Montana Dam Safety Program

TECHNICAL NOTE 11
GUIDANCE MANUAL FOR HIGH FREQUENCY STORM RAINFALL RUNOFF MODELS

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COMMENTS AND FEEDBACK

The Montana Dam Safety Program (MT DSP) is pleased to provide this guidance manual for high-frequency storm rainfall-runoff models. We hope this publication is helpful in providing technical guidance to professionals across Montana. Our intent is to make available relevant and up-to-date information, references, and procedures, much of which is unique for Montana.

This is the first publication of this guidance manual. MT DSP's goal is to offer the best guidance we possibly can, and we welcome and encourage your feedback on the contents of this manual. Please send your comments to:

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MONTANA DAM SAFETY PROGRAM
GUIDANCE MANUAL FOR HIGH FREQUENCY STORM
RAINFALL RUNOFF MODELS

1.0 INTRODUCTION AND PURPOSE

The Montana Dam Safety Program (Dam Safety), which is part of the Department of Natural Resources and Conservation (DNRC), regulates the construction, operation, and maintenance of Montana's dams to protect life and property from damages due to failure. Part of the duties required of Dam Safety is to apply safety restrictions to dams with deficiencies to minimize the risk of failure. Many times, these restrictions include maintaining reservoir levels below normal operating levels to allow more inflow storage. Higher storage minimizes either prolonged hydrostatic loading on the dam embankment or flow over the emergency spillway, depending on the dam's deficiencies. However, Dam Safety struggles with the decision on what restriction level is appropriate for each dam in question. Data to make the decision is often lacking. Therefore, the purpose of this manual is to provide guidance on how to model rainfall-runoff inflow events that have a relatively high probability of occurrence so that Dam Safety can make appropriate level restriction decisions based on best-available information.

This manual can also be used to model frequent storm inflows for the purpose of determining the effects during construction projects. Nearly all construction projects on dams require reservoir level restrictions to maintain the safety of the dam. Since these restrictions are essentially the same as the restrictions for dam safety concerns, this manual is appropriate for use during construction projects.

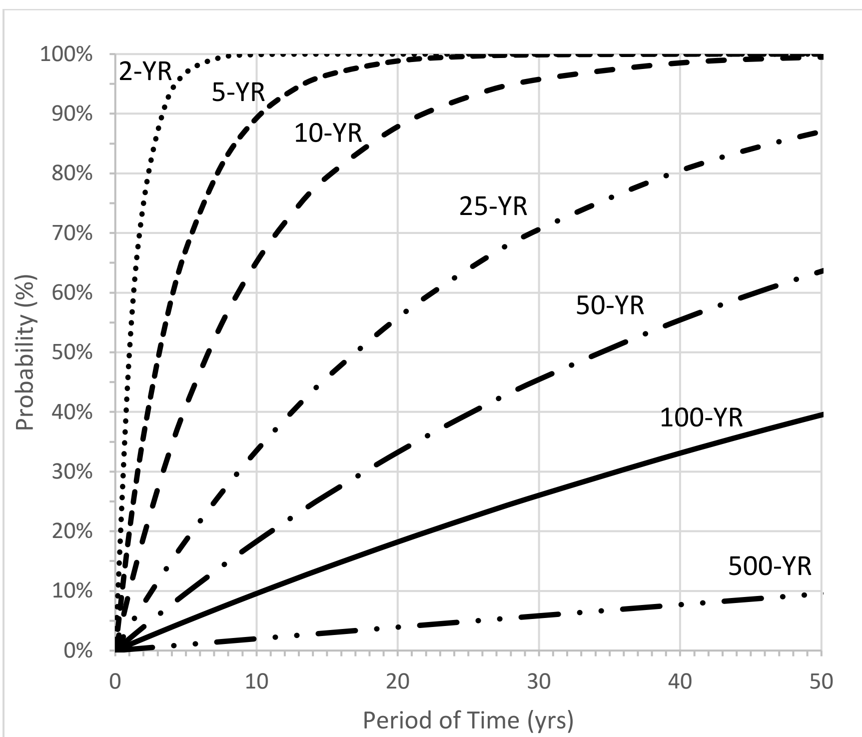
Users of this manual should have a basic understanding of hydrologic analysis, especially related to dam safety. It is not necessary to be proficient in the use of the rainfall-runoff model HEC-HMS (see below) to use this manual, but a basic understanding of the model will help with its application in this manual.

Although the primary use of this manual will be for evaluating the impact of frequent storms on reservoir levels, the principals apply to many other applications, including the evaluation of retention basins, as well as verifying extreme storm rainfall-runoff models.

“High frequency” in terms of dam safety hydrology may have a different meaning and implication compared to other hydrologic disciplines. Inflow design floods for dam safety in Montana are in orders of magnitude that range from 500-year return frequencies to Probable Maximum Floods (PMFs). Therefore, high frequency floods for dam safety range from 5- to 100-year return periods. To many in other disciplines concerned with high-frequency runoff events, these storm ranges are not considered very “frequent.” But the storms considered for the purpose of imposing level restrictions for dams (5- to 100-year return periods) are appropriate when considering the safety of dams.

The likelihood of one of these “high frequency” storm events occurring over time is an important consideration when assessing the length of time that a restriction will be in place for on a reservoir. The longer that the restriction is in place, the higher the probability that one (or more) of these high frequency storms will occur over that time. Figure 1-1 (taken from USDA-NRCS Technical Release 55 (TR-55) (USDA-NRCS, 1986)) shows the probability of different frequency storm events occurring over time.

FIGURE 1-1. PROBABILITY OF STORM EVENT OCCURRING OVER TIME



Dam Safety conducts rainfall-runoff modeling of these high frequency storms with the U.S. Army Corps of Engineers' program HEC-HMS (Hydrologic Engineering Center, Hydrologic Modeling System). HEC-HMS is a powerful software with advanced modeling capabilities, but for the rainfall-runoff analyses considered in this manual, the model will utilize traditional, less involved techniques to facilitate rapid assessments of high frequency storm impacts. This manual will provide guidance on:

- The basic requirements of HEC-HMS.
- Recommended model input resources for:
  - Basin (watershed) data.
  - Dam and reservoir data.
  - Meteorological (rainfall) data.
- The process for verifying the model.
- Storm inflow and effects on reservoirs.

It is important to note that infiltration parameters typically vary according to the frequency of a storm. Extreme storms are often preceded by many days of soaking rain or snow and the drainage basin soils may close to saturation. A more frequent storm is likely to have higher infiltration rates. When verifying an extreme storm model with a high frequency storm model, it is important to realize the infiltration parameters may be different. There are no easy solutions to this verification challenge; advice for dealing with this situation is provided in the manual.

2.0 HEC-HMS BASICS

As mentioned in Section 1.0, HEC-HMS is a rainfall-runoff model that allows the simulation of rainfall, determines the losses due to infiltration and storage, computes runoff, and routes the runoff through a reservoir. The program is a Windows-based software that is reasonably user-friendly, but, as with all computer programs, is sensitive to the input it receives. This section will describe the basic format and function of HEC-HMS. It is assumed that users of this manual have at least a rudimentary knowledge of HEC-HMS and hydrology in general, with specific knowledge of hydrology related to dam safety.

The HEC-HMS model has two main input components: watershed physical parameters and meteorology parameters. There are input elements within each of the main components. The hydrologic elements are connected in a modeled network. Model computation proceeds from upstream elements in a downstream direction. For the analyses used by this manual, the computation ends in the reservoir impounded by a dam.

2.1 WATERSHED PHYSICAL PARAMETERS

The elements representing the physical watershed are described below. Most cases applicable for this guidance manual are relatively straightforward: rainfall on a watershed that produces runoff that flows to a reservoir. This will not cover routing of the runoff hydrograph down a stream network. Therefore, the only elements used to represent the watershed are the subbasin and the reservoir. This section of the manual explains the components of the model only. Section 3.0 provides resources for obtaining the data for each of the components.

2.1.1 Subbasin Parameters

The subbasin is the watershed itself. Its function is to simulate infiltration losses, transform the excess precipitation into surface runoff, and model baseflow for the basin.

2.1.1.1 <u>Drainage Area</u>

The parameter that has the highest influence on the magnitude of runoff from a watershed is drainage area. Area is perhaps the easiest parameter to obtain, but very important in runoff determination.

2.1.1.2 <u>Infiltration</u>

HEC-HMS offers five methods of simulating infiltration losses during a short-term rainfall event. The most common method used by Dam Safety is the SCS Curve Number method. The Curve Number method provides constant infiltration rates after soil saturation, and it has a feature to automatically account for an initial abstraction of the rainfall at the beginning of the storm.

2.1.1.3 <u>Unit Hydrograph</u>

HEC-HMS transforms the excess rainfall left after infiltration into surface runoff by a unit hydrograph. For Montana watersheds, the U.S. Geological Survey produced data for two unit hydrograph methods: the Clark method and the dimensionless unit hydrograph method (input into HEC-HMS as a User-Specified Hydrograph). Because of its simple input functions, the Clark method is most widely used.

2.1.1.4 <u>Baseflow</u>

Baseflow may be the subbasin component that poses the most challenges to incorporate into the model. For larger storms, such as dam safety inflow design floods, baseflow represents a small fraction of the total storm runoff. But for frequent storms, baseflow may be a significant contributor of storm runoff, and quite possibly the dominant runoff factor for small drainage basins. There are, however, tools to help determine baseflow and those will be discussed in Section 3.0.

2.1.2 Reservoir Parameters

The reservoir impounded by the dam in question can be characterized by storage data that has already been determined in previous reports, or by estimates based on topographic data surrounding the reservoir basin. The input parameters are stored in Paired Data files within

HEC-HMS and are input either as storage-elevation or area-elevation data. HEC-HMS computes storage volumes based on the data input to the model.

2.2 METEOROLOGICAL PARAMETERS

Meteorological data, or rainfall data, is input as hyetographs (incremental rainfall depths over time) into Time-Series files within HEC-HMS. There are many options available in HEC-HMS to generate rainfall hyetographs, but for the purpose of frequent storms, the Specified Hyetograph option will be the only one discussed in this report. There are Montana-specific procedures for determining storm depths and hyetographs that are then easily copied into Specified Hyetographs time-series files within HEC-HMS. These procedures will be discussed in Section 3.0.

2.3 CONTROL SPECIFICATIONS

Control specifications are the part of HEC-HMS that control the computational process and provide user-specified output. From the HEC-HMS User's Manual, the control specifications' "principal purpose is to control when simulations start and stop, and what time interval is used in the simulation." (COE, 2021) Since synthetic storms are not dependent on a specific time-period, unless a PRISM-generated or other historical storm is being modeled, the model simulation dates are not important, as long as the same simulation dates match throughout the model. The time interval used for the precipitation gages must be within the control specifications dates; the control specifications also determine which baseflow data are used for the constant monthly baseflow method, as described in Section 3.0. The most important aspect is to maintain a reasonable time interval for output results. For a dependent storm interval of 24 hours, the USGS hyetograph method will extend the storm period to 72 hours. For this case, it is reasonable to maintain a 1-hour time interval for output information. Shorter storm durations should have shorter time intervals. It is up to the user to exercise their professional judgment. The model is fully capable of handling shorter time intervals, regardless of storm duration. If identifying the exact time of peak flow or maximum reservoir elevation, shorter time intervals make sense. In any case, it is always prudent to run a model with a short time interval as a check to verify that the peak of the storm is not being missed.

2.4 TIME-SERIES DATA

Time-series data are entered into Time-Series files for use with HEC-HMS. Time-series data, as the name suggests, are data that provide incremental values that change over time – the main examples being precipitation data or discharge data. There are sixteen types of time-series data "gages" that can be used with HEC-HMS, from precipitation to sunshine gages. For this report, the only time-series data that will be used for high frequency storms will be precipitation gages in the rainfall-runoff simulations. However, discharge gages may be used during pseudo-calibration efforts to verify model results for rainfall-runoff simulations.

2.5 PAIRED DATA

Paired data are part of the HEC-HMS component shared data options, which connect data to program functions. An example of this, which is necessary for the type of analyses covered in this report, is to enter reservoir storage-elevation data into the paired data editor to be used as reservoir parameters.

2.6 TERRAIN DATA

HEC-HMS has recently incorporated sophisticated terrain data modeling capabilities. Terrain data are used in the delineation process and may also be used to visualize the relief of a watershed as a base map. For rapid calculation of high-frequency storm runoff, the analyst can proceed without using terrain data. However, use of terrain data is relatively straightforward, and the analyst may find that it assists in delineating multiple subbasins for a model, developing graphics to communicate with decision-makers, or with more advanced analyses. Appendix A provides information on preparing and using terrain data in HEC-HMS.

3.0 DATA SOURCES FOR HIGH-FREQUENCY STORM MODELS

The sources for data provided in this section are common to typical rainfall-runoff models in Montana. Specific input suggestions for high-frequency storm simulations related to dam safety analyses are provided. Numerous resources have been developed specifically for Montana, which allow the user at least some confidence in site-specific data, but the user is also warned that many of the studies used to develop the resources are plus-or-minus twenty years old and may not accurately represent current conditions. But the resources are the best available at this time and are better than other currently available regional or national data that are not based on local or state-wide conditions.

3.1 DATA SOURCES FOR BASIN CHARACTERISTICS

This section will cover the data sources for HEC-HMS components identified in Section 2.1. Full reference citations for the data sources are listed in Section 7.0, References.

3.1.1 Drainage Area

The current tool most widely used for measuring basin drainage area is StreamStats® (USGS, 2018). StreamStats is an online application (https://streamstats.usgs.gov/ss/) that provides analytical tools based on Geographical Information System (GIS) data that are used for water-resources planning and management, and for engineering and design purposes. The system has a map-based user interface that can delineate drainage areas selected by the user on streams, and then get basin characteristics and estimates of flow statistics for the selected sites.

3.1.2 Infiltration and Ground Cover

Basin infiltration characteristics, or "Loss Method" as it is referred to in HEC-HMS, can be determined by many different methods available in HEC-HMS. *The method that seems to be appropriate for most applications for drainages in Montana is the SCS Curve Number method.* The SCS Curve Number method is described in depth in the United States Department of Agriculture (USDA)-Natural Resources Conservation Service (NRCS) Publication – Urban Hydrology for Small Watersheds, (TR-55) (https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf). For small drainage basins, it is appropriate to estimate an average Curve Number (CN) for the basin. For larger basins, dividing it into subbasins of either similar soil types or into hydrologic tributaries may provide more accurate results. Infiltration properties using the CN method are based both on the soil type and ground cover. The best scenario would be if local and detailed data exists on soil types within a basin. Since that is rarely the case, the next best data sources are the USDA-NRCS (Natural Resources Conservation Service) Web Soil Survey® (USDA-NRCS, 2019) online application and the National Land Cover Database (NLCD). In the Web Soil Survey (WSS), the user interface allows delineation of drainage basins, and then provides the user with a digitized map of published surface soils within the basin. It determines the area of each separate soil map unit and presents it as a percentage of the whole basin. Of importance for dam safety applications, the WSS provides the Hydrologic Soil Group for each soil type.

NLCD products are created by the Multi-Resolution Land Characteristics (MRLC) Consortium, a partnership of Federal agencies led by the U.S. Geological Survey (USGS 2012). The NLCD provides land cover and land condition data based on Landsat satellite imagery and supplementary datasets, as of the date of this publication, the most recent data are from 2019; updates are published periodically every few years. Areas of interest can be downloaded from the MRLC's viewer website (https://www.mrlc.gov/viewer/) and subsequently trimmed to the boundaries of the watershed being studied using GIS software. The user can then analyze the dataset that has both NLCD and WSS information to assign curve numbers to each type of land cover/hydrologic soil group combination. The user can determine the CN by using the tables in the NRCS Hydrologic Soil-Cover Complexes publication (USDA-NRCS, 2004), where tables for various geographical and land-use settings with different types of ground cover provide ranges of CN values. CN is dependent on the cover type, the soil hydrologic condition (poor, fair, good) and the hydrologic soil group (A through D). A basin-wide CN can be developed by weighting based on acreages.

Consideration of the effects of wildfire on the hydrology of a watershed is becoming more important, especially with respect to recent drought conditions and planning for climate change. The near-term effects of wildfires in natural basins are to reduce infiltration losses and to drastically increase direct runoff from a basin. Two guidance references are provided here for modeling basins affected by wildfire:

- USDA-NRCS Technical Note 4: Hydrologic Analysis of Post-Wildfire Conditions (August 2016); and
- State of Washington Department of Ecology. Recommended dam safety protocols for burned watershed hydrology calculations, Publication no. 15-11-013 (Revised April 2018).

3.1.3 Unit Hydrograph

HEC-HMS offers various methods for determining the basin unit hydrograph, or the "Transform Method" as it is referred to in HEC-HMS. If the basin has a streamflow gage, it should be used in determining the unit hydrograph. If not, as will be the case in most drainage basins in Montana, then a synthetic unit hydrograph needs to be developed. The user can use whatever method provides what is deemed to be appropriate. The USGS has developed methods for determining unit hydrographs for ungaged basins in Montana, using gaged-stream data (USGS, 1996). In their publication, the USGS focused on two unit hydrograph methods: the Clark Method and the Dimensionless Unit-Hydrograph Method. *For ease of use, the Clark Method is recommended*. The Dam Safety Program has available a spreadsheet application for the USGS Clark Method as developed for Montana, which computes the basin time of concentration (Tc) in hours, and the basin-storage coefficient (R) in hours. The basin-storage coefficient is determined for "mountain" and "plains" sites. It is up to the user to determine which is appropriate, based on the basin location.

3.1.4 Baseflow

For high-frequency storm applications, baseflow can be a significant contributor to inflow into a dammed reservoir. This component may be the most subjective input parameter of all the subbasin characteristics. The absolute best source of baseflow information is through gage data, if available. Otherwise, determining reasonable values for baseflow is a combination of experience and judgment appropriate for the basin in question. HEC-HMS offers several methods for determining baseflow, most of which are appropriate for the recession end of a storm hydrograph. *For high-frequency storm applications, the Constant Monthly baseflow method appears to be the most versatile and can be adjusted to the season for which the simulated storm takes place.* "Constant Monthly" is a bit misleading because in HEC-HMS, separate average baseflow values can be input for each month of the year. The user can determine the values. If actual stream data is not available, there are other sources of information available. One source is StreamStats, which provides monthly flow statistics for ungaged basins. This type of report results in mean flows for each month for the delineated basin. The user should use caution with using this type of data because the mean flow is determined using all storms within the region that are distributed based on basin size. Therefore, if the mean flow value is used with, say, a 10-year return period storm, it could dominate the inflow hydrograph into a reservoir. The values used for each month should be carefully selected with input from all available sources and also coordination with the Dam Safety Program to help determine reasonableness.

3.2 DATA SOURCES FOR METEOROLOGICAL METHODS

For high-frequency storms, rainfall will be the input parameter to generate inflow floods to a reservoir. Snowmelt will not be considered unless there is compelling reasons to do so. We are fortunate to have two resources developed by the USGS specifically for Montana to determine rainfall depths and storm hyetographs. These are discussed in detail below.

