during One Season at an Observational Site with Computed Segment Slopes. 17
Figure 3-6. Snow Water Equivalent vs Antecedent Temperature Index Output from HEC-HMS 18

LIST OF TABLES

Table 3-1. Sample Antecedent Temperature Index Meltrate Function....18

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Executive Summary

Snowmelt modeling is often a necessary component in the development and implementation of watershed modeling for Corps Water Management Systems (CWMS) for many mountainous and northern basins. This appendix demonstrates how snowmelt modeling, when applicable, fits into the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) modeling process. It also describes the standard procedures and detailed technical aspects of data and model development for incorporation into the CWMS Control and Visualization Interface (CAVI).

Section 1

Snowmelt Modeling Tasks in the Context of Rainfall Modeling Milestones

Development of the HEC-HMS snowmelt model for CWMS includes some tasks that can be done independently of the overall HEC-HMS model development and others that require completion or near-completion of prerequisite HEC-HMS development tasks. This document provides guidance for snowmelt model development pertaining to the previously-established percent development milestones for the rainfall HEC-HMS modeling efforts.

Figure 1-1 provides a visual representation of the sequence of combined rainfall and snowmelt modeling. Snow modeling tasks are displayed in the gray boxes, and the unchanged rainfall runoff tasks are in color. Figure 1-1 is meant to demonstrate where the primary snowmelt tasks fall with regards to the rainfall model milestones, and as stated previously, do not necessarily represent the percent of total HEC-HMS modeling effort when snowmelt modeling is required.

Note

> The 100 percent milestone, “Model Testing and CAVI Integration,” from the MMC Technical Manual for CWMS is not shown in Figure 1-1, but is still required.

Intermediate deliverables will be prepared by the MMC modeler and provided to the watershed project delivery team (PDT) for review at key production points of the model development. A final report, CWMS Snowmelt Modeling Appendix, will be assembled by the MMC modeler detailing the model development and results.

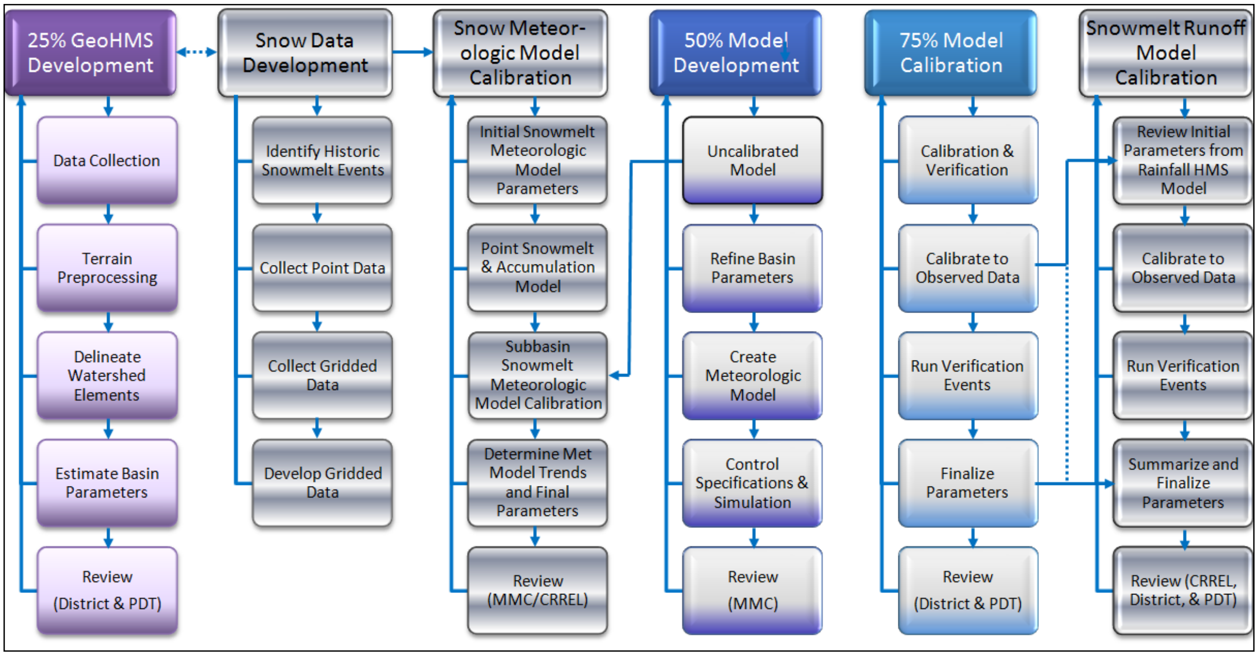

Figure 1-1. HEC-HMS Rainfall Runoff Milestones Workflow in Sequence with Snowmelt Modeling

1.1 GEOSPATIAL HEC-HMS MODEL DEVELOPMENT (25 PERCENT MILESTONE)

Several snowmelt modeling related tasks can be started after project initiation without any prerequisites from the rainfall runoff model. These tasks include the identification of historic snowmelt events and the collection and development of snow and temperature data. Initial meteorological model snow parameters can also be determined during this time through the development and calibration of a simple snow model at locations with historical snow observations. Refer to Section 4.1 for more information.

The 25 percent deliverables are historic snow and temperature data and a calibrated point snow accumulation and melt model with best fit parameter recommendations. These recommended parameters are used as initial parameters in the subbasin snowmelt meteorologic model.

1.2 MODEL DEVELOPMENT (50 PERCENT MILESTONE)

Once the uncalibrated HEC-HMS basin model is developed and the meteorologic model snow parameters are calibrated to observation locations, the HEC-HMS basin model can be used to simulate snowmelt events. The model output could include basin-averaged snow variables such as snow water equivalent (SWE), which could be compared to other basin-averaged snow data to calibrate the snow model further. A discussion on snowmelt parameter calibration is provided in Section 4.2.

The 50 percent deliverable is a calibrated HEC-HMS meteorologic model with suggested final snow parameters.

1.3 MODEL CALIBRATION (75 PERCENT MILESTONE)

Following the determination of meteorologic model snow parameters, the next step in snowmelt HEC-HMS model development is to calibrate the basin model to runoff during snowmelt runoff events. The HEC-HMS model should be calibrated to rainfall-runoff events before proceeding with snowmelt runoff calibration. If there is only a single HEC-HMS modeler performing both rainfall and snowmelt calibration, it is preferred to wait until the rainfall HEC-HMS basin model is fully calibrated and verified. If there are separate snow and rainfall HEC-HMS modelers, it is permissible for this step to commence once a calibrated set of parameters has been developed. The idea is that the same set of hydrologic parameters for some of the basin processes, such as transform and channel routing, could be used during both rainfall and snowmelt events.

Note

> Only one HEC-HMS runoff model project can be implemented into the CWMS CAVI. The HEC-HMS project can have multiple basin models that represent various conditions, such as wet and dry antecedent moisture, or winter and summer conditions; however, it should all be included within one HEC-HMS model project or else the CAVI will not recognize the proper files.

The major deliverable at this point are a fully calibrated HEC-HMS model that includes historic stream flow and precipitation, temperature and snow data for several events, and documentation including a summary of recommended parameters.

1.4 MODEL CALIBRATION AND CONTROL AND VISUALIZATION INTERFACE INTEGRATION (100 PERCENT MILESTONE)

The work performed for this milestone is similar to that for rainfall runoff HEC-HMS models except that the HEC-HMS model implemented into the CWMS CAVI also contains functionality for snowmelt modeling.

Section 2
Snow Data Development

The temperature index snow model within HEC-HMS requires temperature data at each timestep, as well as initial snow conditions at the first timestep of the model. Precipitation data is not required at every timestep, but it is recommended. Snow observations are useful for calibration of the snow meteorological model. These data may come from multiple sources and may require development prior to incorporation into the models.

2.1 DATA SOURCES, COLLECTION, AND DEVELOPMENT

Numerous sources of meteorological and snow data are available—both point and gridded data. Options for obtaining and developing the data depend on several factors including the data type required, location, and date. In some instances, gridded data may need to be developed from point data by using spatial interpolation methods (e.g., GageInterp). In other cases, where point snow data is limited, point data can be extracted from gridded data at locations where other meteorological data (e.g., rain and temperature) are available. This section describes several sources of data and tools available to process the data into the correct format for the model.