3.2.1 Rainfall Depth Determination

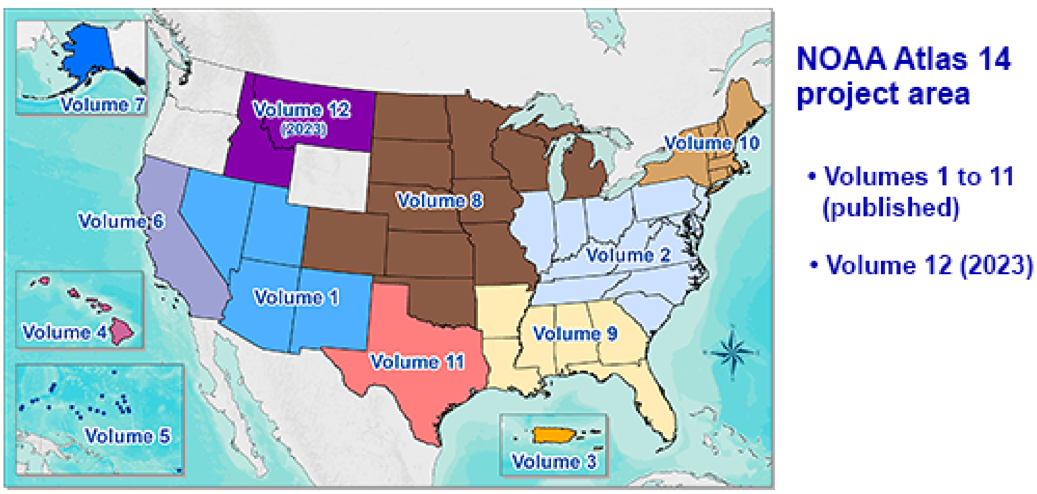
There are different methods to determine rainfall depths for various return frequencies, but the USGS has developed a methodology using Montana rainfall data to come up with rainfall depths for return frequencies ranging from 2- to 5,000-years and durations of 2-, 6-, and 24-hours (USGS, 1997). The methods vary within three geographical regions in the state. The publication is nearly 25 years old, which is an indication that it should be updated, but it is currently the best data available for this purpose. The Dam Safety Program has available a spreadsheet application for using the USGS rainfall depth determination method.

In the relatively near future, precipitation estimates for frequent storms in Montana will be available using the National Oceanographic and Atmospheric Administration (NOAA) Atlas

14. NOAA Atlas 14 has been developed for much of the United States and it is scheduled to be completed for Montana in 2023 (See Figure 3-1). To find out more, the user can visit https://hdsc.nws.noaa.gov/hdsc/pfds/index.html, which is a link to the National Weather Service precipitation data server and will demonstrate on how the Atlas will be used when finalized.

FIGURE 3-1. PROGRESS ON NOAA ATLAS 14 DEVELOPMENT

(from https://www.weather.gov/owp/hdsc_current_projects)



3.2.2 Storm Hyetograph Determination

Accompanying the rainfall depth determination method as described above, the USGS also developed methods for determining the hyetographs for rainfall storm depths for the state of Montana (USGS, 1998). Using rainfall depth distributions for historical storms, the USGS came up with statistically probable depth distributions for the same three geographical regions used for the depth study. To assess the effects of pre- and post-storm precipitation, the USGS method extends the 2-, 6-, and 24-hour independent storm durations to 6-, 18-, and 72-hour duration hyetographs, respectively. The Dam Safety Program has available a spreadsheet application for using the USGS storm hyetograph method.

3.2.3 PRISM

The PRISM Climate Group is based out of Oregon State University and "gathers climate observations from a wide range of monitoring networks" (PRISM Climate Group website www.prism.oregonstate.edu) and develops datasets that account for terrain effects to evaluate short- and long-term climate patterns. A brief supplement to TN1 discusses the use of PRISM data and is included in Appendix B. PRISM allows the modeler to verify a model against precipitation data from an actual storm. The modeler should note that this requires good records at the reservoir (gaged flows, outlet discharge, reservoir levels, etc.) that may not be available.

It is also important for the user to note that the PRISM data is generated by NEXRAD (Next Generation Weather Radar), which is a network of weather radars that are jointly operated by the National Weather Service, the Federal Aviation Administration, and the U.S. Air Force. There are four radars located in Montana: Missoula, Great Falls, Billings, and Glasgow. PRISM's precipitation data quality may be affected by the site's distance from one of the radar locations.

4.0 MODEL VERIFICATION

Any synthetic storm model should be checked for some level of accuracy. Technical Note 1 (TN1) (DOWL, 2019) provides an excellent resource for understanding the steps in conducting calibration or pseudo-calibration analyses for a rainfall-runoff model. TN1 is developed specifically for inflow design floods for dam safety purposes, so the storms considered in TN1 are very large compared to the storms used in this manual. This section is limited to the discussion of higher frequency storms. However, model verification can be a complex process, regardless of the storm frequency, so it is recommended that the user consult TN1 for the details in verification through calibration or pseudo-calibration. If using a high frequency storm model to verify an extreme storm model, it is imperative that uncertainty be considered; TN1 has details. This section provides only general guidance for conducting a rapid evaluation of high frequency storm impacts, without much attention to uncertainty.

TN1 also provides useful definitions used in the processes of checking model accuracy. The definitions, abbreviated here, are:

- Verification - the process of comparing flood frequency results from a hydrologic model to flood frequency estimates developed from an independent method.
- Calibration - the process of adjusting the parameters of a hydrologic model to replicate a measured (or observed) event.
- Pseudo-calibration - the process of adjusting the parameters of a hydrologic model to reasonably approximate a range of flood frequency values obtained independently; for example, comparing results to flood magnitude estimates computed using the USGS regional regression equations.

4.1 SUGGESTED PARAMETERS FOR ADJUSTING A MODEL

The goal of adjusting a model for calibration or pseudo-calibration purposes is to arrive at parameters that help produce verified results. This accomplished in two general ways: adjustment of loss parameters (such as infiltration) or adjustment of routing parameters (for the unit hydrograph). As mentioned in TN1, the user should be aware that adjustment of loss parameters, such as Curve Number, changes runoff volume, while adjustment of the routing parameters, or the unit hydrograph, adjusts the shape of the storm hydrograph without change to runoff volume.

4.1.1 Loss Parameters

The basin loss parameter that is most commonly used to adjust a model is the Curve Number (CN). Adjusting the percentage of impervious areas is also used, but caution is advised in doing this. It is tempting to use parameters such as initial abstraction or baseflow, but it is recommended that those two parameters not be used in verification and there are reasons the user should use caution when considering these as verification parameters.

First, initial abstraction is inherently tied to CN, and it is recommended to allow the model to automatically determine initial abstraction. Initial abstraction is a highly variable parameter, dependent not only on soil type, but also on hydrologic conditions of the basin preceding the storm in question. Because of the natural link to CN, initial abstraction should remain as a parameter that is automatically selected by the model and not independently changed by the user in verification efforts. This makes the model unnecessarily complicated and outside of the scope of this manual.

Second, the use of baseflow as a verification tool does not adjust basin characteristics. As mentioned earlier, baseflow is difficult to develop to represent a reasonable approximation of streamflow within a model. To take the original intent of baseflow and then apply it as a potential verification tool is not recommended. Baseflow is an independent component of a resulting storm hydrograph, but it is constant flow and does not follow the unit hydrograph shape identified as representative of the basin. If the magnitude of the baseflow is increased, it increases the magnitude of the entire outflow hydrograph, adding unnecessary outflow volume. It might help to reach a target peak discharge value, but the volume is out of proportion.

4.1.1.1 Use of Curve Number

Curve Number (CN) is a useful tool in model verification. It provides for an adjustment of the basin infiltration ground cover properties. The variability of these properties allows for some adjustment, at least to an extent. If CN is adjusted to a range well outside of what is documented as the estimated soil/ground cover then it becomes unrealistic. The use of the NRCS Web Soil Survey and the NRCS Soil-Cover Complex documents help in estimating reasonable values of CN. If subbasins are used, the modeler can try adjusting CN in different subbasins to see if that helps in better approximation of the calibration hydrograph.

4.1.1.2 Use of Impervious Area

Adjusting the percentage of impervious area in a basin is also a consideration for model verification, especially if developed areas are within the subject drainage basin and are not accounted for in the Web Soil Survey information. It should be used with caution in natural basins because the Web Soil Survey should have a fairly accurate account of impervious areas, and the adjustment of impervious areas tends to skew the hydrograph. It is recommended to either adjust the percentage of imperious area or adjust the average CN to account for an adjustment of impervious areas, but do not do both. Adjusting the average CN to reflect a change in percentage of impervious areas is the preferred method to handle the verification.

Another consideration is to account for open water areas in the basin. This can make an impact on runoff, especially if lakes and reservoirs make up a substantial portion of the basin. TR-55 recommends assigning a CN of 100 for open water areas (USDA-NRCS, 1986).

4.1.2 Routing Parameters

The other suggested method of verification is adjusting the unit hydrograph of the basin (or hydrographs in a group of subbasins). As mentioned above, the procedures from USGS Water-Supply Paper (WSP) 2420 are useful in developing unit hydrograph parameters in Montana. In WSP 2420, the unit hydrograph parameters that can be adjusted are T_c (time of concentration) and R (basin-storage coefficient) when using the Clark Unit Hydrograph method. In the parameter regression equations developed in WSP 2420, the common independent variable is basin area, so when the user is adjusting the parameters of the unit hydrographs, they are adjusting basin area. Technical Note 1 warns that these parameters may be utilized to pseudo-calibrate the model but should remain within one standard deviation of the estimated value. This is good guidance, but it can become a complicated process to determine the standard deviation of the parameter values as computed by the methods of *WSP 2420*. The measure of error for the parameter regression equations in Table 4 of *WSP 2420* is based on standard error (logarithm base 10), which is different than standard deviation of the regression data. To compute standard deviation from standard error can be a complicated process. Instead, for the purpose of this manual, it is recommended that adjusted parameter values should be compared to the range of the same parameters for the sample basins used in the analysis for *WSP 2420* (found in Table 2 of *WSP 2420*) to verify they are reasonable for the basin location and size.

4.2 CALIBRATION

Calibration, as mentioned above, indicates verification of a hydrologic model by adjusting model parameters using measured or observed data. This would be the preferred method if measured (gaged) data were available. An example of this would be to adjust a model of a 10-year storm so that it matches gage data for a 10-year storm on the same drainage basin. Most dams in Montana do not have gages located on the stream near the point where it enters the reservoir, so the ability to directly use gage data without adjustment is rare.

However, there are drainages with dams that have gages either upstream or downstream of the dam, which would allow for adjustment of the gage data based on a ratio of gaged drainage area to the drainage area at the dam. As mentioned in TN1, methods for transferring flood-frequency estimates from a gaging station on the same stream to an ungaged site upstream or downstream are found in the publication used in the development for StreamStats (USGS, 2018).

4.3 PSEUDO-CALIBRATION

Pseudo-calibration is conducted to adjust a model to approximately match the peak-flow results from a StreamStats regression analysis. TN1 provides considerable discussion on verification to achieve a sense of confidence in the model results and to maintain reasonable conservatism for an inflow design flood. Because TN1 is for design floods that will dictate spillway sizes for dams, the user is urged to provide conservatism at some level above the average regression equation value, typically within one standard deviation of the mean estimate value.

In this manual, the goal of a pseudo-calibration will be to adjust the model to reasonably estimate the peak average regression value for frequent storms. It is recommended that for each parameter to be used in pseudo-calibration, a range of acceptable values be identified. Parameter adjustment should not extend beyond these predetermined ranges.

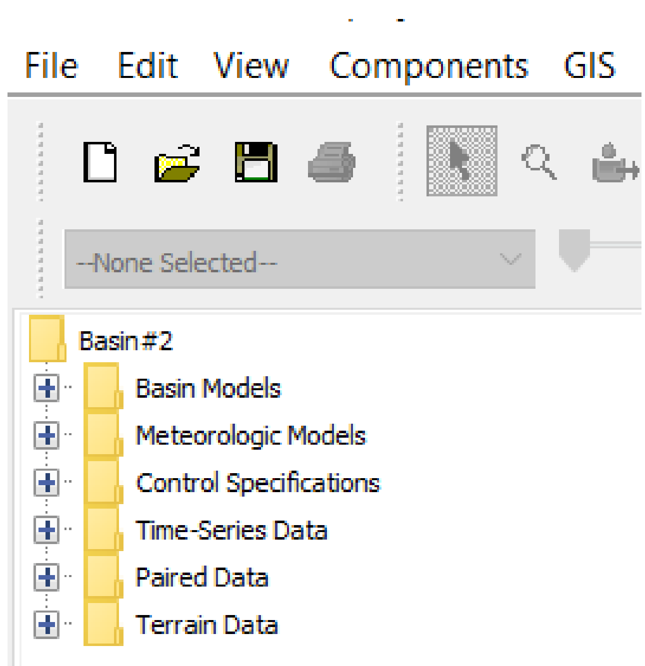
5.0 EXAMPLE OF HEC-HMS MODEL DEVELOPMENT AND VERIFICATION

This section contains an example of developing a HEC-HMS model and an example of verifying its accuracy through a pseudo-calibration method. Note that this example is useful for any rainfall-runoff application in HEC-HMS. This example uses the current version of HEC-HMS Version 4.8. This example will not provide guidance on starting a new HEC-HMS model. Instructions on how to do that can be found in the HEC-HMS User's Manual (COE, 2021). Instead, this example will use an existing model to demonstrate the steps needed for model development. It is recommended that users of HEC-HMS start with an existing model that was initially developed for similar purposes and modify it for their new project. It is helpful to regularly compare the new model with the original to make sure all parameters are accounted for. This will avoid unnecessary set-up steps and will help with developing consistent models.

5.1 MODEL LAYOUT

Figure 5-1 shows the layout and organization tree for a HEC-HMS model. The layers, or components, are listed in the order set by HEC-HMS.

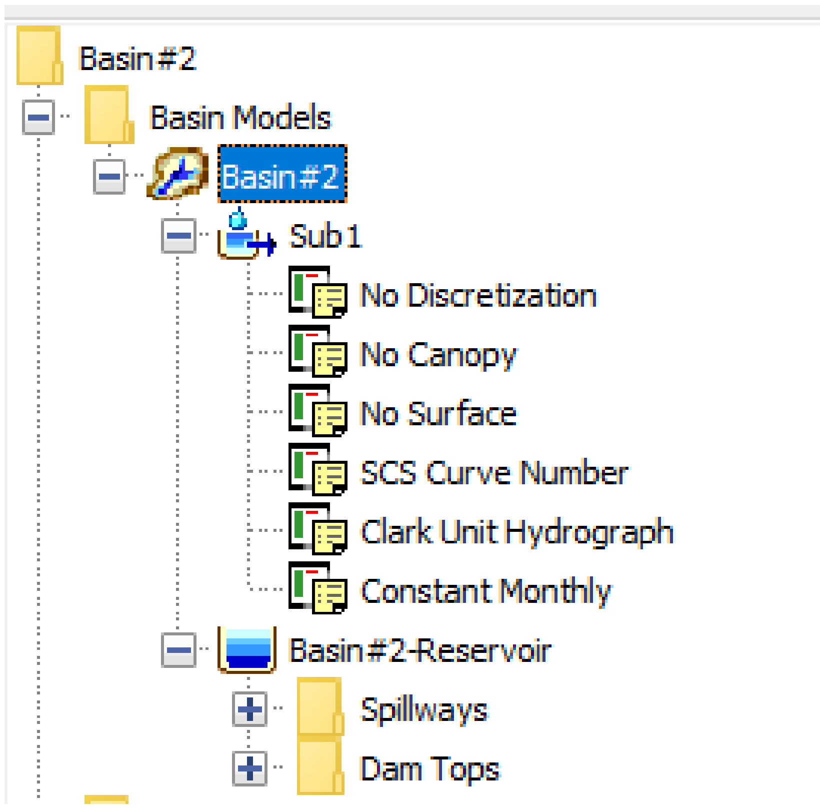
FIGURE 5-1. MODEL ORGANIZATION



5.2 BASIN MODEL

Figure 5-2 show an expanded organization tree for the Basin Model in HEC-HMS. For this example, the basin is labeled Basin #2.

FIGURE 5-2. BASIN MODEL COMPONENTS



In developing the Subbasin (in this example, the subbasin is labeled 'Sub 1') and the Reservoir (Basin #2-Reservoir), the user can use graphic icons located in the program menu and place the icons in a separate window to give a graphic schematic of the model. This schematic represents the upstream-to-downstream flow of the hydrologic model. Figure 5-3 shows the common icons in the menu bar with the subbasin and reservoir icons identified. Figure 5-4 shows the schematic of the subbasin and reservoir. Notice they are connected by a line which indicates hydrologic connectivity. For this example, a Terrain Model was added as background to the schematic diagram. As mentioned in Section 2.6, a Terrain Model is not a necessary component for hydrologic modeling, but it can be a tool for basin delineation and for graphical representation of the watershed. A detailed procedure for adding a Terrain Model is provided in Appendix A.

FIGURE 5-3. MENU COMPONENTS ICONS

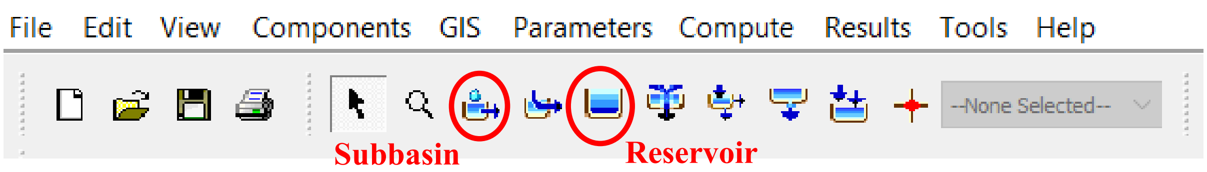
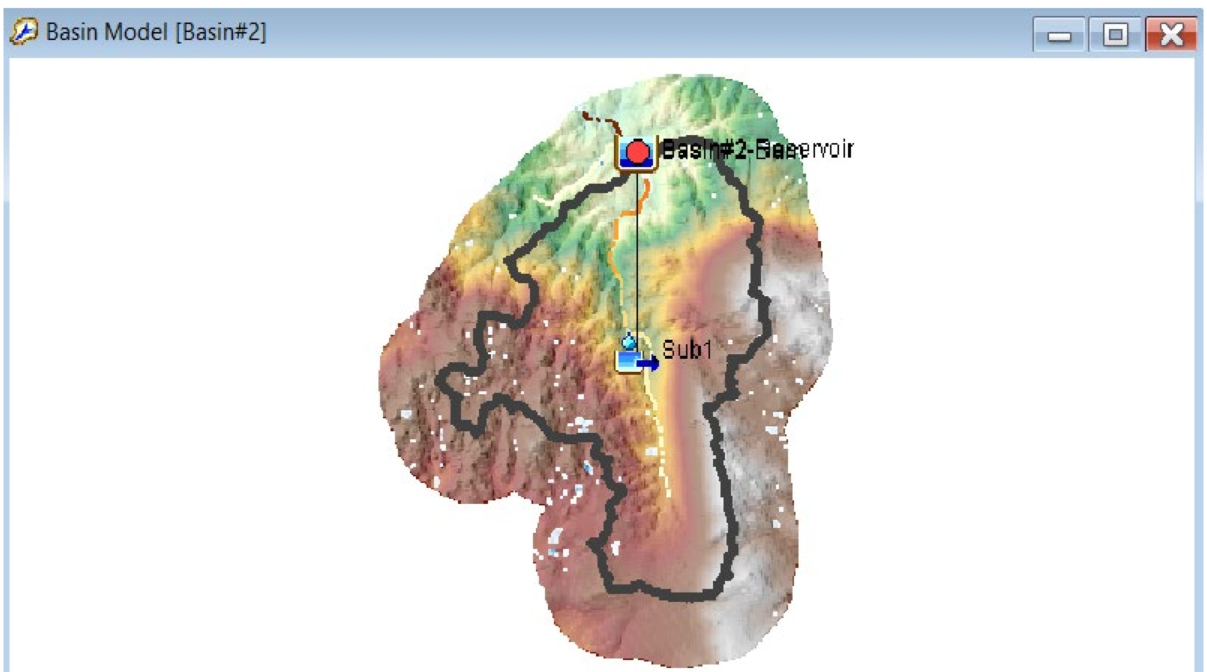


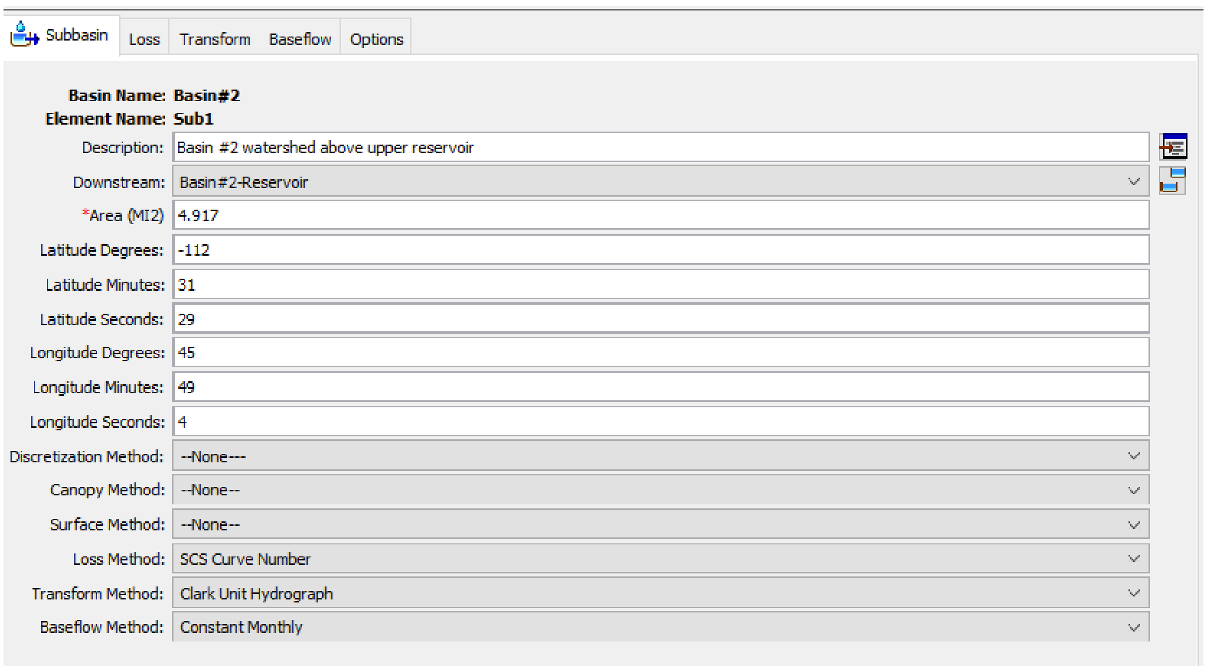
FIGURE 5-4. MODEL SCHEMATIC WITH TERRAIN MODEL



When the subbasin is selected, a window similar to Figure 5-5 appears, showing the different components needed to describe the subbasin.

The fields with a red asterisk are required fields. The basin area, as discussed in Section 3.1.1, can be determined by StreamStats or the by the GIS process in determining Terrain information. The latitude and longitude information are not required but was included in this example. The Loss Method used was SCS Curve Number; the Transform Method was the Clark Unit Hydrograph; and the Baseflow Method was Constant Monthly.

FIGURE 5-5. SUBBASIN PARAMETERS



In Figure 5-6, the parameters required for the SCS Curve Number Method are the Curve Number and the percentage of the basin that is impervious. It is recommended that the user allow HEC-HMS to determine the initial abstraction value, and therefore a value is not entered. A step-by-step procedure for determining the average curve number for the basin is provided in Appendix C.

FIGURE 5-6. SCS CURVE NUMBER DATA

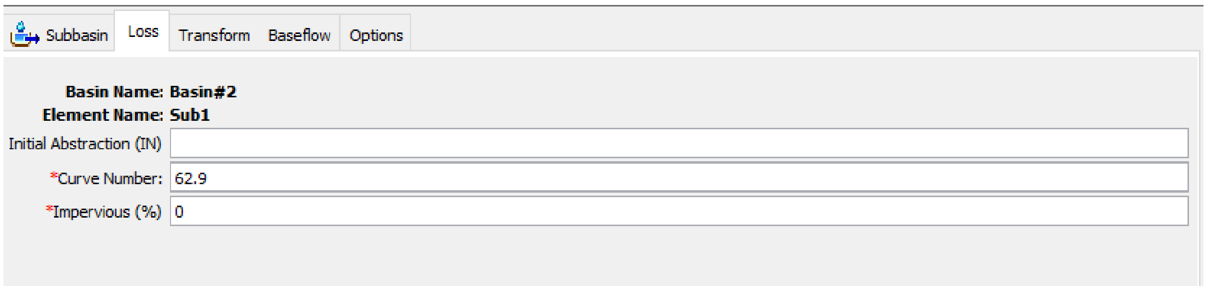
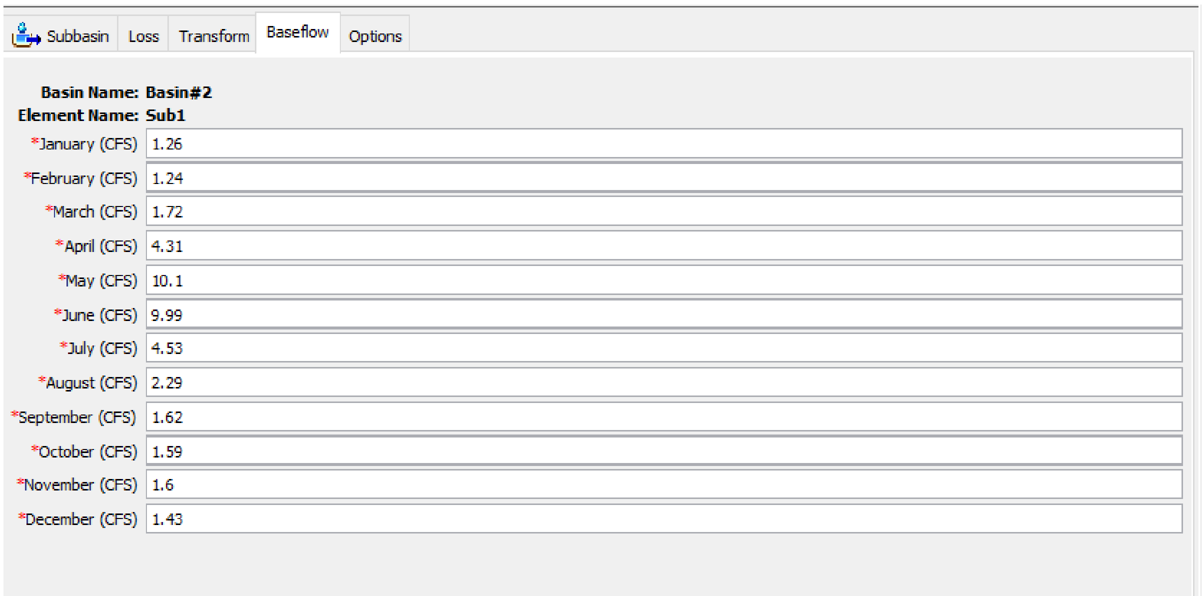


Figure 5-7 shows the data required for the Clark Unit Hydrograph method – the Time of Concentration and the Storage Coefficient. These values are derived from the procedures discussed in Section 3.1.3. A sample spreadsheet image is in Appendix D. The spreadsheet used to determine the Clark Unit Hydrograph parameters can be obtained from the Dam Safety Program's website at http://dnrc.mt.gov/divisions/water/operations/dam-safety/technical-notes/technical-note-1-references-and-additional-information.

FIGURE 5-7. CLARK UNIT HYDROGRAPH PARAMETERS

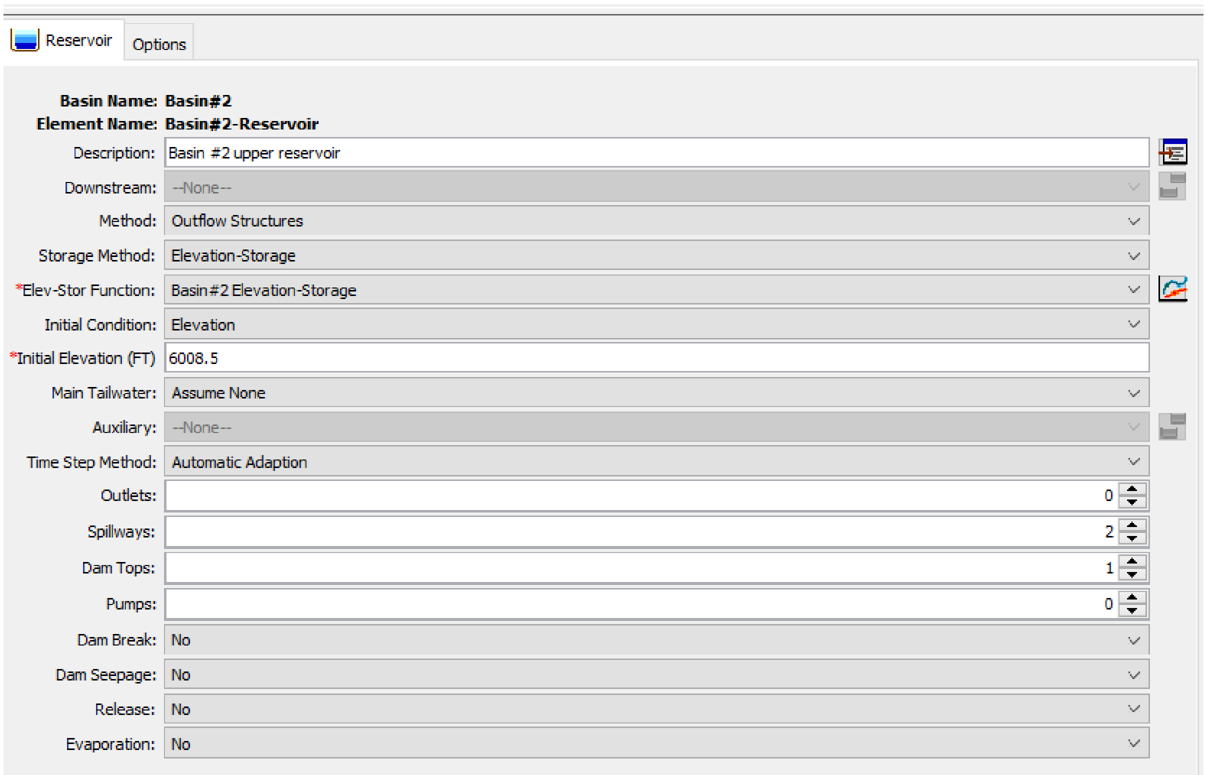
Figure 5-8 shows the data required for the Constant Monthly baseflow method. The procedure for determining constant monthly discharge values was discussed in Section 3.1.4. An image from the StreamStats program for this drainage is in Appendix E.

FIGURE 5-8. CONSTANT MONTHLY BASEFLOW VALUES



Reservoir and dam parameters are obtained from owner records or by field measurement. Figure 5-9 shows the HEC-HMS section for reservoir parameters. You will notice that for this example, the only parameters required are the Elevation-Storage Function and the Initial Elevation of the reservoir, however, these can change depending on the type of information the user chooses to describe the reservoir. Also, for this example, other parameters than those required were used. In this example, the reservoir will be defined by elevation-storage data. The reservoir has two distinct and separate spillways that are defined by the Outflow Structures method and uses elevation discharge rating curves for each spillway to compute outflow from the reservoir. In this example, data for the dam is also entered to define when an overflow situation occurs and the estimated weir flow over the dam top.

FIGURE 5-9. RESERVOIR PARAMETERS



The starting reservoir elevation (6008.5) is the crest of the spillway defined as the "breach spillway." This dam was partially breached because of embankment stability concerns. The breach spillway serves as the normal water surface control. A second spillway, the "emergency spillway," has a crest elevation higher than the breach spillway.

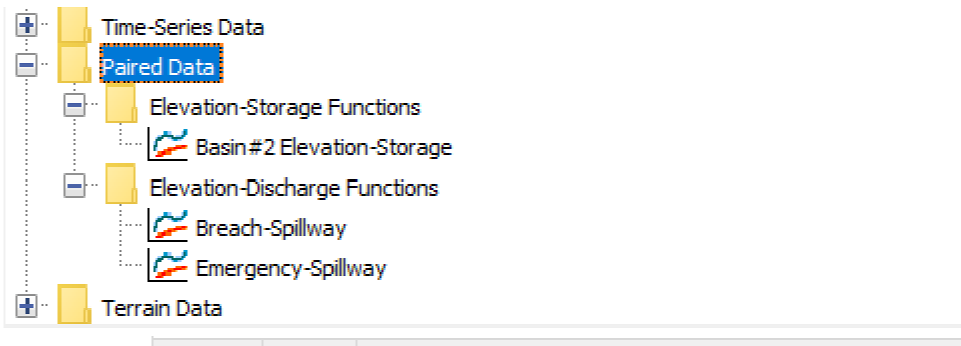
When "Outflow Structures" is selected as the method to determine spillway discharge, the spillways need to be individually described. Figures 5-10 and 5-11 show the options for the breach spillway (Spillway 1) and emergency spillway (Spillway 2), respectively.

FIGURE 5-10. BREACH SPILLWAY INFORMATION

FIGURE 5-11. EMERGENCY SPILLWAY INFORMATION

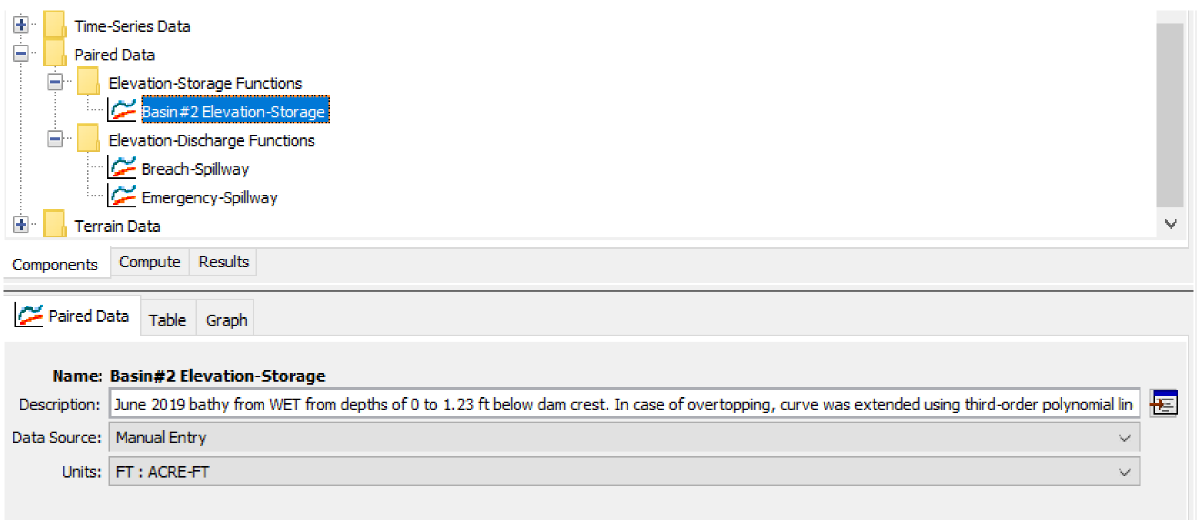
Data for reservoir storage and spillway discharge relationships are entered as Paired Data, shown in Figure 5-12.

FIGURE 5-12. PAIRED DATA



When the user clicks on one of the paired data sets as shown in Figure 5-12, a new window appears. For the Basin #2 Elevation-Storage function, the new window is seen in Figure 5-13.

FIGURE 5-13. ELEVATION-STORAGE FUNCTION



For the Breach Spillway and Emergency Spillway functions, the new windows are seen in Figures 5-14 and 5-15, respectively.

FIGURE 5-14. ELEVATION-DISCHARGE FUNCTION, BREACH SPILLWAY

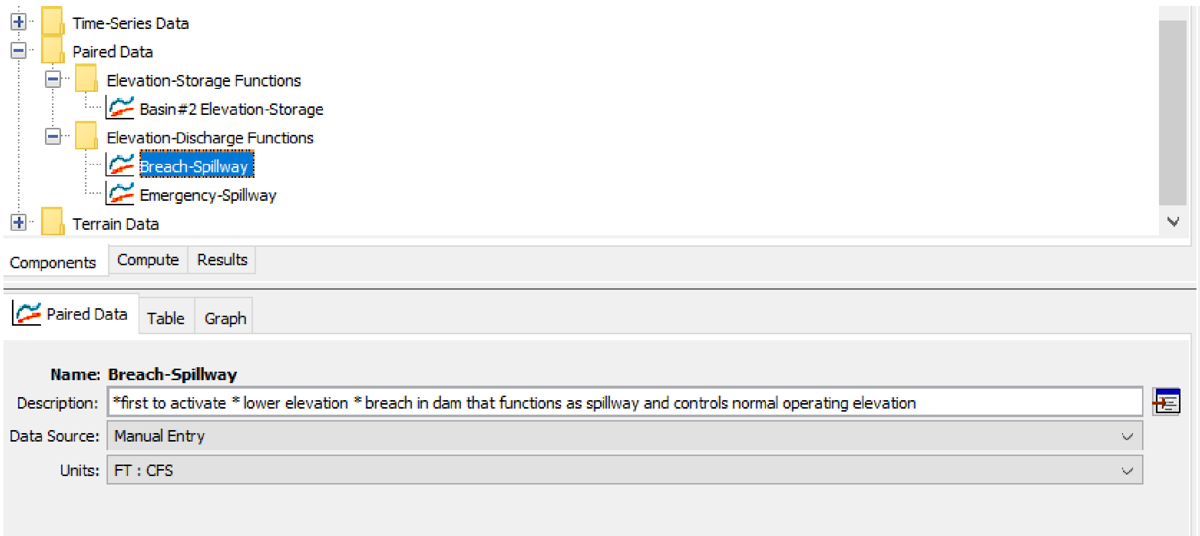
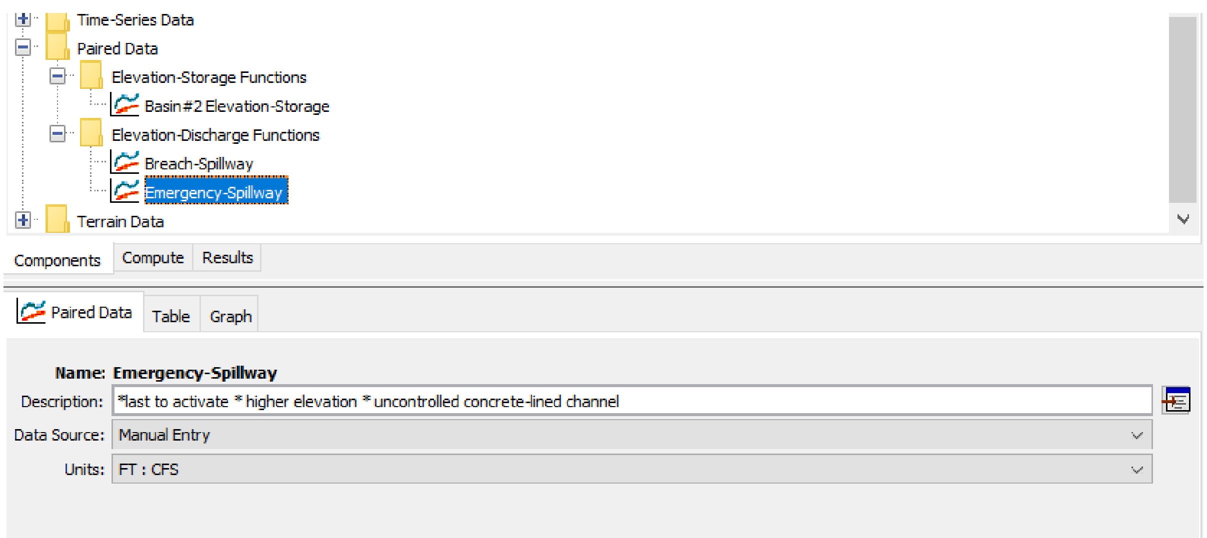
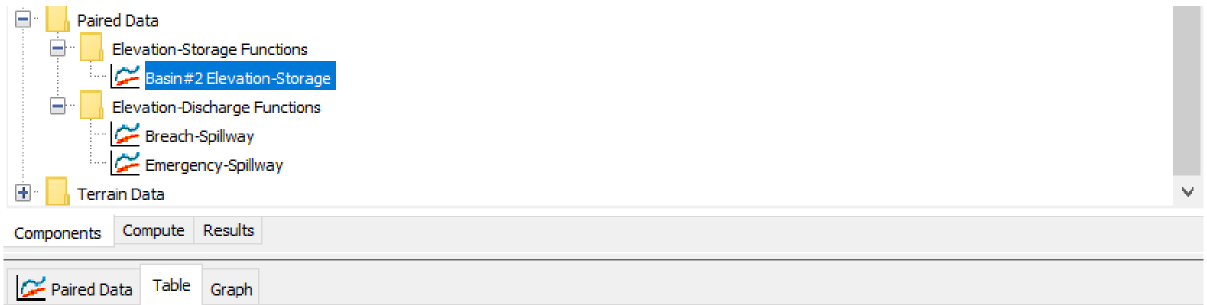