2.1.1 Snow Water Equivalent and Other Snow Data

SWE represents the volume of liquid water available in the snowpack. Changes in SWE are modeled within HEC-HMS. If the simulation begins when there is an existing snowpack, an estimate of initial SWE at the start of the simulation is required as an initial condition; otherwise, an initial value of zero can be used. Additionally, SWE observations are useful for calibration of the snow model. Both point observations and gridded SWE data are available from numerous sources.

2.1.1.1 National Operational Hydrologic Remote Sensing Center Snow Data Assimilation System

The National Oceanic and Atmospheric Administration's (NOAA's) National Operational Hydrologic Remote Sensing Center (NOHRSC) provides modeled snow data output from the SNOw Data Assimilation System (SNODAS) model. SNODAS integrates modeled snow estimates with satellite, airborne and ground observations to create one kilometer-resolution gridded datasets of snow covered areas, SWE, and other snow variables for the continental United States. These data are available daily from October 2003 through the present (http://www.nohrsc.noaa.gov/).

2.1.1.2 Natural Resources Conservation Service Snow Telemetry

The Natural Resources Conservation Service (NRCS) owns and maintains a network of snow observation sites, SNOw TELemetry (SNOTEL). The NRCS also regularly conducts manual snow surveys throughout the mountainous regions of the western United States (http://www.wcc.nrcs.usda.gov/snow/). Each SNOTEL site is an automated, near real-time data collection station that collects hydroclimatic data including SWE, snow depth, precipitation, and temperature observations. SNOTEL data collection began in 1978 at some stations and extends through the present. Snow courses measure snow depth and water content along a designated transect, typically around the first of each month during the winter season. The federal snow course program began in 1934 to help with water supply forecasting.

2.1.1.3 United States Army Corps of Engineers Snow Surveys

Several districts within the United States Army Corps of Engineers (USACE) conduct regular snow surveys during the winter, typically at or near project sites. Surveys are generally done on a weekly or monthly basis and follow a standard procedure, similar to NRCS. Volunteer snow survey programs have also been established in a limited number of locations. USACE districts provide SWE measurement equipment to volunteers, who collect SWE information and provide the data to USACE at various times throughout the snow season.

2.1.1.4 Remote Sensing

Satellite observations can provide spatially-distributed estimates of snow covered area (SCA) and SWE at a regular temporal resolution (daily). HEC-HMS does not currently provide a means to incorporate SCA data within the model, but it can be useful for comparison to the model output of distributed snow. Visible and near-infrared measurements provide fairly high-resolution estimates of SCA, though the data are limited during periods of cloud cover or at night. The National Aeronautics and Space Administration's (NASA's) MOD10A1 daily snow product is an example of remotely-sensed snow cover data (http://modis-snow-ice.gsfc.nasa.gov/?c=MOD10A1). A filtering technique developed at the Cold Regions Research and Engineering Laboratory (CRREL) can help eliminate clouds from the data.

2.1.1.5 Passive Microwave Measurements

Passive microwave measurements are available at a coarser resolution and can provide SWE estimates even during cloudy or night-time conditions. These data are archived at the National Snow and Ice Data Center (NSIDC) (http://nsidc.org). The passive microwave data are limited, however, by deep snowpacks and heavy vegetation, particularly in mountainous regions. The signal is also affected by wet snow. Locations within the United States (U.S.) where this data may be useful are in large basins in the southern Rocky Mountains or in the Northern and Central Plains regions.

2.1.1.6 Daymet

Daymet is a collection of algorithms and computer software designed to interpolate and extrapolate from daily meteorological observations to produce gridded estimates of daily weather parameters for North America. This includes daily continuous surfaces of minimum and maximum temperature, precipitation occurrence and amount, humidity, shortwave radiation, snow water equivalent, and day length. The model produces a gridded output at a spatial resolution of one kilometer and a temporal resolution of one day. The required model inputs include a digital elevation model and observations of maximum temperature, minimum temperature, and precipitation from ground-based meteorological stations. The model method is based on the spatial convolution of a truncated Gaussian weighting filter with the set of station locations. Sensitivity to the typical heterogeneous distribution of stations in complex terrain is accomplished with an iterative station density algorithm. The model output includes minimum and maximum temperature, precipitation, water vapor pressure, shortwave radiation, and SWE. Daymet is supported by funding from NASA and the U.S. Department of Energy's Office of Science (https://daymet.ornl.gov/). The Daymet model results are available from 1980 to the present, for a period of record of 37 years. Limitations include lack of ground-truthing and limited testing. The reliability and limitations of this dataset are currently being investigated.

2.1.1.7 Other Sources

Certain National Weather Service (NWS) offices collect snow depth and SWE data for NWS stations (https://www.ncdc.noaa.gov/snow-and-ice/). Another source of snow data is the Community Collaborative Rain, Hail & Snow network (CoCoRaHS), a volunteer network of weather observers, that can collect snow depth information and sometimes measure SWE (http://www.cocorahs.org). Finally, several state environmental or dam safety agencies collect their own manual snow surveys and may be a source of information.

2.1.2 Precipitation

Precipitation data are used in each timestep during an HEC-HMS simulation, but it is not required in all timesteps. Precipitation in the form of rainfall or snowfall is determined by the HEC-HMS model based on the precipitation discrimination (PX) temperature. These data are typically obtained from the NWS at point observation sites or in gridded format for the current and forecast time periods. Additional gridded options are available during the historical period.

2.1.2.1 National Weather Service

In addition to observational station data available from NOAA's National Center for Environmental Information (NCEI) formerly the National Climatic Data Center (NCDC) (https://www.ncdc.noaa.gov/cdo-web/), each NWS River Forecasting Center (RFC) collects gridded NEXRAD radar data on a daily basis to generate Multisensor Precipitation Estimator (MPE) data. These data are available for download or can be requested through individual RFC's (https://www.ncdc.noaa.gov/data-access/radar-data/noaa-big-data-project). Additional manipulation is required to convert data to data storage system (DSS) for use in HEC-HMS. Stage III precipitation data are available from the mid-1990s through the early 2000s. MPE data are available from the early 2000s to the present.

2.1.2.2 Parameter-elevation Relationships on Independent Slopes Model

The Parameter-elevation Relationships on Independent Slopes Model (PRISM) Climate Group of Oregon State University provides estimates of multiple spatial climate data sets derived from modeled results and climate station networks (http://www.prism.oregonstate.edu/). The precipitation data sets are available in gridded format and in either daily or monthly temporal distributions from 1981 through the present. PRISM precipitation grids include rain and melted snow (http://www.prism.oregonstate.edu/documents/PRISM_datasets.pdf).

2.1.2.3 Reanalysis Data

Reanalysis is a method of producing gridded estimates of meteorological data sets for a historical period through a combination of modeling and observational data assimilation. These data are typically generated for climate research on a global scale and may be less accurate for regional studies, depending on the availability of observational data. Some examples of reanalysis data include, NASA Modern Era Retrospective-Analysis for Research Applications (MERRA, http://gmao.gsfc.nasa.gov/reanalysis/merra/), the European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int/en/research/climate-reanalysis), as well as NOAA's National Centers for Environmental Prediction-North American Regional Reanalysis (NCEP-NARR, http://www.esrl.noaa.gov/psd/data/gridded/data.narr.html).

2.1.3 Temperature

Temperature data are required for each timestep of an HEC-HMS snowmelt simulation. Temperature data are used as an index for all of the energy fluxes into the snowpack and they are used to determine whether precipitation falls as rain or snow, whether snow melts, and at what rate melting occurs. Data are available at point locations from the NWS. Gridded temperature data can be obtained from several sources or created through interpolation of point measurements. When creating gridded temperature data from point data, it is important to account for the effects of elevation. Within GageInterp, a lapse rate, or rate at which temperature drops with increasing elevation can be incorporated. An average lapse rate is 3.6 °F/1000 feet (6.5 °C/1000 meter), though this value can be calculated from available data as shown in Figure 2-1. The slope of the lines represent the lapse rate.