FIGURE 5-15. ELEVATION-DISCHARGE FUNCTION, EMERGENCY SPILLWAY



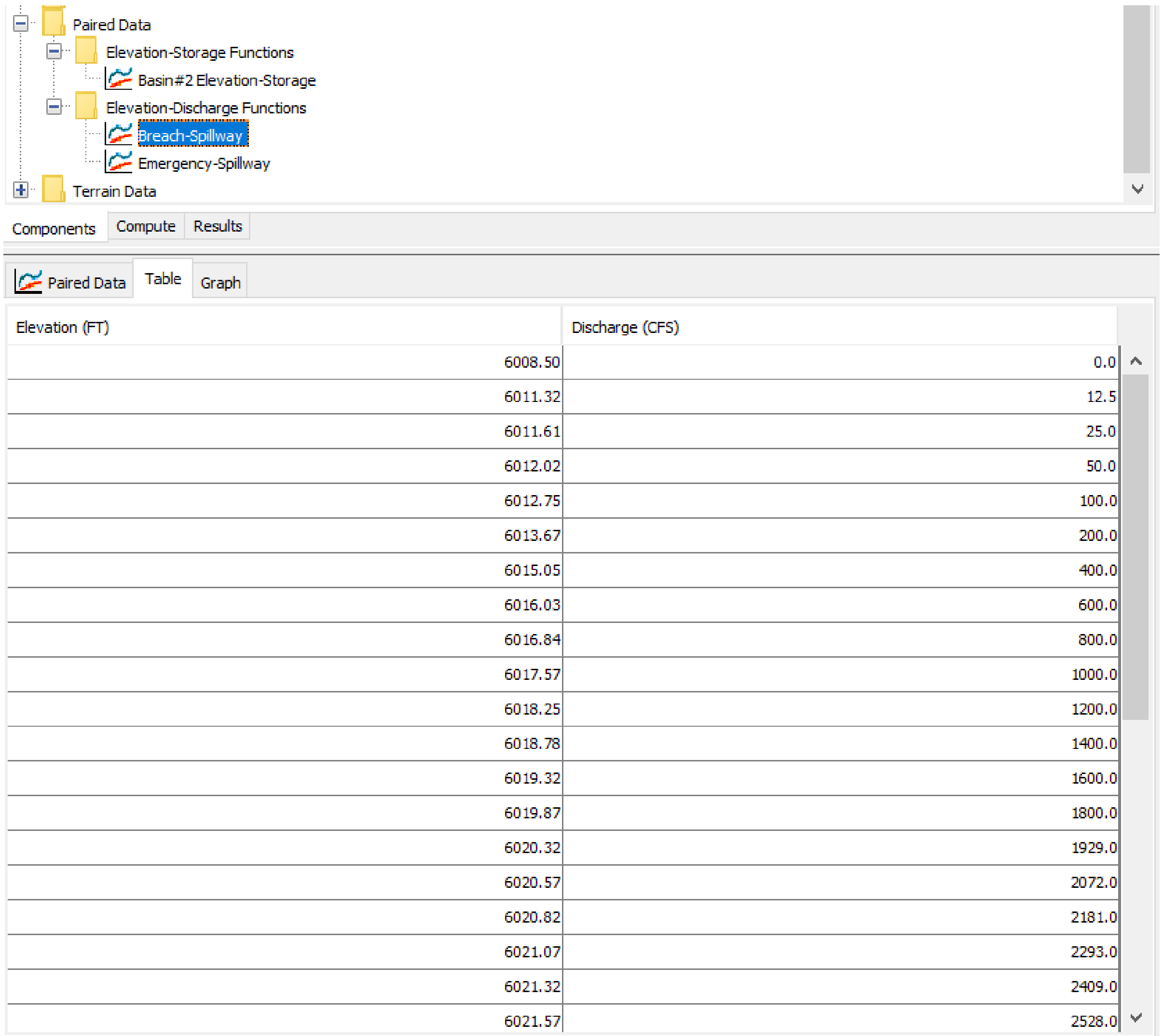
Data tables for reservoir elevation-storage, and breach and emergency spillway elevation-discharge information are shown in Figures 5-16, 5-17, and 5-18, respectively. Note that not all data are shown in the tables.

FIGURE 5-16. RESERVOIR ELEVATION-STORAGE TABLE



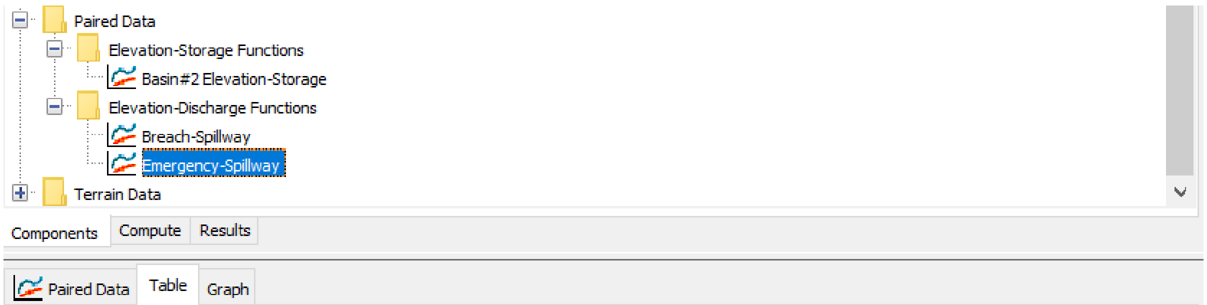
Elevation (FT)	Storage (ACRE-FT)
5987.5	0.0
5991.5	1.0
5993.0	2.1
5994.0	3.1
5995.0	4.4
5995.5	5.2
5996.0	6.1
5996.5	7.2
5997.0	8.4
5997.5	9.7
5998.0	11.2
5998.5	12.8
5999.0	14.6
5999.5	16.4
6000.0	18.4
6000.5	20.6
6001.0	22.9
6001.5	25.4
6002.0	28.1
6002.5	30.9

FIGURE 5-17. BREACH SPILLWAY ELEVATION-DISCHARGE TABLE



Elevation (FT)	Discharge (CFS)
6008.50	0.0
6011.32	12.5
6011.61	25.0
6012.02	50.0
6012.75	100.0
6013.67	200.0
6015.05	400.0
6016.03	600.0
6016.84	800.0
6017.57	1000.0
6018.25	1200.0
6018.78	1400.0
6019.32	1600.0
6019.87	1800.0
6020.32	1929.0
6020.57	2072.0
6020.82	2181.0
6021.07	2293.0
6021.32	2409.0
6021.57	2528.0

FIGURE 5-18. EMERGENCY SPILLWAY ELEVATION-DISCHARGE TABLE



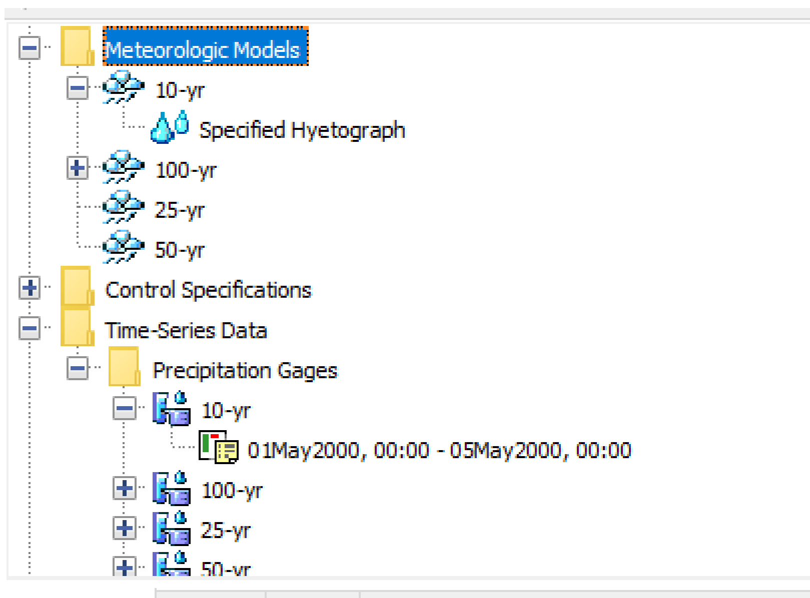
Elevation (FT)	Discharge (CFS)
6015.32	0
6015.52	5
6015.72	10
6015.87	15
6016.02	20
6016.16	25
6016.28	30
6016.39	35
6016.52	40
6016.62	45
6016.72	50
6016.80	55
6016.89	60
6017.06	70
6017.22	80
6017.36	90
6017.50	100
6018.12	150
6018.68	200
6019.19	250

5.3 METEOROLOGICAL MODELS

Meteorological model input comes from Precipitation Gages. For HEC-HMS, a precipitation gage is any rainfall data that is presented as incremental depths over time. It can be actual gage data or synthetic hyetographs. In Figure 5-19, the model component tree shows the meteorological models as synthetic storms that represent different return period events. These storms are what are considered "high-frequency" for this manual.

Information for only one precipitation gage will be shown for this example. In this case, it will be the 10-year return period storm. Input format for the other storms is the same as the 1-year storm, but data values will be different.

FIGURE 5-19. METEOROLOGICAL MODEL PRECIPITATION GAGES



The information window for the meteorological model is shown in Figure 5-20. Figure 5-21 is provided to remind the user that the Basin tab in the information window needs to be clicked on to indicate that subbasins will be included with this storm. This is an often-over-looked parameter that has led to countless hours of troubleshooting and forehead smacking when the problem is discovered.

FIGURE 5-20. INFORMATION WINDOW FOR 10-YEAR STORM

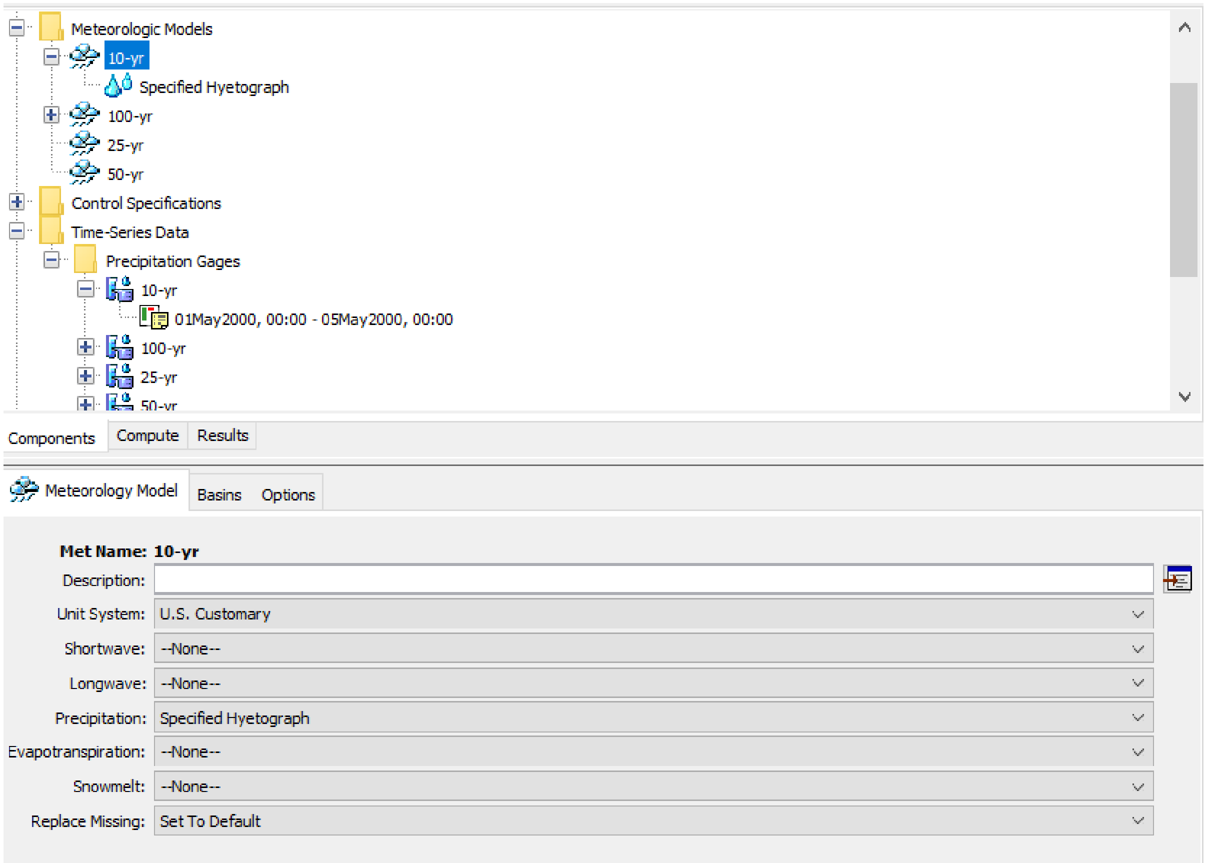
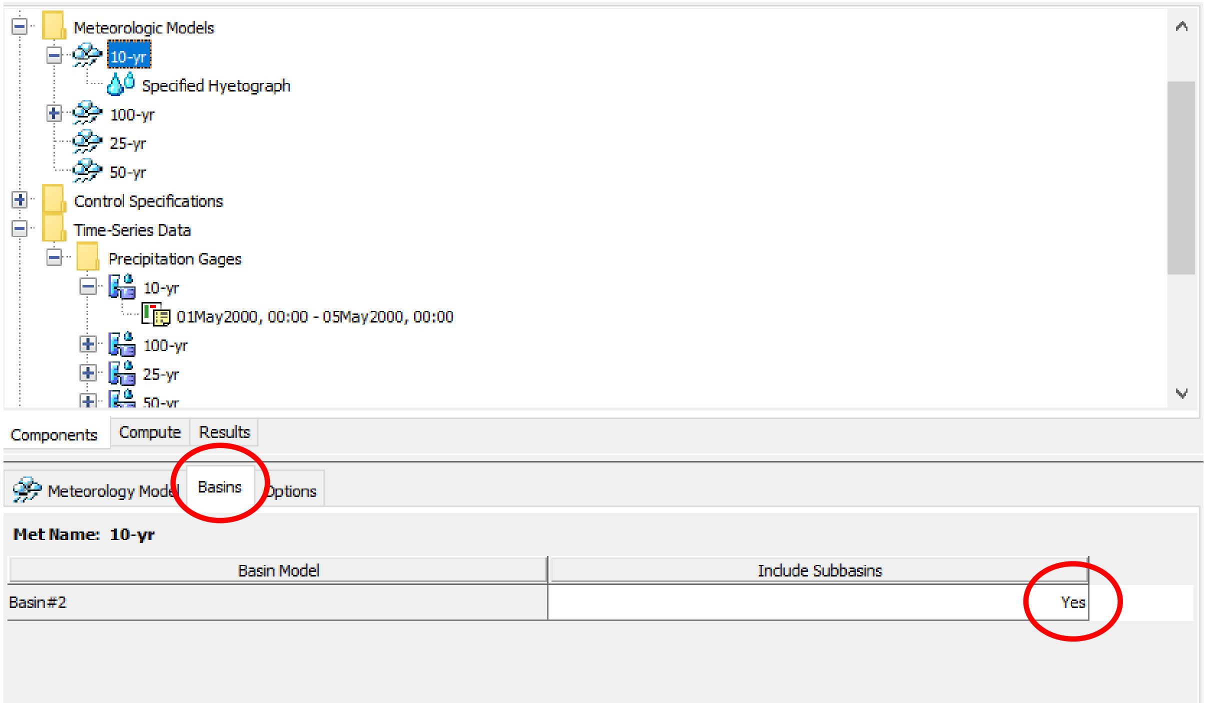
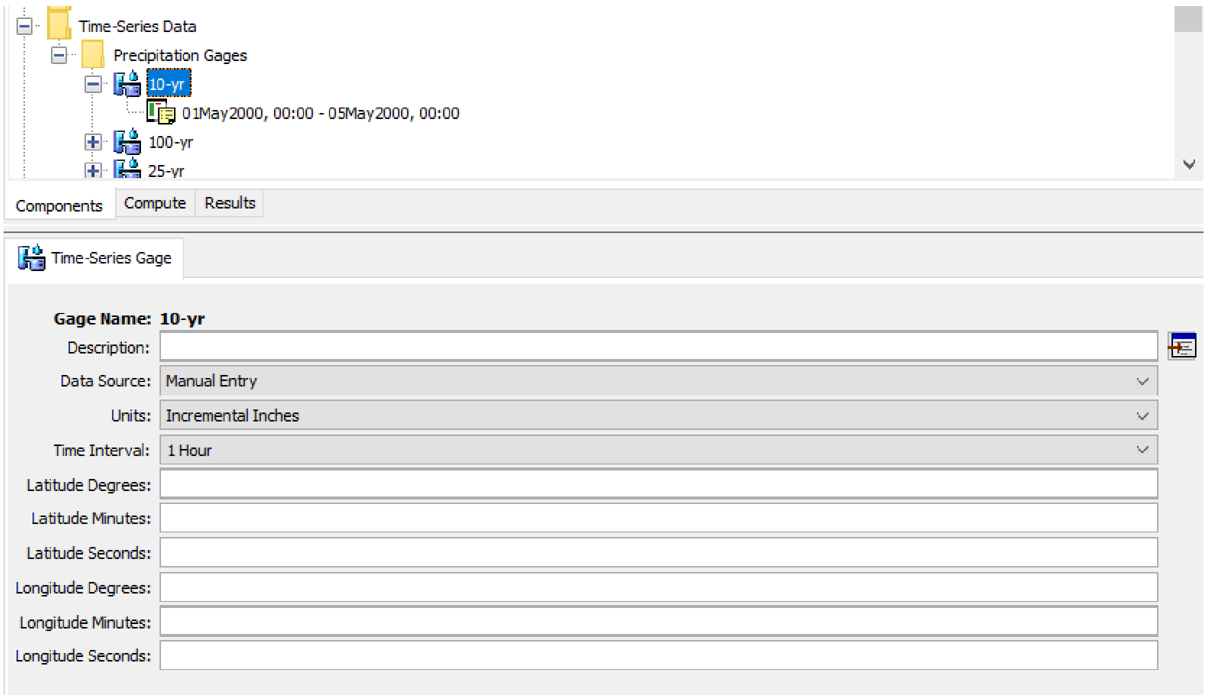


FIGURE 5-21. BASIN TAB IN METEOROLOGICAL MODEL INFORMATION



The data for meteorological models are stored in Time Series tables. Figure 5-22 shows the first window of a precipitation gage. The user enters how data will be entered and indicates the time increment for the data.