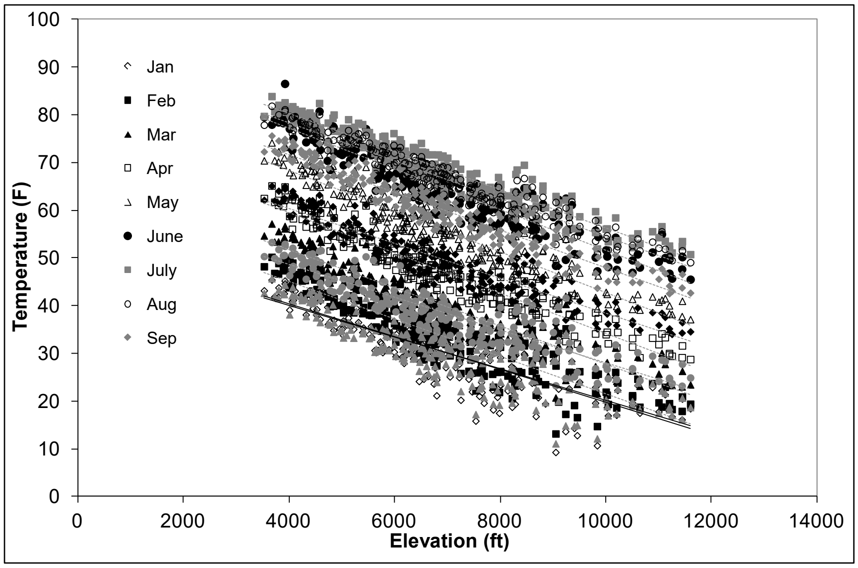

Figure 2-1. Average Monthly Observed Temperatures by Elevation at Several Stations with a Watershed.

2.1.3.1 National Weather Service

The primary source of historical temperature data is from NWS observation stations, which can be accessed through the NCEI (https://www.ncdc.noaa.gov/cdo-web/). Point observations can be converted to gridded data using a calculated lapse rate and HEC's GageInterp program.

2.1.3.2 Parameter-elevation Relationships on Independent Slopes Model

The PRISM Climate Group of Oregon State University provides estimates of multiple spatial climate data sets derived from modeled results and climate station networks (http://www.prism.oregonstate.edu/). The temperature data sets are available in gridded format and in either daily or monthly temporal distributions. The daily temperature data comes in the form of Max Temperature, Min Temperature, and Mean Temperature for a given day. For snowmelt models within HEC-HMS, further data development would be required to create gridded temperature data for an hourly timestep. Contact HEC for assistance.

2.1.3.3 Reanalysis Data

See Section 2.1.2.3 for further information on reanalysis data regarding precipitation.

2.1.4 Gridded Data Development

If gridded data are not available at the location or for the time period of interest, it can be developed through interpolation of point data. The HEC software package GageInterp can convert a time series of point data into DSS gridded objects, and can use a bias grid or lapse rate to account for elevation effects. The HEC point of contact and the local district system administrator should work together to produce this product.

Section 3

Snow HEC-HMS Meteorologic Model Creation and Calibration

It is recommended that the HEC-HMS snowmelt parameters be developed and calibrated separately from the basin runoff calibration using ground observations or independent SWE estimates (e.g., SNODAS) at the 25 percent and 50 percent rainfall HEC-HMS milestones. Snowmelt parameter calibration is discussed in Section 4.2 of this appendix. Snowmelt parameter calibration reduces the number of tuning parameters affecting the hydrological results during hydrologic model runoff calibration. Once the snow parameters have been calibrated to match observed snow accumulation and melt, selected snowmelt runoff events can be simulated within the HEC-HMS model (at the 75 percent Model Calibration milestone). The hydrological parameters calibrated for rainfall events can be further adjusted to match snowmelt events.

3.1 INITIAL SNOWMELT HEC-HMS METEOROLOGICAL PARAMETERS

Within the HEC-HMS snow meteorological model there are several initial snow conditions that must be set in addition to the snow model parameter values. This section describes both initial snow conditions and snow model parameters.

3.1.1 Initial Conditions

The initial conditions of the model represent the physical conditions of the snowpack at the start of the simulation. This section describes those parameters and explains how to determine their values for the start of the model.

3.1.1.1 Initial Snow Water Equivalent

The Initial SWE is the SWE, in inches, that exists at the beginning of the simulation. This information can be obtained from ground measurements of SWE or available gridded estimates (e.g., SNODAS). If there is no snow, this value can be set to zero.

3.1.1.2 Initial Cold Content

The cold content (CC) represents the heat required to raise the temperature of the snow pack to 32 °F and is expressed in inches of water. This value can be calculated with the following SNODAS equation if the initial SWE and snowpack temperature are known:

$$CC = \frac{SWE x C_p x \Delta T_S}{L_f}$$

Where:

$\Delta T_s = T_{savg} - T_{base}$

T_{savg}=Snow pack average temperature

T_{base}=Base temperature (melting temperature of snow)

L_f =latent heat of fusion of water (334,000 J/kg)

C_p=specific heat of ice (2100 J/kg-ºC)

If this value is not known at the start of simulation or if there is no snow, it can be set to zero. The error in doing this when the value is unknown may be small for relatively shallow ephemeral snow covers, but it may cause melt to begin too early for deep, seasonal snowpacks.

3.1.1.3 Initial Liquid Water Content

The initial liquid water content is the liquid water, in inches, held within the snowpack. For any melt or precipitation to be released from the snowpack, the liquid water holding capacity of the snow must first be satisfied. Liquid water can persist in the snow only if the snowpack temperature is at 32 °F; at which point the cold content is zero. A snowpack with liquid water is said to be ripe. Generally, this value is not known at the start of the simulation unless there is no snow, in which case it can be set to zero. Initial liquid water content can also be set to zero if the snow is assumed to be below freezing at the start of the simulation. If the simulation begins during the melt period, the error in setting the initial value to zero may cause a delay in melt runoff.

3.1.1.4 Antecedent Temperature Index for Cold Content

The Antecedent Temperature Index for Cold Content (ATICC) is an index used to represent the snow temperature near the surface of the snowpack. It is calculated assuming an approximation to the transient heat flow equations. This value is used to estimate the cold content of the snow. It should be set to the approximate snowpack temperature, if known (often this is not known or documented, but this information may be included in a snow survey). If unknown, it can be set to 32 °F.

3.1.1.5 Antecedent Temperature Index for Meltrate

The seasonal variation of the meltrate is indexed by the Antecedent Temperature Index for Meltrate (ATIMR). The initial melt antecedent temperature index (ATI) should be thought of as similar to the accumulated thawing degree days. This antecedent temperature function allows the meltrate to change over the course of the spring melt period. If there is no snow on the ground at the start of the simulation, or if the simulation begins before the onset of spring melt this term can be set to zero. Once the spring melt period begins, the antecedent temperature index should be calculated based on observed air temperature data above the base temperature since the onset of melt.

3.1.2 Snow Model Parameters

The snow model parameters influence how a snowpack changes over time, and those parameters are described in this section.

3.1.2.1 Discrimination Temperature

The discrimination temperature (PX temperature) is the threshold between precipitation falling as rain or snow. When the air temperature is less than the specified PX temperature, any precipitation is assumed to be snow. When the air temperature is above the specified PX temperature, any precipitation is assumed to be rain. Typical values range from 32 ºF to 35 ºF.

3.1.2.2 Base Temperature

The base temperature is the temperature at which snow melts. The difference between the base temperature and the air temperature defines the temperature index used in calculating snowmelt. If the air temperature is less than the base temperature, then the amount of melt is zero. Typically, the base temperature is set to 32 °F, or a value close to it.

3.1.2.3 Rain Rate Limit

The rain rate limit is the discrimination rain rate which determines whether the dry meltrate (snowmelt during warm periods with no precipitation) or wet meltrate (snowmelt that is precipitation induced) is used. The wet meltrate is typically greater than dry meltrate primarily due to the condensation of water vapor from the rain inside the snowpack. If the rain rate is less than the rain rate limit, the meltrate is computed as if there were no precipitation. Suggested values of the rain rate limit range from 0.25 to 1.0 inches/day.

3.1.2.4 Wet Meltrate

The wet meltrate is used during periods of rainfall precipitation when the precipitation is falling at rates greater than the rain rate limit. The wet meltrate is applied as the meltrate when it is raining at rates greater than the rain rate limit and the dry meltrate is applied when the rate of rain is less than the rain rate limit (as if there was no precipitation). Typical values set at the high end of the dry meltrate range from 0.08 to 0.15 inches/°F-days.

3.1.2.5 Antecedent Temperature Index Meltrate Coefficient

The ATI meltrate coefficient is the model die-away coefficient used to adjust the meltrate ATI calculated during the previous timestep. It should be set to 0.98.