FIGURE 5-22. PRECIPITATION GAGE WINDOW



The next window is the time window for the specified hyetograph. This is where the user enters the time period over which the storm will occur. The months entered for this type of analysis need to match the month intended because it will dictate the baseflow magnitude, which is dependent on the month chosen. It is recommended that the storm occur in a month that has the highest probability for large storms. In Montana, this is typically May or June (see Figure 5-23).

FIGURE 5-23. TIME WINDOW FOR METEOROLOGICAL MODEL

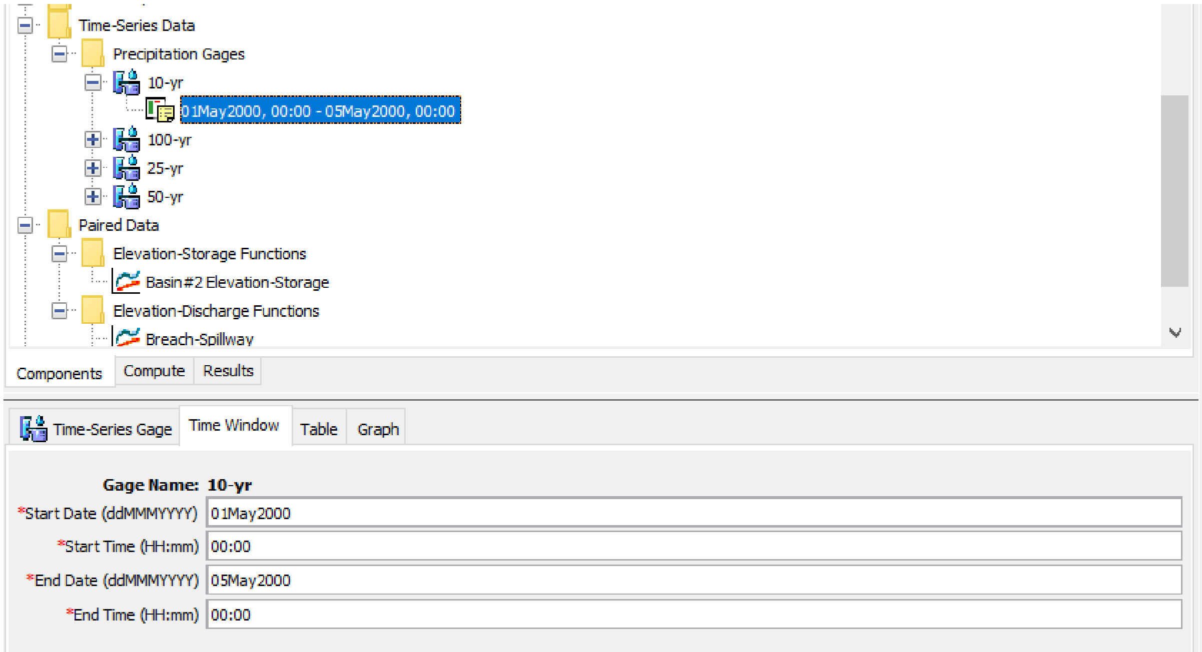


Figure 5-24 shows a partial precipitation gage table. Note that the time increments match that shown in Figure 5-22.

FIGURE 5-24. PRECIPITATION GAGE TABLE (PARTIAL)

Time (ddMMMYYYY, HH:mm)	Precipitation (IN)
01May2000, 00:00	
01May2000, 01:00	0.01095
01May2000, 02:00	0.01095
01May2000, 03:00	0.01095
01May2000, 04:00	0.01095
01May2000, 05:00	0.04050
01May2000, 06:00	0.04050
01May2000, 07:00	0.04050
01May2000, 08:00	0.06300
01May2000, 09:00	0.06300
01May2000, 10:00	0.06300
01May2000, 11:00	0.06300
01May2000, 12:00	0.06300
01May2000, 13:00	0.06780
01May2000, 14:00	0.06780
01May2000, 15:00	0.08160
01May2000, 16:00	0.08160
01May2000, 17:00	0.25200
01May2000, 18:00	0.14760
01May2000, 19:00	0.14220

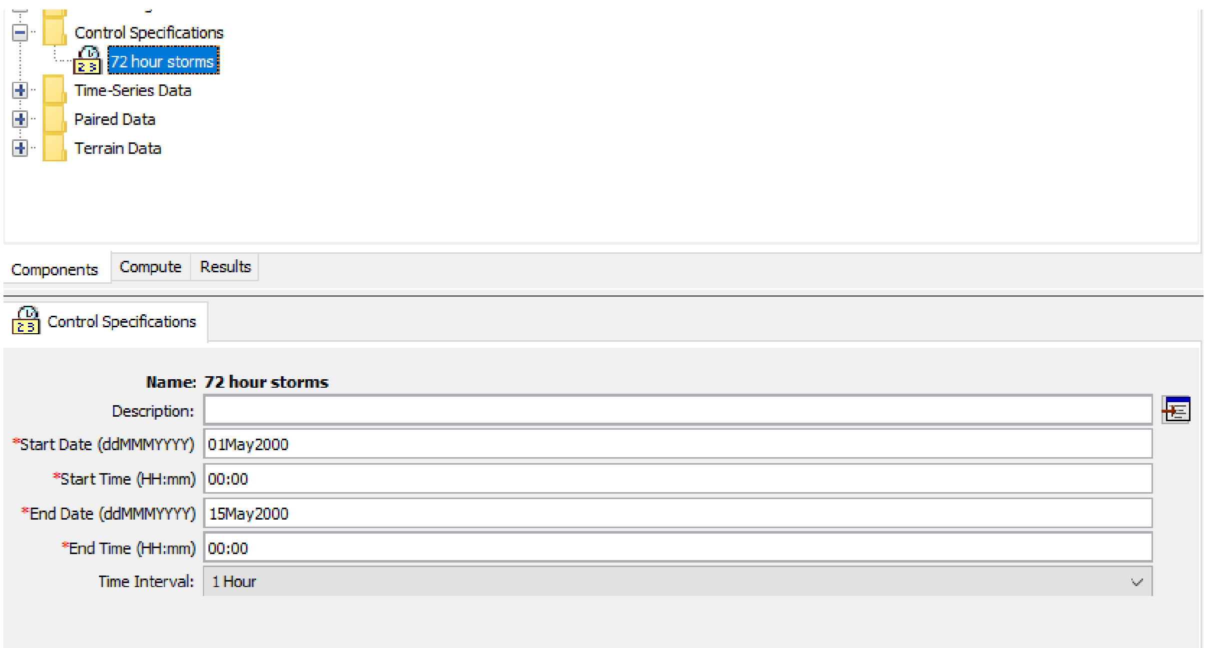
As previously mentioned in Sections 3.2.1 and 3.2.2, synthetic rainfall data come from spreadsheets developed using USGS methods for storms of a wide range of return periods. The first spreadsheet computes a rainfall storm depth. Sample spreadsheet images for the 10-year return period are in Appendix D. The second spreadsheet computes the hyetograph based on the storm depth. Sample spreadsheet images are in Appendix F. The spreadsheets used to determine the storm depth and hyetograph values can be obtained from the Dam Safety

Program's website at http://dnrc.mt.gov/divisions/water/operations/dam-safety/technical-notes/technical-note-1-references-and-additional-information.

5.4 CONTROL SPECIFICATIONS

Control Specifications do not require a lot of input data, but they are important for controlling when simulations start and stop and determining the time interval used in the simulation. Figure 5-25 shows an example control specifications panel. Note that the simulation takes place in the month of May, which is the highest baseflow and also is the month that has the best chance of major storms occurring in Montana.

FIGURE 5-25. CONTROL SPECIFICATIONS

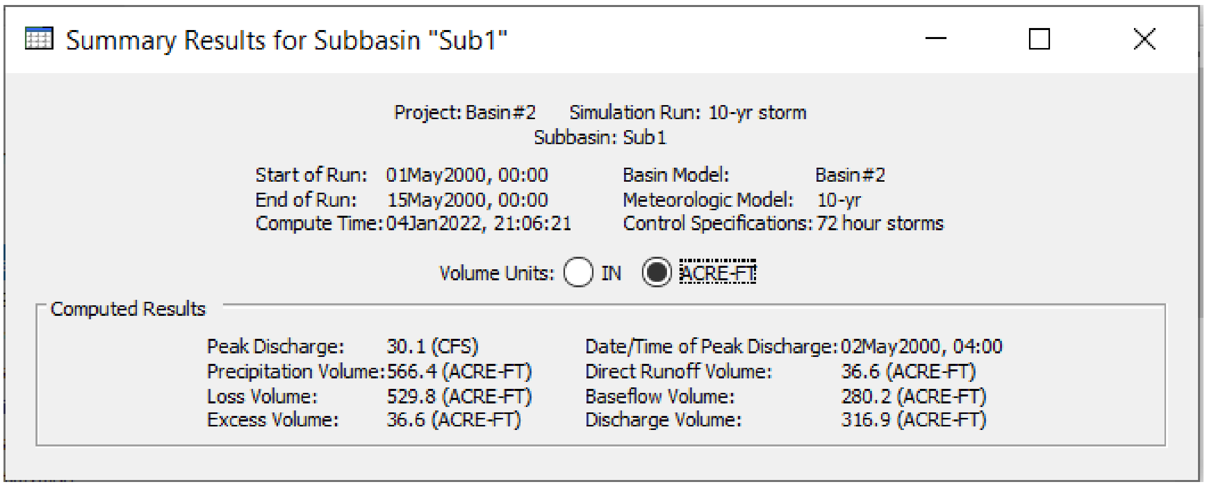


5.5 PSEUDO-CALIBRATION

In the discussion in Section 4.3, it was mentioned that pseudo-calibration is a method of model verification for ungaged streams where the model target is average peak flow values derived from StreamStats regression equations. In this example we are focusing on a 10-year return period runoff event. In this section we will present the HEC-HMS results for a 10-year storm simulation and compare it to the average peak flow generated by StreamStats.

Figure 5-26 shows the summary results of the run for the 10-year return period storm for the basin we have been considering. The peak discharge from the simulation is 30.1 cubic feet per second (cfs).

FIGURE 5-26. SUMMARY RESULTS FOR 10-YEAR STORM



The StreamStats analysis for the basin produced the table shown in Figure 5-27. The average peak discharge for the 10-year storm (or the 10 percent AEP (Annual Exceedance Probability) flood, as indicated in Figure 5-27) is 34.7 cfs, which is very close to 30.1 cfs, the value the HEC-HMS model predicted. It is also within the prediction interval for the StreamStats analysis, as indicated by the PIl (prediction interval lower) value of 14.9 cfs and the PIu (prediction interval upper) value of 81 cfs.

FIGURE 5-27. STREAMSTATS RESULTS FOR THE BASIN

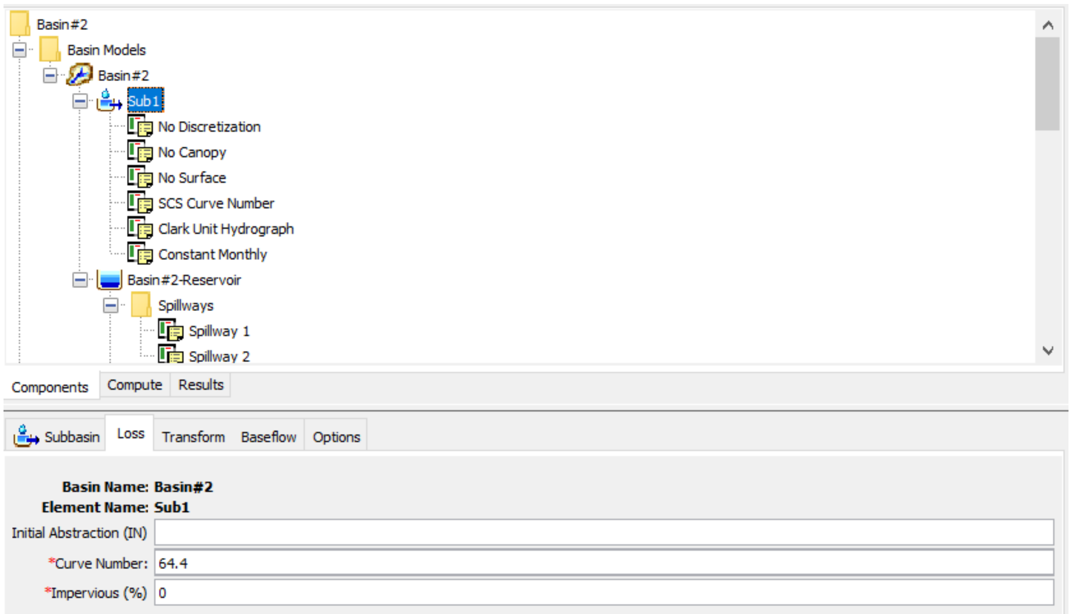
12/15/21, 5:33 PM StreamStats

Statistic	Value	Unit	PIl	PIu	ASEp
66.7-percent AEP flood	8.8	ft^3/s	3.46	22.4	59.4
50-percent AEP flood	12.4	ft^3/s	5.05	30.4	56.5
42.9-percent AEP flood	14.3	ft^3/s	5.88	34.8	55.7
20-percent AEP flood	23.9	ft^3/s	10.2	56.2	53.4
10-percent AEP flood	34.7	ft^3/s	14.9	81	52.8
4-percent AEP flood	48.3	ft^3/s	20.6	113	53.2
2-percent AEP flood	60.4	ft^3/s	25.3	144	54.2
1-percent AEP flood	73.7	ft^3/s	30.2	180	56
0.5-percent AEP flood	88	ft^3/s	35	221	58
0.2-percent AEP flood	107	ft^3/s	40.7	281	61.4

In an analysis such as what has been presented, the results would be deemed adequate for the purpose of determining high frequency inflow into a reservoir. But in most cases, there would be the need for adjustment of the model to result in a peak flow close to that determined by StreamStats. To demonstrate the effect of adjusting the model, a slight change in the CN value will be tried to see if the model can come even closer to the Streamstats average peak of 34.7 cfs.

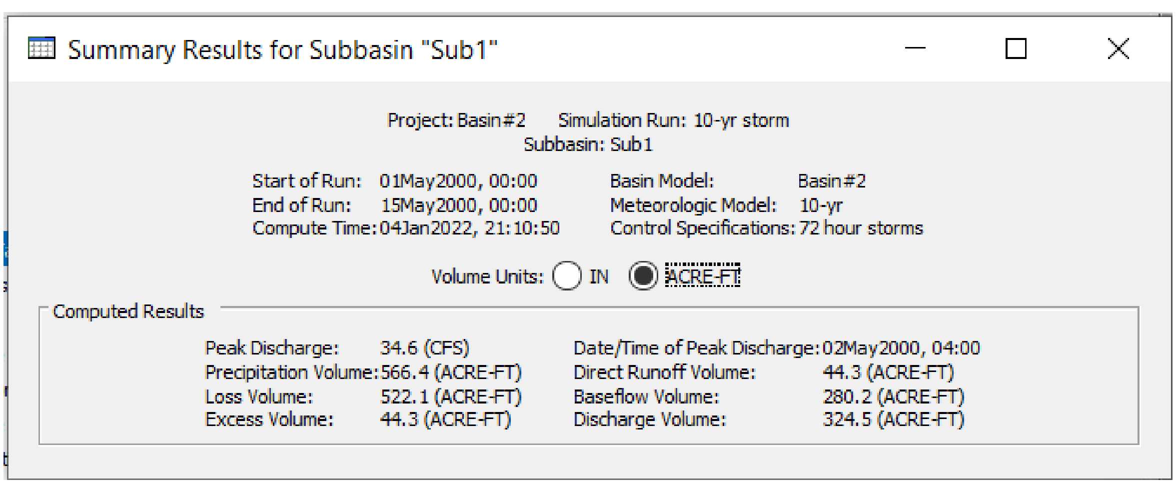
For this demonstration, the CN value was adjusted from 62.9 to 64.4, as shown in Figure 5-28.

FIGURE 5-28. CURVE NUMBER ADJUSTMENT IN PSEUDO-CALIBRATION



The resulting peak flow was 34.6 cfs, as shown in Figure 5-29. This is very close to the StreamStats value of 34.7 cfs.

FIGURE 5-29. 10-YEAR PEAK AFTER CN ADJUSTMENT



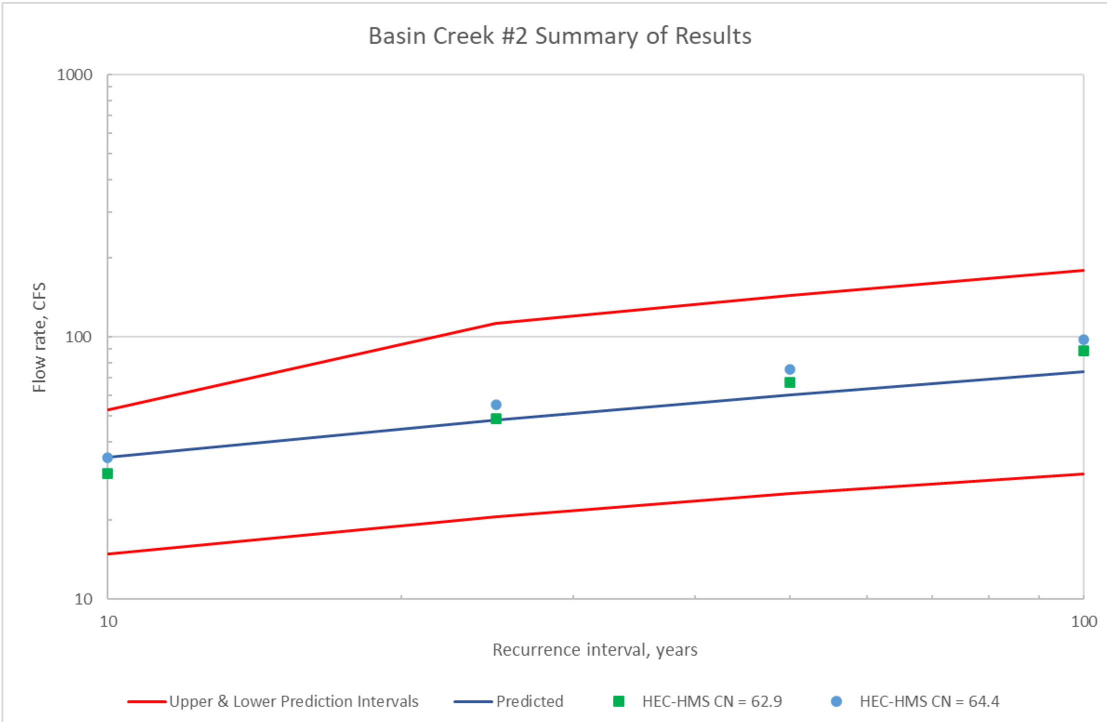
This pseudo-calibration proved to be very accurate (in relation to the average StreamStats value) for the 10-year storm, but does the new CN value of 64.4 fit well for average peak discharges of different return periods?

A quick analysis to check how changing the CN affects peak flow values over a range of return periods showed interesting results. While changing CN to 64.4 was better for the peak discharge of the 10-year storm, it caused a wider variation between the HEC-HMS peak flows and the predicted StreamStats values in other storms, ranging from 25- to 100-year storms. Figures 5-30 and 5-31, taken directly from an Excel spreadsheet originally developed by Brent Zundel, P.E. of DNRC, demonstrate this. Note that Figure 5-31 is plotted on a log scale for both axes. The gap between the HEC-HMS peaks and StreamStats predicted values increases with the CN of 64.4 and higher return periods, when compared to the HEC-HMS values resulting from a CN of 62.9. In this case, using CN of 62.9 is likely the better choice when considering the full range of high frequency storms.

FIGURE 5-30. TABULAR RESULTS OF CN ADJUSTMENT (FROM EXCEL)

Basin #2 peak flow data						Results	
AEP (%)	RI (yrs)	Lower	Predict	Upper	Std Err	CN = 62.9	CN = 64.4
10	10	14.9	34.7	52.8	52.8	30.1	34.6
4	25	20.6	48.3	113	53.2	48.9	55.4
2	50	25.3	60.4	144	54.2	67.2	75.3
1	100	30.2	73.7	180	56	88.8	98.2

FIGURE 5-31. GRAPHICAL RESULTS OF CN ADJUSTMENT (FROM EXCEL)



In an analysis that is trying to find the best pseudo-calibration application, the user would not stop with the two values of CN considered in this example but would put in the effort to find a best-fit CN over the range of flows.

The choice in this example was to adjust the model to produce peak discharges for the various return intervals that came close to the average estimate of the StreamStats regression equations. For other purposes, the goal may be to be conservative in the verification effort and to pseudo-calibrate to values higher than the estimate. This is likely the goal in verifying spillway capacity or in cases of reservoir restrictions that require conservative analysis for dam safety concerns. For these cases, it is recommended that the pseudo-calibration goal be to adjust the model to produce peak flow values that correspond to the average estimate plus one standard deviation value. Statistically, this makes sense given the uncertainty of a pseudo-calibration analysis, and it adds a level of conservatism (some engineers will refer to this as a “comfort level”) to information that can have a wide range of variability.

6.0 STORM INFLOW EFFECTS ON RESERVOIR

At the beginning of this manual, it was stated that its purpose is to determine the effects of relatively frequent storms on dammed reservoirs, specifically reservoirs on which restrictions have been placed for dam safety purposes. Restrictions can be placed for many reasons, such as inadequate spillway capacity or concerns for embankment stability, and it follows then that the study on the effects of frequent storm inflows can have many purposes. In the case of the reservoir used as the example for this manual, the dam safety concern is embankment stability due to excessive and uncontrolled seepage. The low point on the dam crest is elevation 6020.32. The dam has two spillways – one is the original emergency spillway with a crest elevation at 6015.32, the other is a breach spillway (instituted because of embankment concerns) whose crest elevation is 6008.5. Without knowing anything else about the dam, it appears that the elevation difference between the breach spillway crest and the emergency spillway crest is substantial (nearly 7 feet) and then there is another 5 feet of freeboard between the emergency spillway crest and the top of the dam. The capacity of the spillways to pass large storms appears to be ample; in fact, the capacity of the breach spillway is slightly above 400 cfs before the water surface reaches the emergency spillway crest, which is nearly four times greater than the 500-year flood peak for the drainage.

However, spillway capacity is not the concern for this dam. The issue with this dam is high rates of seepage and shaky embankment stability. So even if there is a slight rise in the reservoir, even as little as a foot above the breach spillway crest, there are serious concerns with the stability of the embankment. With that in mind, Table 6-1 shows the effects of the frequent storm inflows. Even with only a 10-year storm inflow, the reservoir rises almost 3 feet.

TABLE 6-1. RESERVOIR RISE FROM FREQUENT STORM INFLOWS

Basin #2 peak flow data		Reservoir		Rise above Breach Spillway Crest (El. 6008.5)
AEP (%)	RI (yrs)	Peak Storage (ac-ft)	Peak Elevation (ft)	
10	10	114	6011.4	2.9
4	25	118.9	6011.8	3.3
2	50	123.5	6012.1	3.6
1	100	128.1	6012.4	3.9

The dam safety implications of this are concerning. The dam is not a high hazard dam, but failure would have serious sedimentation effects on a water supply reservoir downstream.

As can be seen, modeling frequent storm inflows into reservoirs is an effective tool for the Dam Safety Program. It can be used to better understand the effects on impoundments, especially if they have restrictions placed on them. This manual clarifies the use of HEC-HMS, the program that performs the rainfall-runoff modeling. Hopefully, it will aid in effectively and confidently conducting these types of analyses.

7.0 REFERENCES

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U.S. Geological Survey (USGS), 1998. Characteristics of Extreme Storms in Montana and Methods for Constructing Synthetic Storm Hyetographs, Water-Resources Investigations Report 98-4100.

U.S. Geological Survey (USGS), 2012. The National Land Cover Database, U.S. Geological Survey Fact Sheet 2012-3020.

U.S. Geological Survey (USGS), 2018. Scientific Investigations Report 2015–5019–F, Version 1.1, Methods for Estimating Peak-Flow Frequencies at Ungaged Sites in Montana Based on Data through Water Year 2011, Chapter F of Montana StreamStats. February.

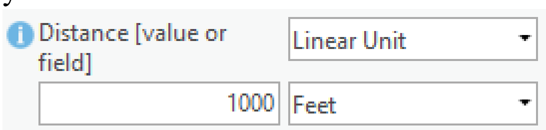
APPENDIX A

PREPARING AND IMPORTING TERRAIN INTO HEC-HMS 4.9

APPENDIX A: PREPARING AND IMPORTING TERRAIN INTO HEC-HMS 4.9

A.1 BUFFERING YOUR WATERSHED SHAPEFILE

1. Before you import a terrain into HEC-HMS, you need to trim your DEM appropriately. First, delineate your watershed using StreamStats (or other method of choice). In order to ensure that your HEC-HMS model doesn't "spill" outside the boundaries of your terrain, you need to buffer the watershed shapefile.
2. Pull in your watershed shapefile to the ArcPro document.
3. On the Analysis tab in the upper left corner of ArcPro, select the Tools button. This will open a search bar on the right-hand side of the page. Search for Buffer and select the Buffer (Analysis Tools) tool.
4. A form will display on the right-hand side of your window:
    a. Input Features – select your watershed shapefile
    b. Output Feature Class – click the folder icon to the right and navigate to where you would like to save your buffered watershed
    c. Distance (value or field) – Linear Unit. Fill in the two fields below. The left field indicates the numerical unit you would like to buffer to. Choose an appropriate buffer distance based on the size of your model. The right field indicates the unit you would like to use for the buffer. Example:



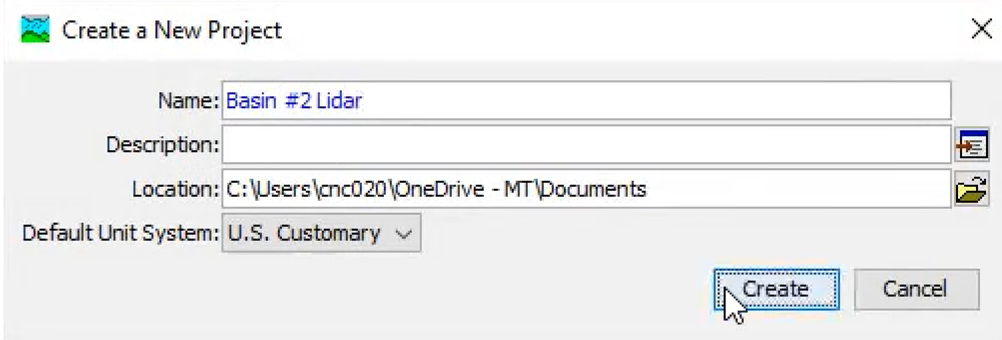
    d. Side Type – Full
    e. Method – Planar
    f. Dissolve Type – Dissolve all output features into a single feature
    g. Press "Run"
5. Once the tool has finished running, the new buffered watershed will show up in the table of contents on the left-hand side.

A.2 CLIPPING YOUR DEM WITH BUFFERED SHAPEFILE

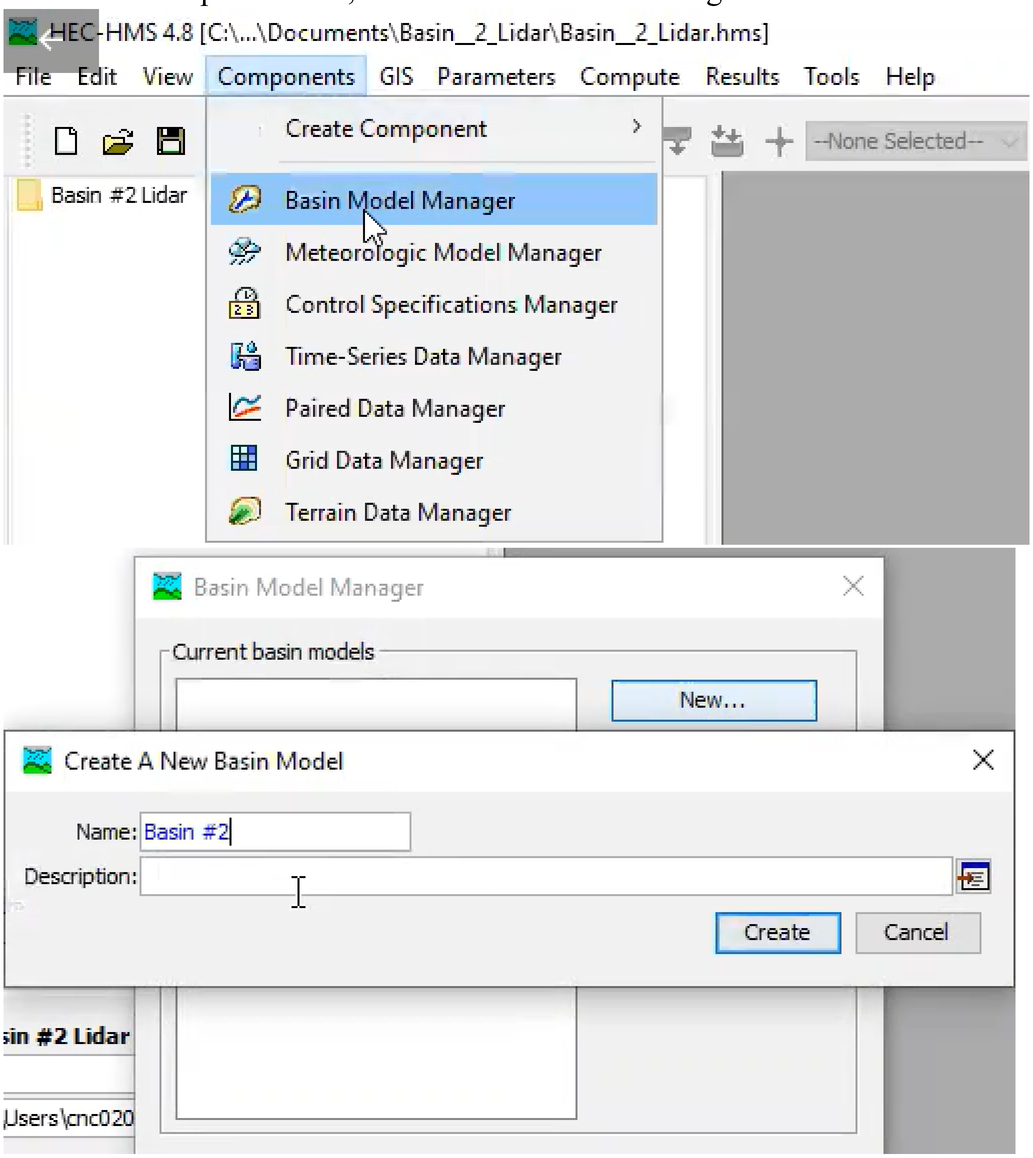
1. On the Analysis tab in the upper left corner of ArcPro, select the Tools button. This will open a search bar on the right-hand side of the page. Search for Clip Raster and select the Clip Raster (Data Management Tools) tool.
2. A form will display on the right-hand side of your window:
    a. Input Raster – select your digital elevation model
    b. Output Extent – select your buffered watershed shapefile
    c. Below Rectangle, Check the Use Input Features for Clipping Geometry
    d. Output Raster Dataset – click the folder icon to the right and navigate to where you would like to save your clipped DEM
    e. NoData Value – leave as is
    f. Press "Run"
3. Once the tool has finished running, the clipped DEM will show up in the table of contents on the left-hand side.

A.3 IMPORT TERRAIN INTO HEC-HMS

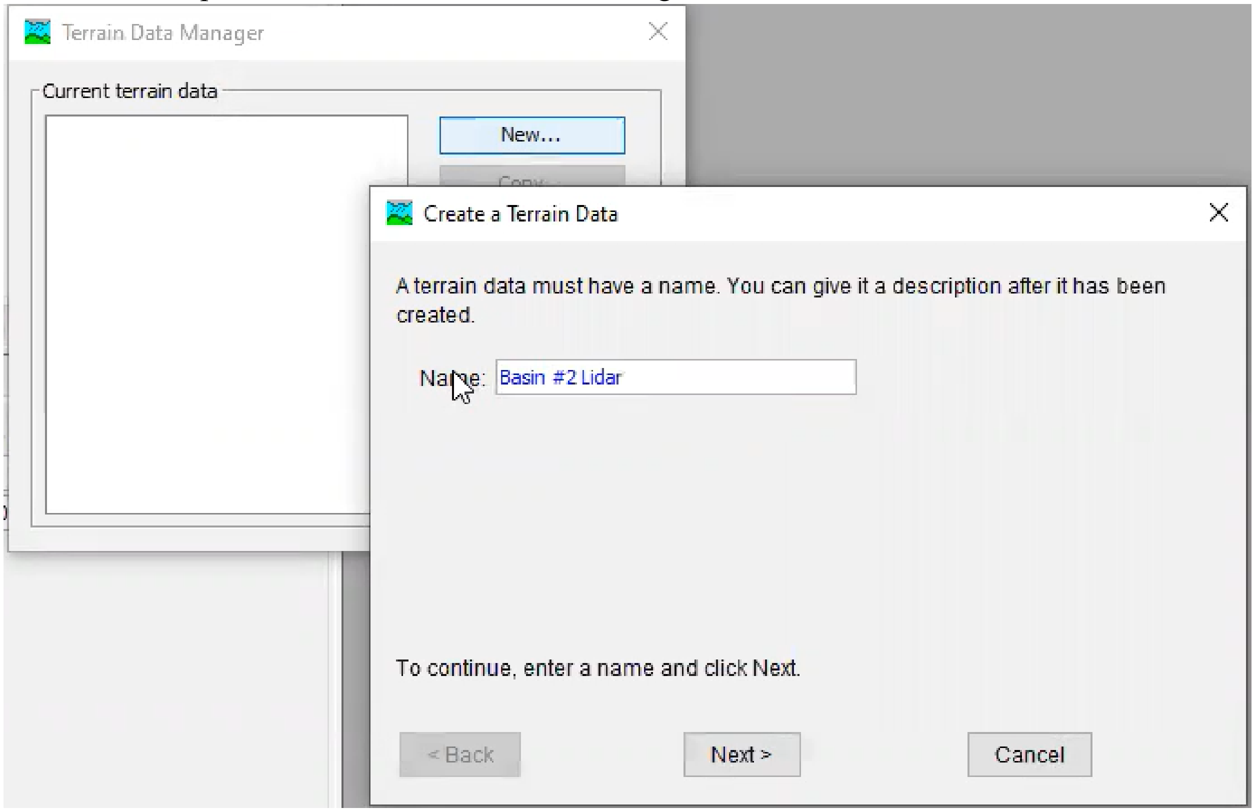
1. Open HEC-HMS and create a new project



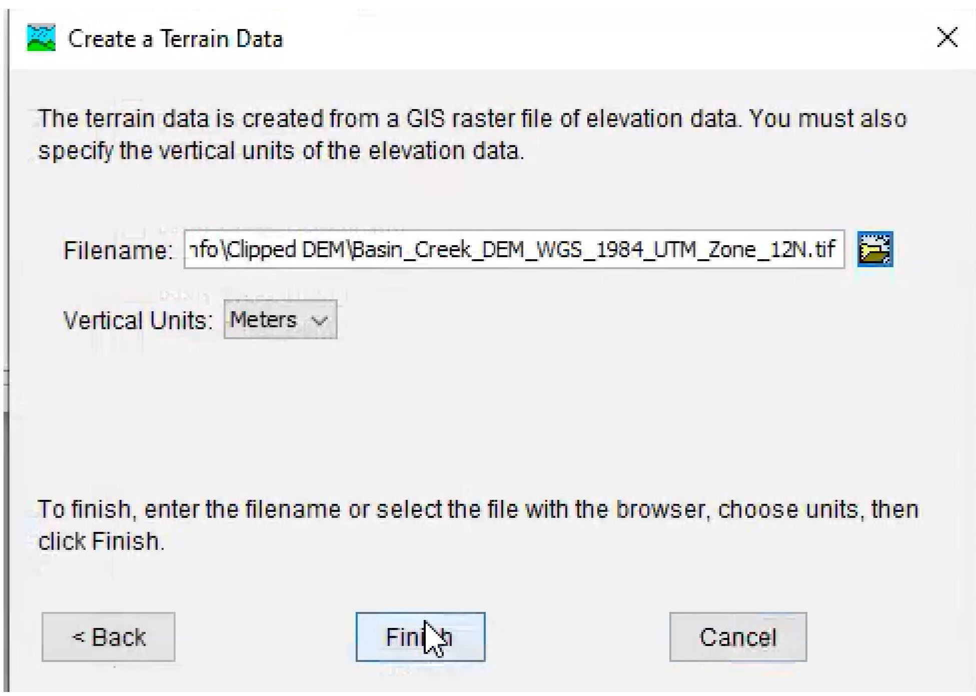
2. Under the Components tab, use the Basin Model Manager to **Create a New Basin Model**



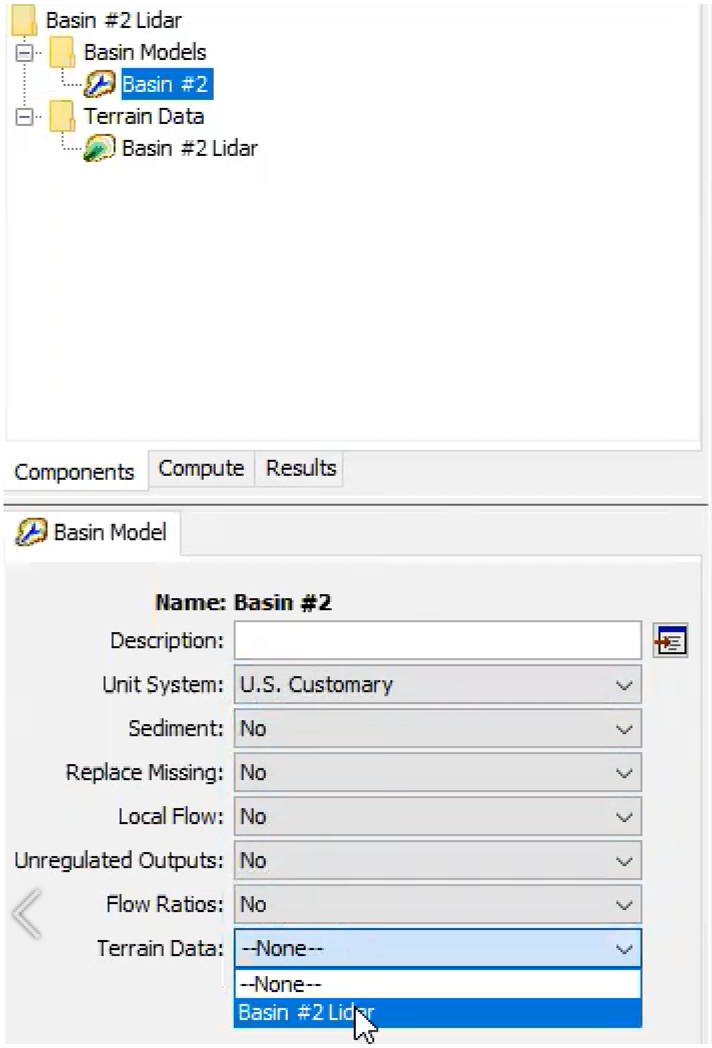
3. Under the Components tab, use Terrain Data Manager to **Create a Terrain Data**.