3.1.2.6 Antecedent Temperature Index Meltrate Function

The ATI meltrate function allows the meltrate to change as snowpack matures and ages as a function of accumulated thawing degree-days. Typically, a deep snowpack (e.g., 10–20 inches SWE) with a long melt period will have a meltrate that changes seasonally to account for increased solar radiation. A shallow snowpack that melts quickly can typically be modeled reasonably well with a constant meltrate function. A table of meltrate versus ATI values is required, which adjusts the dry meltrate based on the antecedent temperature index for meltrates (ATIMR). The function should define appropriate meltrates to use over the range of meltrate index values that will be encountered during a simulation. Meltrates typically range from 0.015 to 0.15 inches/°F-days. See Section 3.4 for additional information.

3.1.2.7 Meltrate Pattern

The meltrate pattern is used to adjust the dry snow meltrate computed from the index meltrate function. Changes in a snowpack albedo and/or incoming solar radiation can be captured through the use of a meltrate pattern. A paired dataset defines the meltrate pattern as a percentage adjustment as a function of the time of year.

3.1.2.8 Cold Limit

The cold content of an existing snowpack is reset when a sufficient amount of new snowfall precipitation accumulates. When the precipitation rate exceeds the specified cold limit, the cold content index is set to the air temperature at the time of the precipitation if the air temperature is below base temperature. If the temperature is above base temperature, the cold content index is set to base temperature. If the precipitation rate is less than the cold limit, the cold content index is computed as an antecedent index. The suggested value for the cold limit is 0.2 inches/day.

3.1.2.9 Antecedent Temperature Index Coldrate Coefficient

The ATI Coldrate Coefficient (ATICC) represents the influence of air temperature on the internal temperature of the snowpack. Values can range from 0 to 1.0, with higher values more closely tracking the observed air temperature. Suggested values range between 0.2 (shallow snowpacks) to 0.5 (deep snowpacks).

3.1.2.10 Antecedent Temperature Index Coldrate Function

The ATI Coldrate Function is a table of values that adjust the coldrate based on the ATICC. Values typically range from 0.01–0.028 inches/°F-days, with a reasonable constant value of 0.02 inches/°F-days recommended.

3.1.2.11 Liquid Water Capacity

The liquid water capacity is the maximum amount of liquid water that can be held in the snowpack before runoff occurs. Liquid water can persist in the snow only if the snowpack temperature is at 32 °F (0 °C). This is calculated for every timestep as SWE decreases. Suggested values range from 3 to 5 percent.

3.1.2.12 Groundmelt

Groundmelt is the rate at which snowmelt occurs due to heat from the ground entering the snowpack. The value is typically set to 0 inches/day.

3.2 POINT SNOWMELT AND ACCUMULATION MODEL

The primary purpose of this step is to accurately simulate SWE accumulation and melt over the snow season at a location within the basin with SWE, temperature, and precipitation observations. This process allows the modeler to converge on temperature index parameters that will be used in the HEC-HMS model.

It is recommended that ground observations of SWE be used to develop initial estimates of the snow model parameters. This can be done using HEC-HMS to simulate the snow accumulation and melt at one or several point locations and comparing the modeled SWE to observed SWE. In HEC-HMS a simple basin model can be set to run the temperature index snowmelt (not gridded) meteorologic model with observed precipitation and temperature data. A typical location would be at a SNOTEL location where observed SWE, temperature, and precipitation data can be gathered.

The following steps are a general workflow for this process. Figure 3-1 provides an example basin point model.

1. Create subbasins for each point location that has observed temperature, precipitation and SWE data. Enter one square mile for the subbasin areas. Change all the modeling methods to none.

2. Create precipitation and temperature gages with all of the observed data. The temperature gages will require an elevation.

3. Create a meteorologic model using specified hyetograph and temperature index methods for the precipitation and snowmelt components, respectively. Within the meteorologic model, assign one elevation band to each subbasin using the elevation of the SWE gage. If the SWE and temperature data come from different locations, then a lapse rate will be required for the model to estimate the temperature at the elevation of the SWE observations.

4. Enter initial temperature index parameters and assign all precipitation and temperature gages to their respective subbasins.

5. Create a control specification to run a desired length of time, which typically includes the complete snow accumulation and melt cycle for a given year. If data is available, running multiple years with snowpack is recommended. The timestep used will be dependent on the observed data. Most SNOTEL sites collect daily data.

6. Create a simulation run and compare modeled and observed SWE at each point location. Figure 3-2 shows example results of the HEC-HMS model run at a point location compared to observations.

7. Make changes to parameters and continue calibrating simulations to match the observed results.

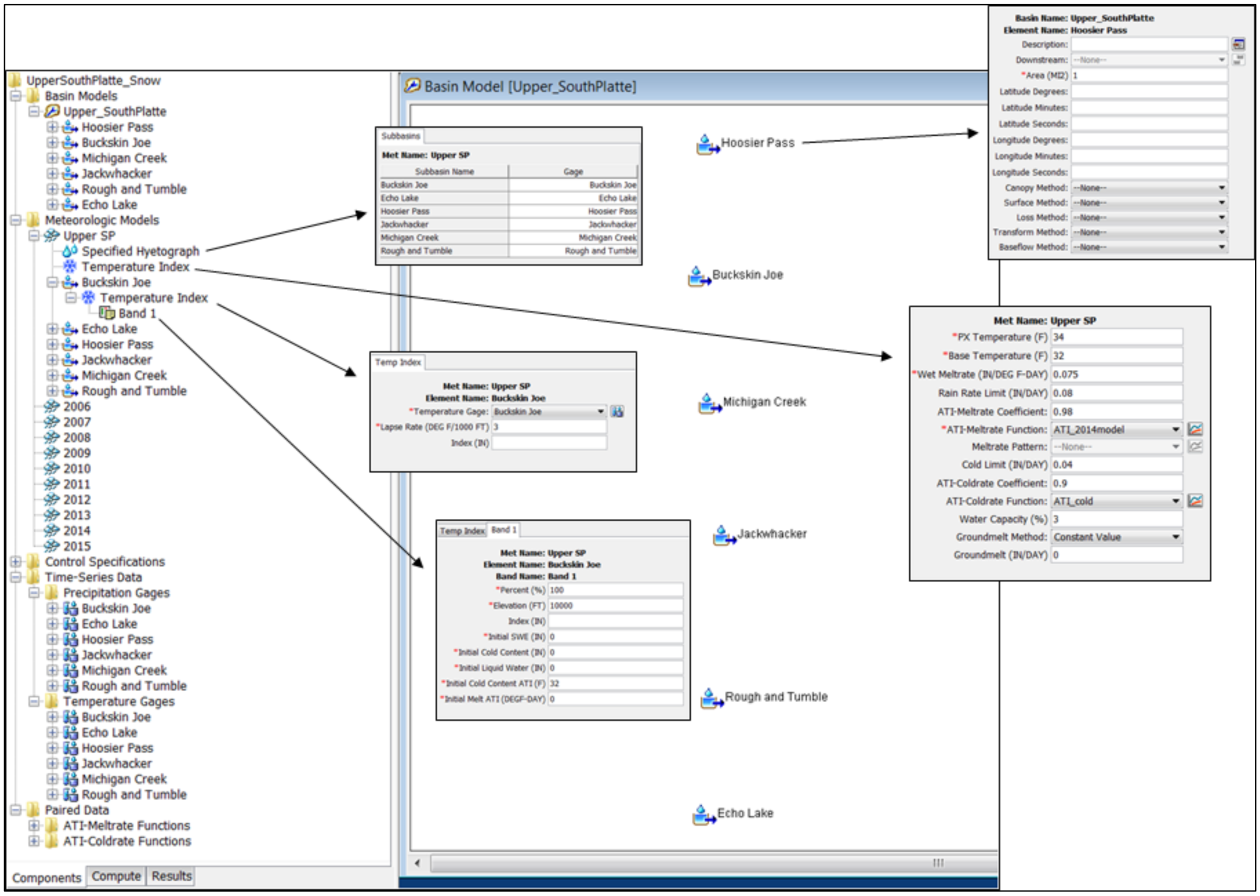

Figure 3-1. Sample Point Snowmelt and Accumulation Model

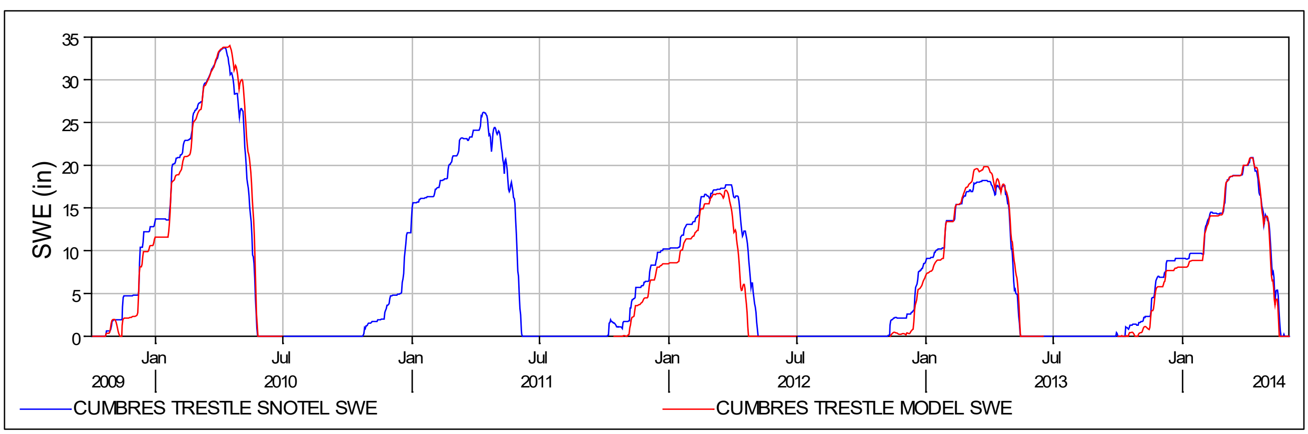

Figure 3-2. Modeled and Observed Snow Water Equivalent for 4 Years at a Snow Telemetry Station

For water resource applications, the snow melt period is generally the most important. To model the melt period from the peak SWE, a similar process is followed; however a simulation should be created for each year analyzed. Within the meteorologic model, the initial SWE needs to be defined for each subbasin which can be obtained from the observational data. This process is time consuming, but allows the modeler to refine the temperature index model parameters, specifically the ATI meltrate function, before moving on to the gridded HEC-HMS model. Engineering judgment should be used to determine a set of recommended meteorological model parameters to be used for initial basin snowmelt and accumulation model analysis (step 1.4.3); however, it is worth noting, that these parameters will undergo further refinement so significant time should not be spent getting a perfect parameter set.

3.3 GRIDDED BASIN SNOWMELT AND ACCUMULATION MODEL

Once the development of a gridded HEC-HMS model is completed (i.e., Geospatial Hydrologic Modeling Extension (GeoHMS) delineated subbasins have been imported into HEC-HMS with associated grid cell file), the meteorologic parameters in the snowmelt model developed through point analysis can be further calibrated with comparison to available gridded snow data. The default modeled snow output in HEC-HMS are time series of basin-averaged snow variables. To evaluate the gridded snow model results, the basin-averaged SWE from HEC-HMS can be compared to other gridded SWE estimates averaged over the same basins. A typical application is to extract basin-averaged SWE from an observed gridded dataset such as SNODAS and to use HEC-MetVue to compute a basin-averaged SWE hyetographs for each subbasin. A comparison can then be made between the two basin averaged SWE hyetographs for multiple subbasins. Snowmelt meteorologic parameters can then be adjusted to better match observed data.

Figures 3-3 and 3-4 show an example of the basin-averaged SWE results from a gridded HEC-HMS model compared to basin-averaged SNODAS data. Initial SWE and cold content grids were obtained from SNODAS data, and initial ATICC, ATIMR, and liquid water content were set to default values (see section 3.1.1). During this process, the modeler can refine meteorological parameters (i.e., ATI meltrate function) to better fit SNODAS results. Because only one set of gridded temperature index parameters can be used for the entire basin model, it is important to perform comparisons for multiple subbasins to verify that the parameters are representing the snowmelt process adequately.

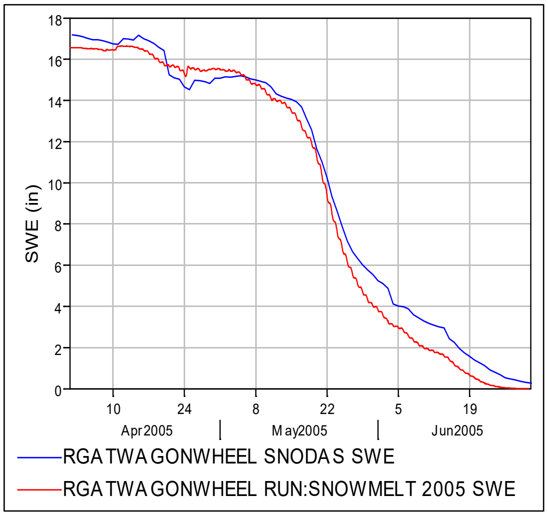

Figure 3-3. Basin-averaged SWE Estimated from HEC-HMS and SNODAS for 2005 Melt Period

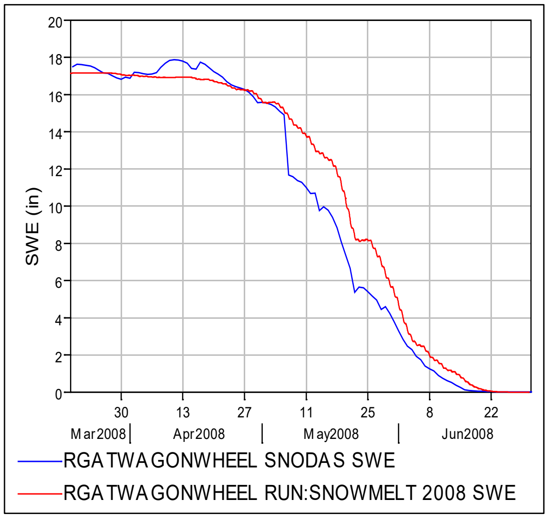

Figure 3-4. Basin-averaged SWE Estimated from HEC-HMS and SNODAS for 2008 Melt Period

An alternative method for evaluating the performance of the gridded HEC-HMS snowmelt model is to compare the spatial extent of the gridded model output to observed SCA observations. Within the HEC-HMS program settings, the option is available to store gridded state variable results. With this option checked, the model will output modeled DSS gridded estimates of the snow variables which can be viewed in HEC-MetVue or exported to geographic information systems (GIS) and compared spatially to observed data. Sources of distributed snow extent data include satellite imagery from Moderate Resolution Imaging Spectroradiometer (MODIS) or Visible Infrared Imaging Radiometer Suite (VIIRS), as well as the SNODAS model data.

Several standard statistical measures are appropriate for evaluating the performance of the HEC-HMS snow model compared to SWE observations. If the entire winter season is modeled, the difference between observed and modeled peak SWE is used to evaluate the total volume of SWE calculated. The difference between the modeled and observed post-melt snow-free day of year will provide information on the timing performance of the model. Several additional statistics can be used to assess the model performance throughout the winter or snowmelt season (Moriasi et al., 2007). These include mean bias, Pearson correlation coefficient (R), the normalized root mean squared error (RMSE), and the Nash-Sutcliffe model efficiency (NSE). Ultimately a recommended snowmelt parameter set should be identified for use for runoff modeling. If a single parameter set is not applicable and it has been determined that various stimuli result in the need for multiple parameter sets, recommendations should be provided to determine when each parameter set should be selected for runoff modeling.

It is recognized that the temperature index model has limitations. For example, it does not account for all hydrometeorological phenomenon that naturally occur in a basin (e.g., hillshading, aspect, sub-grid variability, etc.), and only one meteorologic model can be used per basin model. Some situations may warrant the need to break down the greater basin into smaller basins which could be modeled with separate meteorologic models. Consultation with the PDT and advisors should be sought before deciding to go this route.

3.4 ANTECEDENT TEMPERATURE INDEX-MELTRATE FUNCTION DEVELOPMENT

Two of the most influential parameters affecting snowmelt are temperature and meltrate, which are defined by ATI-Meltrate functions. In a general sense, the meltrate at a particular timestep is equivalent to computed degree days of the timestep (instantaneous, not accumulated degree days) multiplied by the meltrate, which is determined from the meltrate function. This function largely dictates the ability of the model to simulate correctly the rate at which snow melts as well as the timing of the snow-free date. This section provides additional information about the development of the meltrate function to help in model calibration.