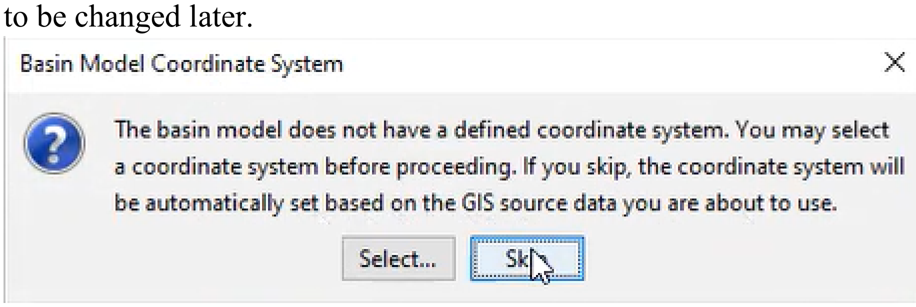
4. Browse to where the terrain data you want to use is saved. DNRC engineers have had good luck using terrain data in the WGS 84 / UTM zone 12N projection; EPSG:32612. This projection is appropriate for Montana.



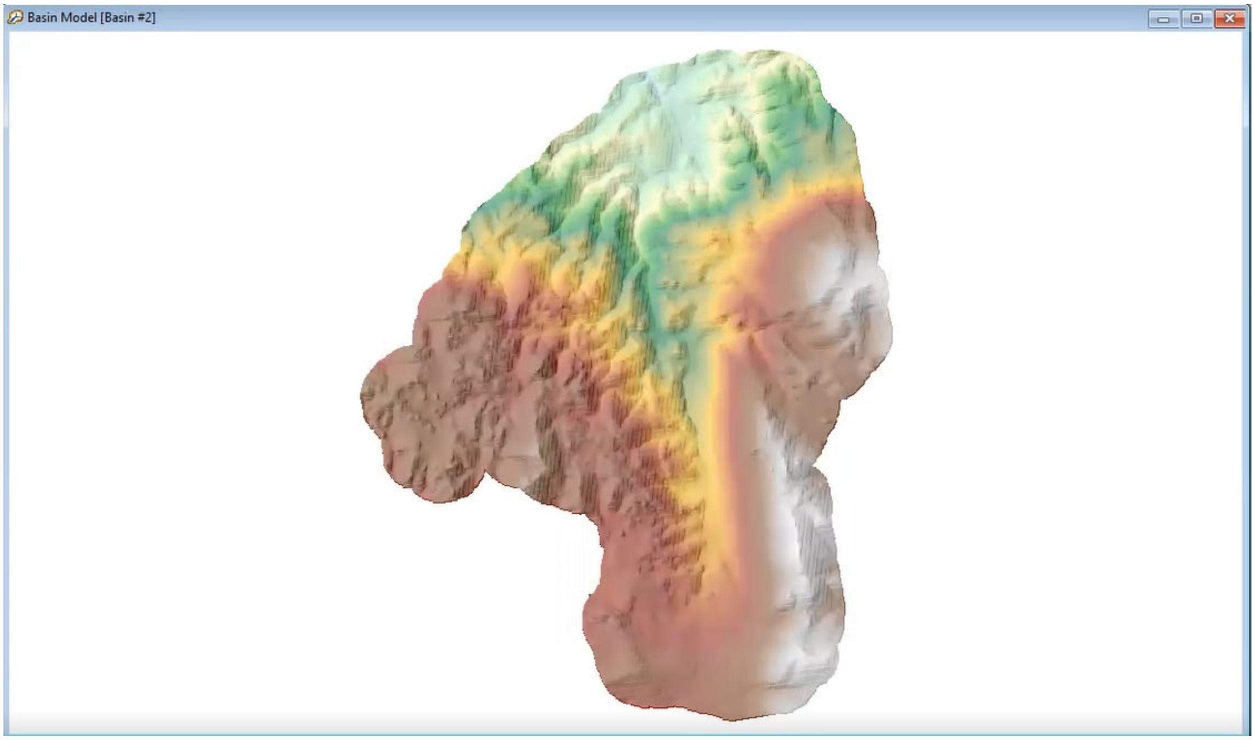
5. Associate the Terrain Data with the Basin Model and save the project.



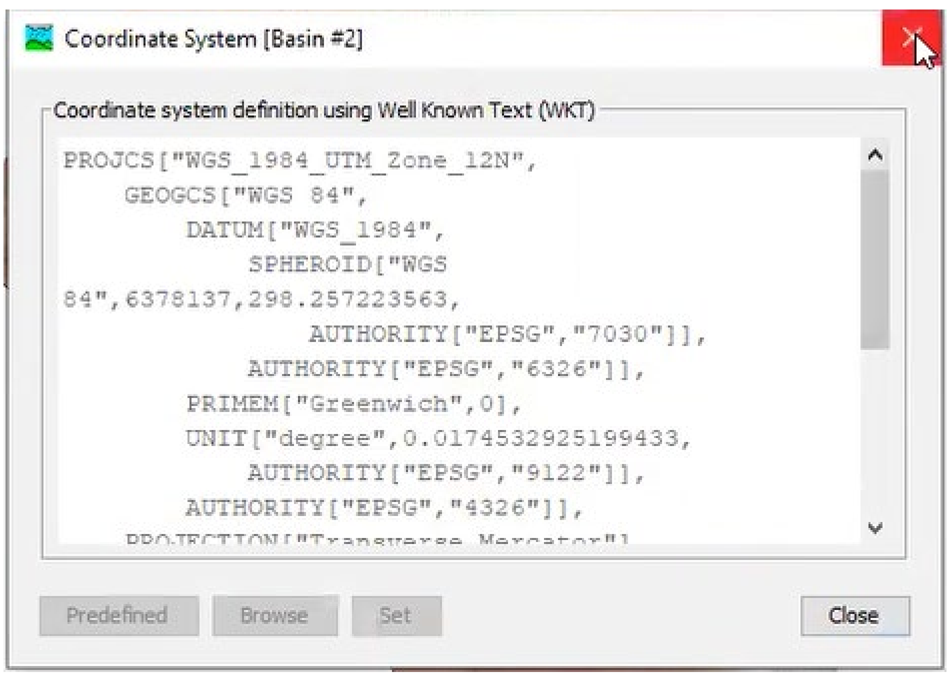
6. After clicking the save button, you will be asked to Define the Model coordinate system. If the Terrain Data contains an appropriate coordinate system, choose to skip in the window below. This will result in your Basin Model having the coordinate system of your terrain data, e.g., WGS 84 / UTM zone 12N projection; EPSG:32612. HEC-HMS v.4.9 has the ability for Basin Reprojection allowing the basin model coordinate system to be changed later.



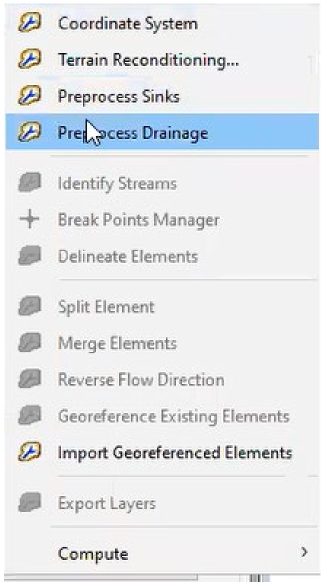
After choosing the skip the terrain definition, your terrain data should appear in the Basin Model Window.



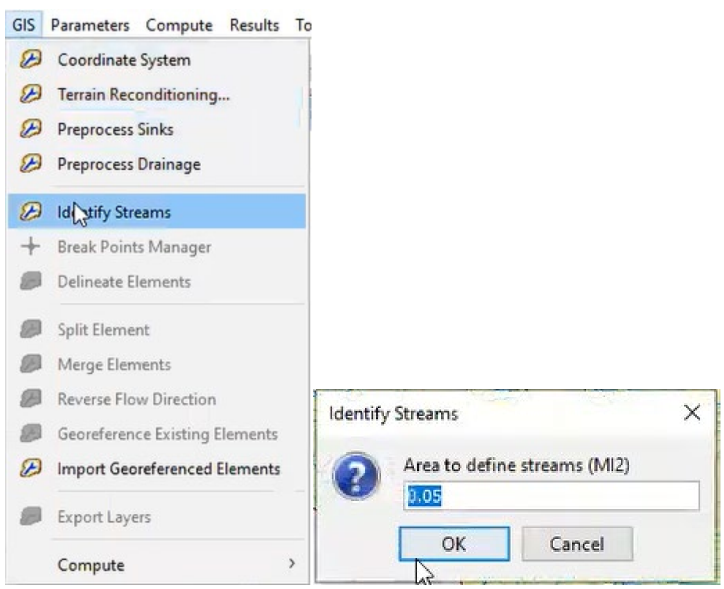
You can check your Coordinate system under the GIS tab by Choosing **Coordinate System**.



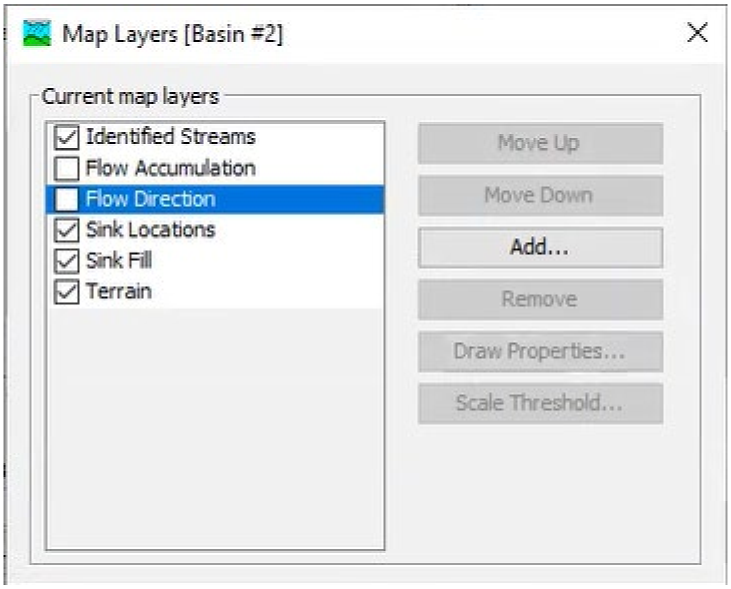
7. You are now ready to begin the watershed delineation.
   a. Under the GIS tab, select and run both **Preprocess Sinks and Preprocess Drainages.**



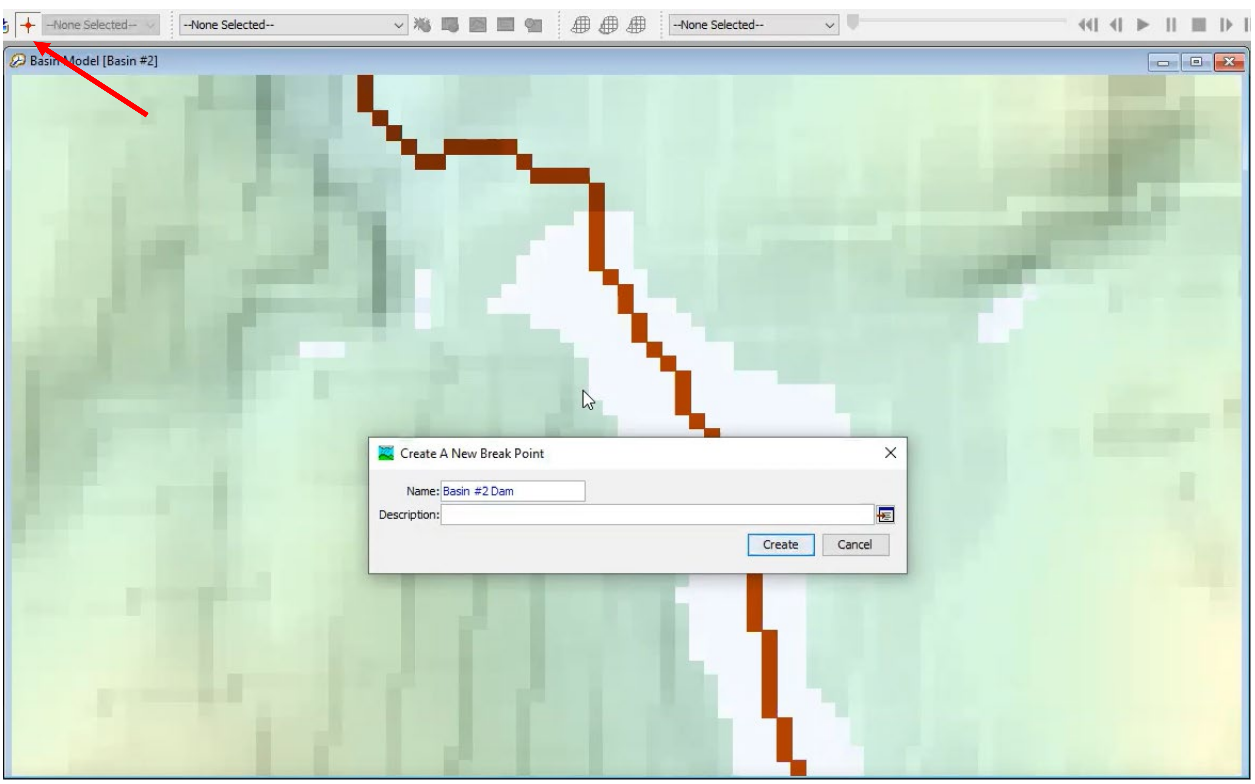
   b. Next, under the GIS tab, choose Identify Streams, which will open a window asking you to define an Area to define streams. <u>This is an iterative process that requires the analyst to use engineering judgement.</u> The larger the area to define streams, the few subbasin you will have. If you are analyzing a large area, you will need multiple subbasins; if you are analyzing a small area, one may be sufficient. Subbasins can also be merged or split later using GIS tools in HEC HMS.



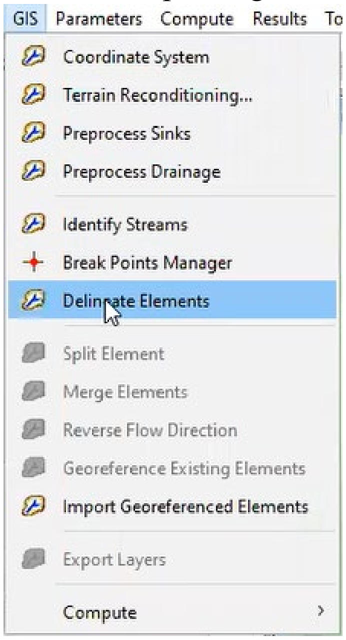
8. Under the View tab, choose **Map Layers** and turn off the Flow Accumulation and Flow Direction Layers. This allows you to see the terrain sink that HEC-HMS identified as the reservoir you are modeling.



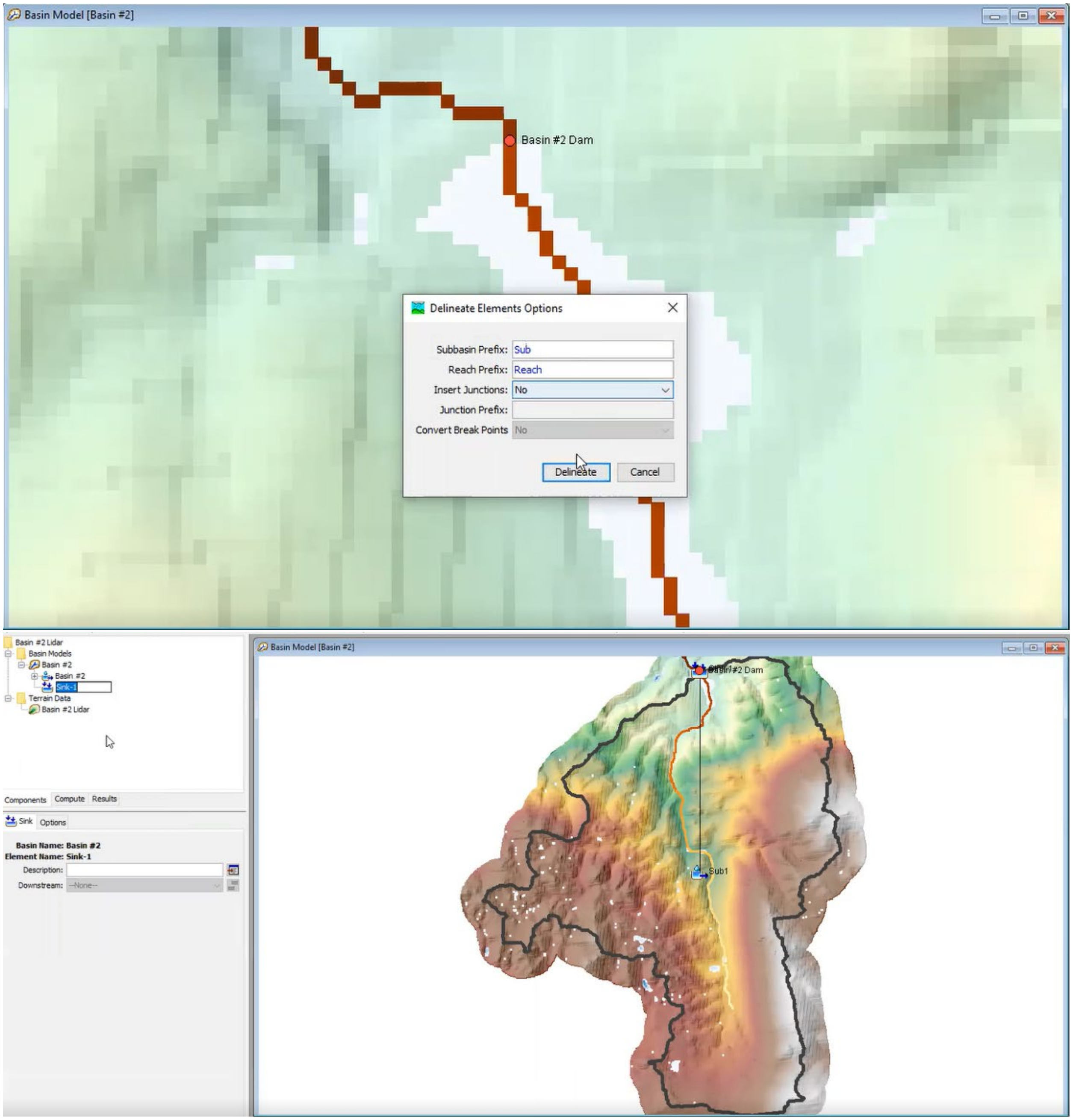
Use the mouse wheel to zoom into the location of your reservoir, then choose the Junction tool to create the downstream delineation point for your watershed.



9. The final step is to go back to the GIS tab and elect to Delineate Elements.



You can rename your basins and sinks appropriately. If you have more subbasins than desired, adjust your identified stream area and repeat the subsequent steps.