The rate of snowmelt typically increases as the snowmelt season progresses due to increased solar radiation input and metamorphic changes within the snowpack. In the HEC-HMS temperature index model, the ATIMR function relates the change in meltrate throughout the season to the accumulated thawing degree days. A deep snowpack with a long melt period will likely have a meltrate that changes seasonally to account for increased solar radiation and more mature snowpack. Observed data within the basin can be used to develop the ATI-meltrate relationship that best fits across multiple locations and years. Figure 3-5 is a plot of the SWE versus the ATI at a station during one season. The absolute values of the slopes of the lines represent meltrate and can be determined using a linear trendline for the segments of approximate constant slope. A steeper slope as the ATI increases corresponds to a faster meltrate. Breaks in slope indicate a potential need to use an ATIMR function that varies with ATI. Table 3-1 provides a sample ATIMR function representative of the observed data shown in Figure 3-5 for that particular gage and year.

Typically, a shallow snowpack that melts quickly (e.g., plains) can be modeled reasonably well with a constant meltrate function. Data can be developed for a point or basin such as in Figure 3-5 to verify this assumption. In order to demonstrate meltrate in HEC-HMS, Figure 3-6 illustrates a plot of SWE versus ATI from output of HEC-HMS when a constant ATIMR function is used in the meteorologic model. Note how the absolute value of the slope of the line (0.0975 inches/°F-days) is approximately the indicated meltrate (0.09 inches/°F-days). The small difference is likely due to the higher wet meltrate having some influence during the melt and causing the average meltrate to be higher than the dry meltrate.

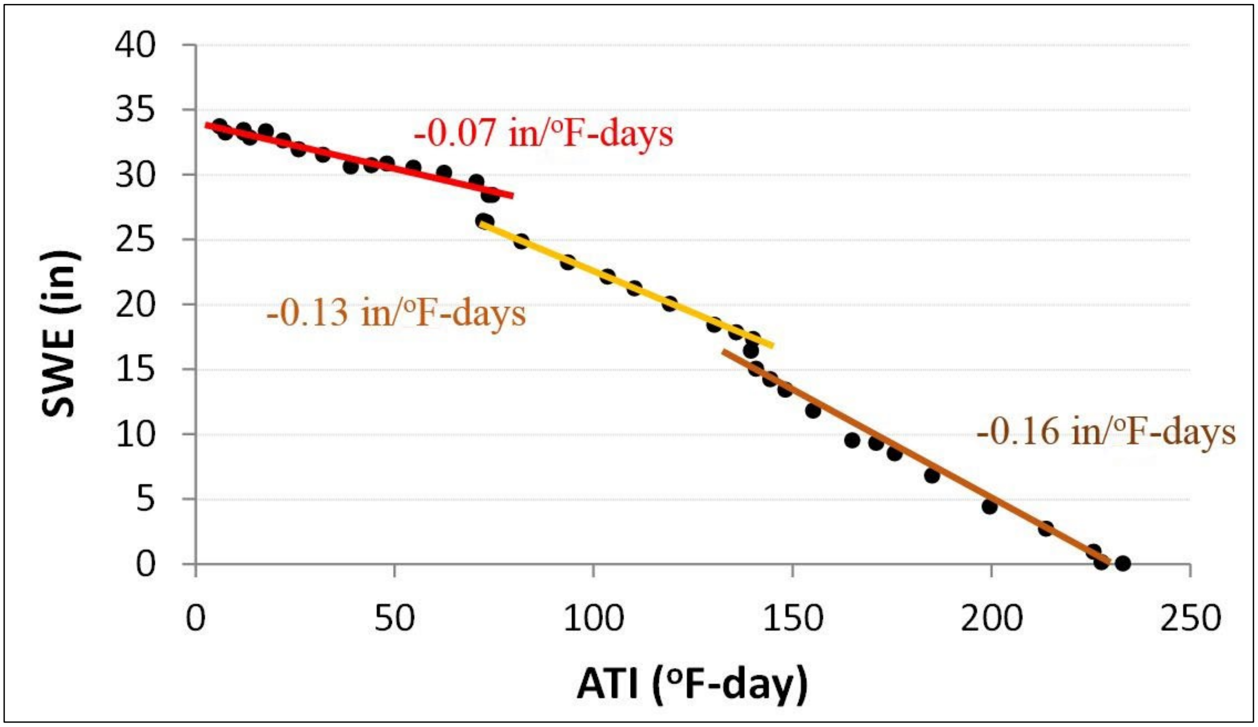

Figure 3-5. Snow Water Equivalent vs Antecedent Temperature Index during One Season at an Observational Site with Computed Segment Slopes.

Table 3-1. Sample Antecedent Temperature Index Meltrate Function

ATI (°F-days)	Meltrate (in/°F-days)
0	0.07
74	0.07
75	0.13
139	0.13
140	0.16
1000	0.16

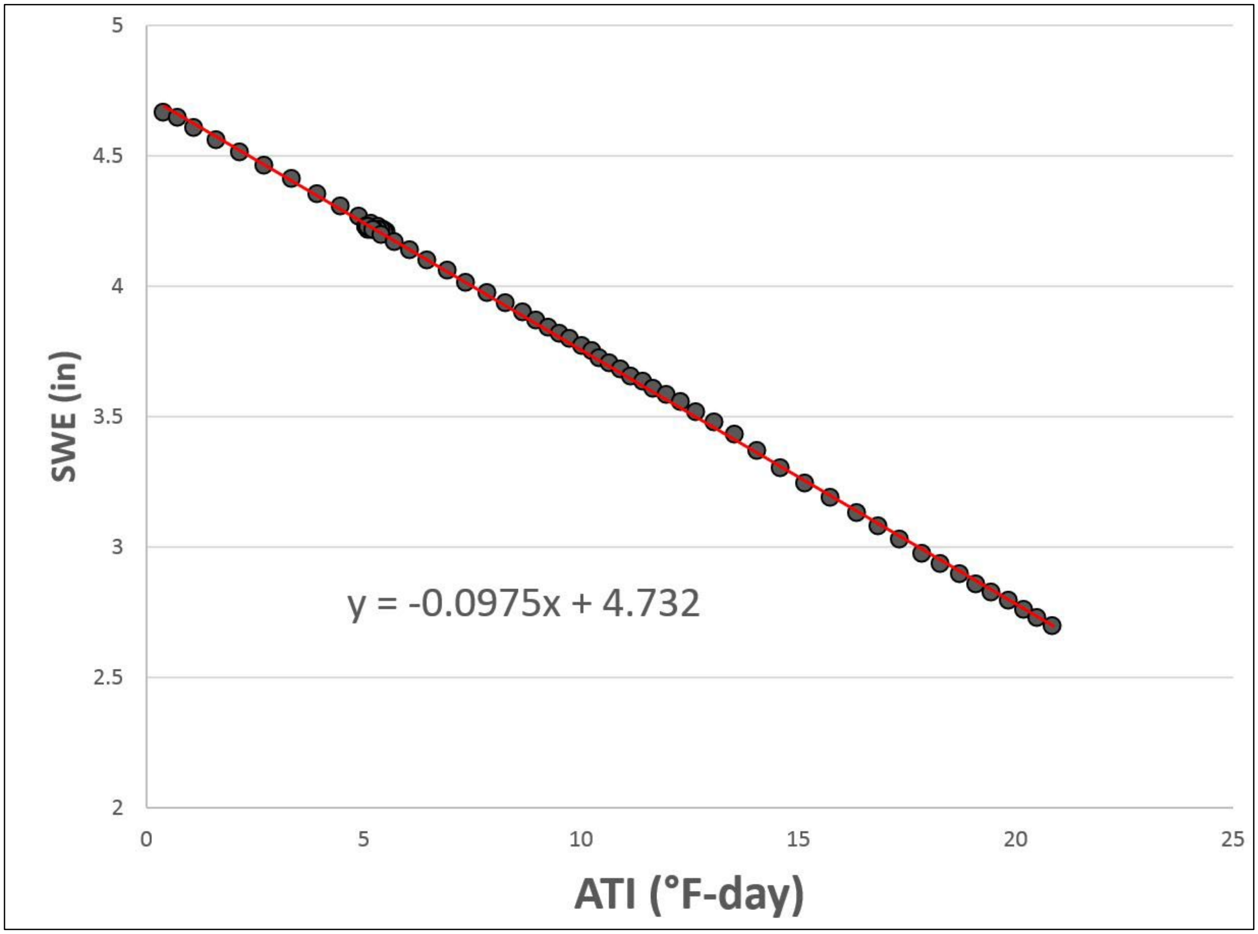

Figure 3-6. Snow Water Equivalent vs Antecedent Temperature Index Output from HEC-HMS

Snow meltrates are a function of the physical characteristics of a region, including forest cover, topography, and average weather conditions. A heavily forested basin where incoming solar radiation and wind are reduced will typically have lower meltrates than an open area. Basins with large variations in topography (i.e., slope and aspect) will generally have lower average meltrates across the basin than flat areas. Basins with heavy forest cover or generally cloudy or humid conditions have meltrates that vary less during the melt season than open, dry locations. When developing the ATI-Meltrate table it is important to understand how the basin characteristics affect the meltrates and analyze the available ground measurements.

3.5 INTERIM MODEL REVIEW (50 PERCENT MILESTONE REVIEW)

Once the HEC-HMS snow meteorologic model has been successfully calibrated, the team member submits the model and the draft report describing the snow model parameter development process for interim review. The report identifies any outstanding issues of which the watershed PDT, district, or USACE division should be made aware. The deliverables should include:

- Calibrated HEC-HMS temperature index snow parameters with historical precipitation, SWE, and temperature data

- Documentation of 50 percent progress.

3.6 INCORPORATE REVIEW COMMENTS

Comments from the interim review should be addressed and incorporated during the next phase of model development.

Section 4

Snowmelt Runoff Model Calibration and Verification

Although required input is different, calibration and verification of a HEC-HMS snowmelt model is similar to that of a rainfall runoff model. The purpose of calibration is to match the peak (flow and timing) and volume of historic events within the basin. This section describes event selection, calibration, verification, and determination of preferred parameter sets for snowmelt runoff modeling using HEC-HMS.

4.1 IDENTIFY SNOW EVENTS OF INTEREST

The type of snow data available often depends on the time period of interest. During this step, various historical snowmelt events should be identified with particular interest paid to recent years where data are most readily available. Types of snowmelt events that should be considered include years with a significant peak snowpack, years when the melt occurred late in the season (thus possibly resulting in a rapid melt-out and high flows), and events with combined rainfall precipitation and snowmelt contributing to runoff. Consultation with district water managers is recommended during the selection of calibration and verification events. Often it is easiest to select the same years which were used to calibrate the gridded snowmelt parameters, as many of the required inputs have already been developed

4.2 CALIBRATION OF HEC-HMS MODEL

To simulate a snowmelt runoff calibration event in HEC-HMS, observed streamflow, precipitation, and temperature data are required over the entire time period, as well as initial snow conditions at the start of the simulation. The basin model calibrated for rainfall runoff events should initially be used in the snowmelt runoff calibration. It is expected that most of the hydrologic parameters should remain the same regardless of the time of year. However, the initial loss and baseflow conditions will likely be different depending on the antecedent conditions. In addition, the process of seasonal snowmelt runoff is generally better represented by a multiple layer baseflow method that accounts for percolation and basin response, versus a single recession curve relationship which is better suited for event-based runoff. It is recommended that a linear reservoir baseflow method be used in basins where seasonal volumetric runoff is an important consideration in addition to peak flows.

If calibrating for numerous events, multiple basin models should be created to track parameters during calibration. Only events for which gridded precipitation/temperature data and streamflow records are available or can be developed should be used for calibration. If historical flow and meteorological data has not already been collected, it can be obtained and processed from the sources described above and in the MMC Technical Manual for CWMS. Calibration and verification of snowmelt runoff is similar to the process for the rainfall model. The modeler may choose to use optimization trials or to calibrate manually. The process described herein uses optimization trials, but is applicable to manual calibration as well.

4.2.1 Initial Basin Parameters

Initial basin parameters should be developed according to guidance provided in the MMC Technical Manual for CWMS, and as discussed at the initial CWMS model development kickoff meeting. The only difference for snowmelt model development may be in the selection of the linear reservoir method to model baseflow during snowmelt events. Additional guidance on method and parameter selection can be found in the HEC-HMS

Technical Reference Manual. Additional helpful references for developing the linear reservoir parameters are Fleming (2002) and Bennett and Peters (2000).

4.2.2 Creation of Optimization Trials

Once historic data is collected and entered into the HEC-HMS project, a new simulation run must be created for each historic event for which calibration will be conducted. Using the simulation run and observed streamflow data as inputs, a new optimization trial can be created from the compute menu in HEC-HMS. When creating the optimization trial, users must specify the HEC-HMS element being optimized for; only elements with observed flow can be selected. Only parameters at or upstream of the selected element will be evaluated and adjusted during the optimization trial. An optimization trial should be created for each gaged location within the watershed and not just at the outlet.

4.2.3 Parameter Search Method

The optimization trial can either adjust one parameter at a time while holding other parameters constant (univariate gradient method) or evaluate all parameters simultaneously and determine which parameters to adjust (Nelder and Mead method); for CWMS the Nelder and Mead method is recommended. The optimization method can be specified by clicking on the optimization trial under the compute tab of the Watershed Explorer and selecting the appropriate method in the component editor. The tolerances and number of iterations should remain at the default values.

4.2.4 Objective Function

The objective function measures the goodness of fit between the computed outflow and the observed streamflow at the selected element. Several functions are available for measuring goodness of fit; however, the peak weighted RMS error function is recommended for CWMS. The objective function used in the optimization trial can be specified in the component editor for the objective function.

4.2.5 Specify Parameters

Parameters that will be adjusted should be added to the optimization trial by right clicking the optimization trial in the watershed explorer and selecting add parameter. Select the watershed element and associated parameter to be evaluated during the optimization process. Leave the default values for minimum and maximum. Add as many parameters for as many watershed elements as needed to calibrate the model.

4.2.6 Optimization Trial Simulation

Run the optimization trial and view results and recommended optimization parameters for each trial under the results tab of the watershed explorer. Iteratively, continue adjustments to watershed parameters until all targets are met; if any locations exist where calibration targets cannot be achieved. Then, reevaluate the model configuration, boundary conditions, basic characteristics, and reasonability of calibration targets. For additional discussion on model calibration refer to the HEC-HMS User’s Manual and Technical Reference.

4.3 VERIFICATION OF HEC-HMS MODEL

Once the model is calibrated to historic events, model adequacy is verified by running other snow events that were not used in the calibration. The verification events should be entered into the HEC-HMS project as observed data (streamflow, precipitation, temperature, and initial snow) and a new control specification and simulation created for each event. Calibration targets are set appropriately by the team lead based on schedule and funding limits, and are targeted to provide best calibration results within the given team schedule. It is expected that the district will further calibrate and validate the models.

4.4 DEVELOPMENT OF FINAL SUGGESTED PARAMETER SET

The HEC-HMS modeler should compare output from the verification simulation runs to the observed streamflow data. If the simulation does not adequately match the observed data, further adjustment to model parameters may be needed, using the same procedure described for the calibration process. Once adjustments to watershed parameters have been made for the verification events, the user will re-run all events used in both the calibration and verification processes. This may be an iterative process until reasonable calibration targets are met for the events.

4.5 DOCUMENTATION OF CALIBRATED/VALIDATED HEC-HMS MODEL

Documentation describing model development and the calibration process should be prepared to supplement the model deliverables once model development and calibration is complete. This documentation should be included in the final watershed report.

4.6 INTERIM MODEL REVIEW (75 PERCENT MILESTONE REVIEW)

The calibrated model, with supporting documentation and data, should be delivered to the team lead and district PDT for review. For more information on the review process, refer to Section 2 of the MMC Technical Manual for CWMS.

4.7 INCORPORATE REVIEW COMMENTS

Any comments received from the review should be addressed and incorporated into the model as needed before the final submittal.

Section 5

Model Testing and CAVI Integration

Calibration and verification of the HEC-HMS model concludes major model development. The remaining tasks primarily focus on preparing the model for incorporation into CWMS, and follow the same process for snowmelt and rainfall model development. For more information on the model testing and integration process, refer to Section 2 of the MMC Technical Manual for CWMS.

Section 6
Sources of Information

This section provides information on data and documentation that may be relevant to the development of snowmelt models for CWMS implementation.

6.1 MISCELLANEOUS DATA SOURCES

Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS). 2019. “CoCoRAHS Website.” Accessed August 28. https://www.cocorahs.org/

European Centre for Medium-Range Weather Forecasts (ECMWF). 2019. “Climate Reanalysis.” Accessed August 28. https://www.ecmwf.int/en/research/climate-reanalysis

National Aeronautics and Space Administration (NASA). 2019. “MODIS and VIIRS Snow and Ice Global Mapping Project.” Accessed August 28. https://modis-snow-ice.gsfc.nasa.gov/

——— Global Modeling and Assimilation Office. 2019. “MERRA: Modern-Era Retrospective Analysis for Research and Applications.” Accessed August 28. https://gmao.gsfc.nasa.gov/reanalysis/MERRA/

——— Oak Ridge National Laboratory–Distributed Active Archive Center (ORNL DAAC). 2019. “Daily Surface Weather and Climatological Summaries (Daymet).” Accessed August 28. https://daymet.ornl.gov/

National Climatic Data Center (NCDC). 2019. “Snow and Ice Data and Products.” Accessed August 28. https://www.ncdc.noaa.gov/snow-and-ice/

——— 2019. “Climate Data Online Search.” Accessed August 28. https://www.ncdc.noaa.gov/cdo-web/search

National Oceanic and Atmospheric Agency (NOAA). 2019. “National Operational Hydrologic Remote Sensing Center.” Accessed August 28. http://www.nohrsc.noaa.gov/

——— 2019. “Radar Data in the NOAA Big Data Project.” Accessed August 28. https://www.ncdc.noaa.gov/data-access/radar-data/noaa-big-data-project

——— Earth Sciences Research Laboratory, Physical Sciences Division. 2019. “NCEP North American Regional Reanalysis.” Accessed August 28. https://www.esrl.noaa.gov/psd/data/gridded/data.narr.html

National Snow and Ice Data Center. 2019. “NSIDC Website.” Accessed August 28. http://nsidc.org/

Northwest Alliance for Computational Science and Engineering. 2019. “PRISM Climate Data”. Accessed August 28. http://www.prism.oregonstate.edu/

U.S. Department of Agriculture, Natural Resources Conservation Service. 2019. “Snow Telemetry (SNOTEL) and Snow Course Data and Products.” Accessed August 28. https://www.wcc.nrcs.usda.gov/snow/

6.2 SOFTWARE PUBLICATIONS

The following publications can be found at: http://www.hec.usace.army.mil/publications/

Hydrologic Engineering Center (HEC). 2018. *CWMS User’s Manual.* Davis, CA: U.S. Army Corps of Engineers.

——— 2009. *HEC-DSSVue Data Storage System Visual Utility Engineer User's Manual*. Davis, CA: U.S. Army Corps of Engineers.

———2013. *HEC-GeoHMS Geospatial Hydrologic Modeling Extension User's Manual*. Davis, CA: U.S. Army Corps of Engineers.

——— 2017. *HEC-HMS Hydrologic Modeling System Applications Guide.* Davis, CA: U.S. Army Corps of Engineers.

——— 2018. *HEC-HMS Hydrologic Modeling System Quick Start Guide*. Davis, CA: U.S. Army Corps of Engineers.

——— 2000. *HEC-HMS Hydrologic Modeling System Technical Reference Manual.* Davis, CA: U.S. Army Corps of Engineers.

——— 2018. *HEC-HMS Hydrologic Modeling System User's Manual.* Davis, CA: U.S. Army Corps of Engineers.

——— 2019. *HEC-MetVue Meteorological Visualization Utility Engine User's Manual.* Davis, CA: U.S. Army Corps of Engineers.

6.3 UNITED STATES ARMY CORPS OF ENGINEERS PUBLICATIONS

Modeling, Mapping, and Consequences Production Center. 2017. *Modeling, Mapping, and Consequences Technical Manual.* U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers. 1956. *Snow Hydrology: Summary Report of the Snow Investigations.* Oregon: North Pacific Division, Portland

———. 1991. *SSARR Model Streamflow Synthesis and Reservoir Regulation User's Manual,* D-15-17. Oregon: North Pacific Division, Portland District. D-15–D-17.

———. 1994. *Engineer Manual 1110-2-1417: Flood Runoff Analysis*. Washington, D.C.: U.S. Army Corps of Engineers

———. 1998. *Engineer Manual 1110-2-1406: Runoff from Snowmelt.* Washington, D.C.: U.S. Army Corps of Engineers

6.4 PROSPECT COURSES

HEC (Hydrologic Engineering Center). PROSPECT Course 178: *Hydrologic Modeling with HEC-HMS.*U.S. Army Corps of Engineers.

———. PROSPECT Course 219: *Hydrologic Engineering Applications for GIS.*U.S. Army Corps of Engineers.

———. PROSPECT Course 369: *Advanced Applications of HEC-HMS*. U.S. Army Corps of Engineers.

6.5 OTHER SOURCES

Bennett, T. and J. Peters. 2000. "Continuous Soil Moisture Accounting in the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS)", Building Partnerships: pp. 1-10, doi: 10.1061/40517(2000)149.

Daly, S.F., E.S. Ochs, P.F. Brooks, and T. Pangburn, 1999. "Distributed snow process model for use with HEC-HMS", In *Proceedings, ASCE Conference on Cold Regions Engineering*, American Society of Civil Engineers.

Fleming, M. 2002. “Continuous Hydrologic Modeling with HMS: Parameter Estimation and Model Calibration and Validation.” Master’s Thesis, Tennessee Technological University.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. ASABE, 885-900.

Reclamation. 2014. “Gridded Snow Water Equivalent Data Set Development – Processing Methods Using the Geospatial Data Abstraction Library,” Dam Safety Technology Development Program.

List of Acronyms and Abbreviations

ATI	Antecedent Temperature Index
ATICC	Antecedent Temperature Index for Cold Content
ATIMR	Antecedent Temperature Index for Meltrate
CAVI	Control and Visualization Interface
CC	Cold Content
CRREL	Cold Regions Research and Engineering Laboratory
CWMS	Corps Water Management System
DSS	Data Storage System
DSSVUE	Data Storage System Visual Utility Engine
ECMWF	European Centre for Medium-Range Weather Forecasts
EM	Engineer Manual
GeoHMS	Geospatial Hydrologic Modeling Extension
GIS	Geographic Information Systems
HEC	Hydrologic Engineering Center
HEC-HMS	Hydrologic Modeling System
HEC-MetVue	Meteorological Visual Utility Engine
KM	Kilometer
MERRA	Modern Era Retrospective-Analysis for Research Applications
MMC	Modeling, Mapping, and Consequences
MODIS	Moderate Resolution Imaging Spectroradiometer
MPE	Multisensory Precipitation Estimator
NASA	National Aeronautics and Space Administration
NCDC	National climatic Data Center
NCEI	National Center for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Model Efficiency
NSIDC	National Snow and Ice Data Center
NWS	National Weather Service
PDT	Project Delivery Team
PRISM	Parameter-elevation Relationships on Independent Slopes Model
PX	Precipitation Discrimination

R	Pearson Correlation Coefficient
RFC	River Forecasting Center
RMSE	Root Mean Squared Error
SCA	Snow Covered Area
SNODAS	Snow Data Assimilation System
SNOTEL	Snow Telemetry
SOP	Standard Operating Procedure
SWE	Snow Water Equivalent
USACE	U.S. Army Corps of Engineers
VIIRS	Visible Infrared Imaging Radiometer Suite

Glossary

Cold Content. The amount of energy required to raise a snowpack to 0º C.

Liquid Water Content. Liquid water being stored within a snowpack. Temperature must be above freezing.

Ripeness. The degree of maturity of a snowpack as measured by the internal temperature, character of snow crystals, and liquid-water content.

Snow Density. The mass per unit volume of snow. More commonly, it is expressed as a percentage of the depth of SWE divided by the depth of snow (i.e., 1 inch SWE/10 inch Snow = 10 percent)

Snow Depth. The depth of snow (ice crystals) measured on the ground.

Snowmelt (Ablation). Timing and magnitude of the snow melt process.

Snow Water Equivalent (SWE). The equivalent depth of water within a snowpack

Temperature Index. A simplified method of computing snowmelt in which the air temperature is used to index all the energy sources involved in the melt process.

Water Capacity. Amount of melted water that must accumulate in the snowpack before liquid water becomes available at the soil surface.