Basin Model [Basin #2]
Basin #2 Dam
Delineate Elements Options
Subbasin Prefix: Sub
Reach Prefix: Reach
Insert Junctions: No
Junction Prefix:
Convert Break Points No
Delineate
Cancel
Basin #2 Lidar
Basin Models
Basin #2
Basin #2
Sink-1
Terrain Data
Basin #2 Lidar
Components
Compute
Results
Sink
Options
Basin Name: Basin #2
Element Name: Sink-1
Description:
Downstream: --None--
Basin Model [Basin #2]
Sub1

APPENDIX B

PRISM SUPPLEMENT

SUPPLEMENT TO TECHNICAL NOTE 1

USING PRISM TO ESTIMATE PRECIPITATION FOR STORM EVENTS

INTRODUCTION

This supplement to the Montana Dam Safety Programôs *Technical Note 1, Determination of the Inflow Design Flood for High Hazard Dams in Montana*, provides short, practical guidance for using an interactive tool provided by the PRISM Climate Group for determining precipitation for historical rainfall events. This data can be used for verification, or calibration, of *HEC-HMS (Hydrologic Model System – US Army Corps of Engineers)* rainfall-runoff models on basins nearby or on the same basin as where the historical storm occurred. In order for this to be a complete verification tool, the rainfall data needs to be coupled with historical streamflow data for the same storm on the same basin.

The PRISM Climate Group is based out of Oregon State University and it ñgathers climate observations from a wide range of monitoring networksò (PRISM Climate Group website www.prism.oregonstate.edu) and develops datasets that account for terrain effects to evaluate short- and long-term climate patterns. PRISM has developed an interactive tool called Explorer that downloads time series values for individual locations in the United States. Steps on how to use the tool are explained below.

USING THE PRISM EXPLORER TOOL

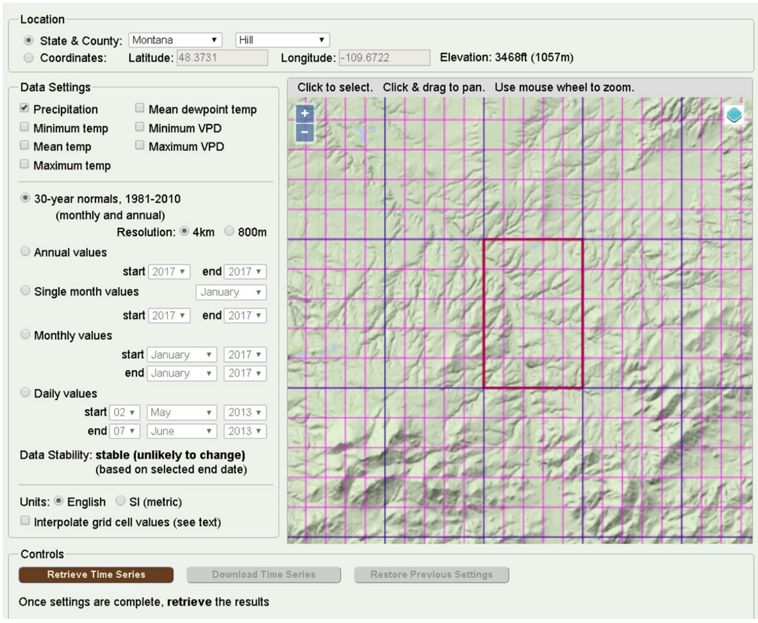
The PRISM Explorer tool is found at www.prism.oregonstate.edu/explorer/. On this page you will find an interactive map, an image of which is shown in Figure 1. Navigating to the area you are considering is easy and straightforward. The easiest way to step through the process is to explain it in an example application.

EXAMPLE USING PRISM EXPLORER TOOL

For this example, we will retrieve data from a storm that occurred in 2013 over the Beaver Creek drainage in Hill County, Montana. This storm was used in a meeting of the Extreme Storm Working Group for the Dam Safety Program as a calibration tool in verifying a rainfall-runoff model in the same drainage. The darker red rectangle shown in Figure 1 is the grid area used for retrieving the precipitation data. Here are the steps in using the Explorer tool:

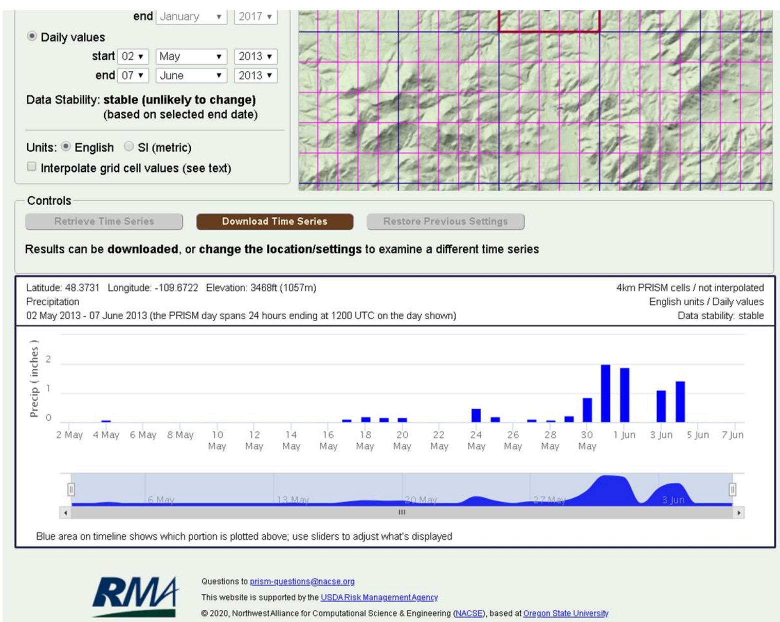
1. In the information text boxes above and to the right of the interactive map, enter the State and County (Montana and Hill). Under Data Settings, check the Precipitation box. Check the Daily Values box and enter a start date of 02 May 2013 and an end date of 07 June 2013. Under units, select English.
2. Click ôRetrieve Time Series.ö

FIGURE 1. PRISM EXPLORER TOOL INTERACTIVE MAP.



3. The hyetograph results are displayed in Figure 2.
4. The time series can be downloaded by selecting the ôDownload Time Seriesô button shown in Figure 2.

FIGURE 2. STORM DATA RESULTS, 02 MAY 2013 TO 07 JUNE 2013.



The downloaded data is shown in Figure 3.

FIGURE 3. DOWNLOADED STORM DATA, MS EXCEL *.CSV FORMAT.

PRISM Time Series Data	
Location: Lat: 48.3731 Lon: -109.6722 Elev: 3468ft	
Climate variable: ppt	
Spatial resolution: 4km	
Period: 2013-05-02 - 2013-06-07	
Dataset: AN81d	
PRISM day definition: 24 hours ending at 1200 UTC on the day shown	
Grid Cell Interpolation: Off	
Time series generated: 2020-May-14	
Details: http://www.prism.oregonstate.edu/documents/PRISM_datasets.pdf	
Date	ppt (inches)
5/2/2013	0
5/3/2013	0
5/4/2013	0.08
5/5/2013	0
5/6/2013	0
5/7/2013	0
5/8/2013	0
5/9/2013	0
5/10/2013	0
5/11/2013	0
5/12/2013	0
5/13/2013	0
5/14/2013	0.03
5/15/2013	0
5/16/2013	0
5/17/2013	0.11
5/18/2013	0.21
5/19/2013	0.17
5/20/2013	0.18
5/21/2013	0
5/22/2013	0
5/23/2013	0.01
5/24/2013	0.49
5/25/2013	0.2
5/26/2013	0
5/27/2013	0.12
5/28/2013	0.1
5/29/2013	0.24
5/30/2013	0.86
5/31/2013	1.99
6/1/2013	1.9
6/2/2013	0
6/3/2013	1.12
6/4/2013	1.43
6/5/2013	0
6/6/2013	0
6/7/2013	0

It is downloaded in MicroSoft Excel *.csv (comma-delineated) format. This can be changed to Excel Workbook (*.xlsx) format if desired. As shown in Figure 3, each data entry is a daily precipitation value, in inches. In the training session for the Dam Safety program that used this data, the day with the highest precipitation total (5/31/2013 with 1.99 inches of rain) was used to develop a storm to be used in a rainfall-runoff model with time increments of 1 hour. The distribution of the total daily precipitation was conducted according to the Montana Dam Safety Program spreadsheet supplement *2 - Hyetograph Spreadsheet Calcs_24 hr duration.xlsx*, which uses US Geological Survey methods for developing storm hyetographs for extreme storms. If you are fortunate to have good records at the reservoir during the storm (flows, outlet discharge, reservoir levels, etc.), this actual storm event can be used to calibrate a rainfall runoff model.

CONSIDERATIONS AND CAUTIONS

The suggested methods in this supplement use data from a third-party organization (PRISM Climate Group) that uses precipitation data from various sources and accounts for terrain effects to produce data for any location in the country. The data used may be subject to variation and interpretation, but it appears to be high quality data and is useful for the purposes outlined in this supplement. Attempts to access National Weather Service (of the National Oceanic and Atmospheric Agency (NOAA)) NEXRAD data proved to be complicated with results in formats that are not common for most engineering applications intended for this supplement.

The PRISM Explorer tool is easy to use, fast, and produces data that can be easily adapted to rainfall-runoff applications.

Note that if this method is used when calibrating a rainfall-runoff model that will later be used to estimate an inflow design flood, it is important to understand the following:

1. A drainage basin subject to an extreme storm, may behave differently than a drainage basin subject to a common rain event used for calibration. Thus, when calibrating using estimated runoff parameters, the modeler must be aware that infiltration loss and other parameters may be quite different for the extreme storm as compared to the calibration storm.
2. It is important to look at the days leading up to the main storm event. Were there many days of drenching rain in advance? If so, initial abstraction estimates may need to be reduced.
3. Calibrating a rainfall runoff model with an actual event is one of many tools that should be used to verify a model, if data are available and applicable to the drainage basin being considered. Due to the many uncertainties described above, the modeler must carefully balance the results from all verification methods used.
4. Rainfall-runoff models of actual storms can be used in HEC-HMS to optimize hydrologic parameters, such as unit hydrographs, infiltration losses, or initial abstraction. The same cautions should be exercised in these types of analyses as is mentioned above.

APPENDIX C

DETERMINATION OF THE
SCS CURVE NUMBER USING THE WEB SOIL SURVEY

APPENDIX C: HOW TO WEIGHT A CURVE NUMBER USING WEB SOIL SURVEY, NATIONAL LAND COVER DATASET, AND GIS TOOLS

Many approaches for computing a weighted curve number exist, and each engineer or hydrologist may have their own preference. The following methods are presented as one procedure to take advantage of readily available national datasets.

The NRCS publication Urban Hydrology for Small Watersheds (TR-55) is recommended reading for more detailed background. Additionally, Tables 2-2a through d suggest CN values for a wide range of scenarios; Figures 9-1 and 9-2 from the NRCS National Engineering Handbook, Part 630 Hydrology, Chapter 9 Hydrologic Soil-Cover Complexes also provide supplemental CN data for forest-range regions of the Western US. These sources are suggested because they are well established and frequently cited.

At a basic level, selecting a CN requires two considerations: land cover type and hydrologic soil group. TR-55 provides guidance on weighting CNs and provides sample worksheets for the analyst to fill out – below is sample Worksheet 2. The weighted average is simply:

$$\overline{CN} = \frac{\sum CN_i * A_i}{\sum A_i}$$

Worksheet 2: Runoff curve number and runoff

Project: Heavenly Acres | By: WJR | Date: 10/1/85

Location: Dyer County, Tennessee | Checked: NM | Date: 10/3/85

Check one: [X] Present [ ] Developed

1. Runoff curve number

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN 1/ Table 2-2	CN 1/ Figure 2-3	CN 1/ Figure 2-4	Area ☐ acres ☐ mi² ☒ %	Product of CN x area
Memphis, B	Pasture, good condition	61			30	1830
Loring, C	Pasture, good condition	74			70	5180
1/ Use only one CN source per line				Totals ➡	100	7010

CN (weighted) = total product / total area = 7010 / 100 = 70.1 ; Use CN ➡ 70

This manual method may be sufficient for smaller basins, but it requires the analyst to select a CN when they may not know both the land cover type and soil group for the same acreage. Many experienced analysts are able to select accurate CNs for smaller projects and then refine their initial choices through calibration. A small basin that is dominated by one or two land cover types may not require much GIS analysis – for example, many alpine basins in Montana have predominantly evergreen land cover. The analyst could estimate the percentage of each land cover and then review results from the Web Soil Survey to assign CNs based on land cover type and hydrologic soil group.

For larger or more complicated projects, it is recommended to use datasets like the Web Soil Survey and National Land Cover Dataset. Ideally, a project area would have high-resolution, local data, but that is infrequently the case in Montana; lower-resolution national datasets like the WSS and NLCD often produce good results for rainfall-runoff modeling and provide statewide coverage. For those comfortable with GIS software, these datasets can be downloaded and analyzed using GIS. This method also has the benefit of being more defensible, since it relies on published national data, rather than simply citing "engineering judgment" in choosing a CN.

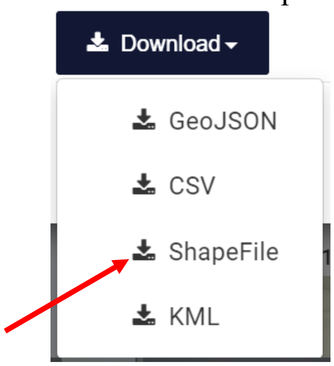
Intermediate projects could use a combination of these approaches – for example, downloading results from the Web Soil Survey and quickly weighting them in Excel. The analyst should decide the right level of detail for their project.

TR-55 provides an excellent overview of weighting CNs, so this example focuses on using the WSS and NLCD with GIS tools.

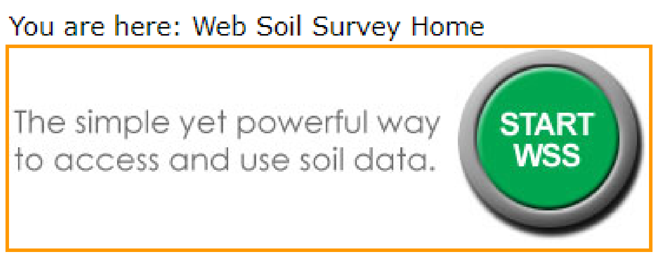
B -1 HOW TO OBTAIN HYDROLOGIC SOIL GROUP FROM NRCS WEB SOIL SURVEY

Note that these instructions are long, but the process itself is relatively quick if using the screenshots. If using the GIS tools, some familiarity with GIS products is helpful, but expertise is not required; savvy analysts can produce good results, while relying on their staff GIS expert if needed.

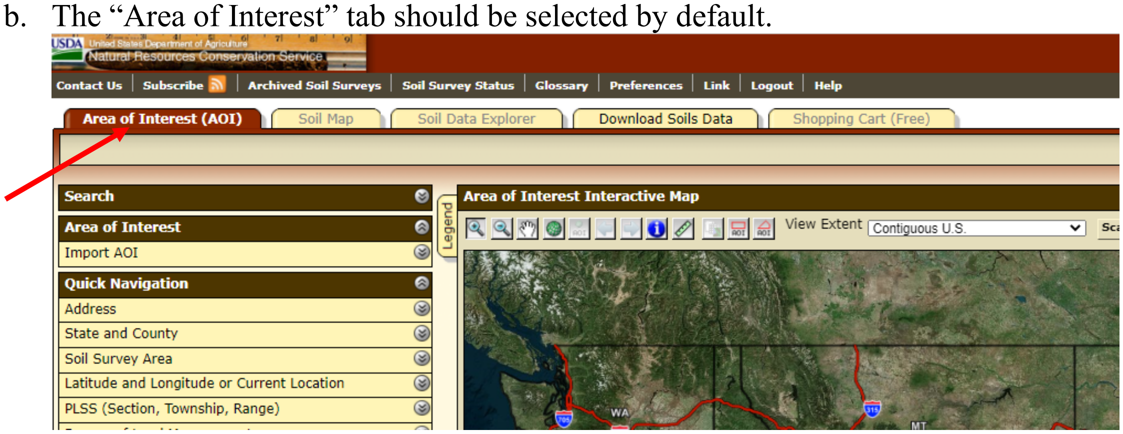
1. Delineate the watershed using StreamStats (or other method of the analyst's choice)
    a. Review the watershed for correctness; add or remove areas as needed
    b. Download the shapefile; the screenshot below is from StreamStats



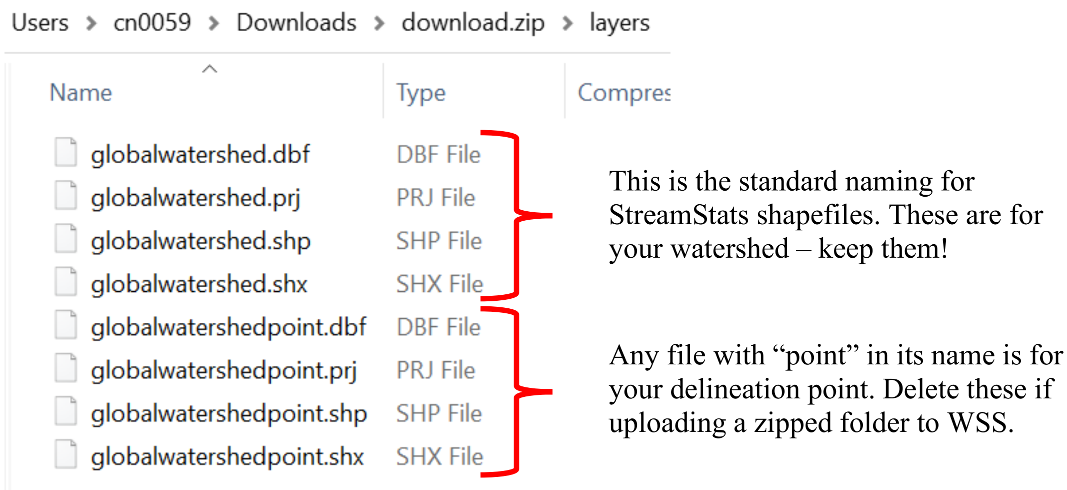
2. Navigate to the main Web Soil Survey page. https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm
    a. Click on the "Start WSS" button.



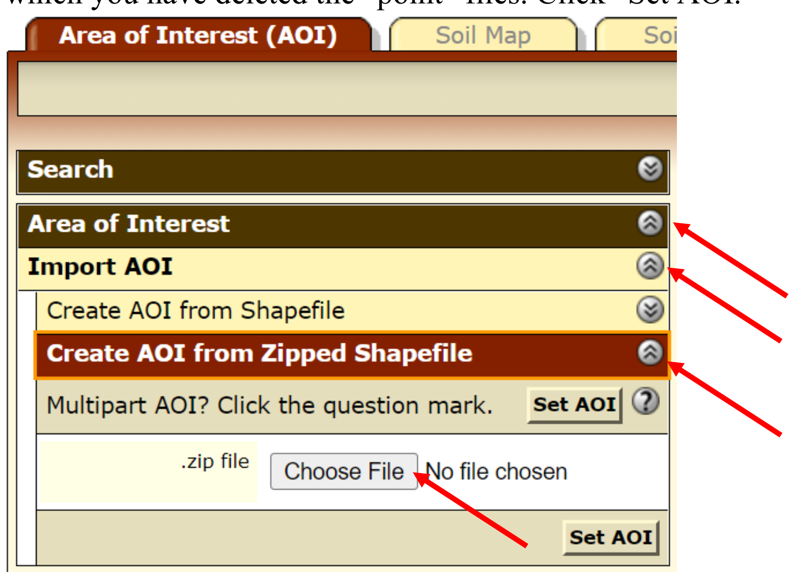
    b. The "Area of Interest" tab should be selected by default.



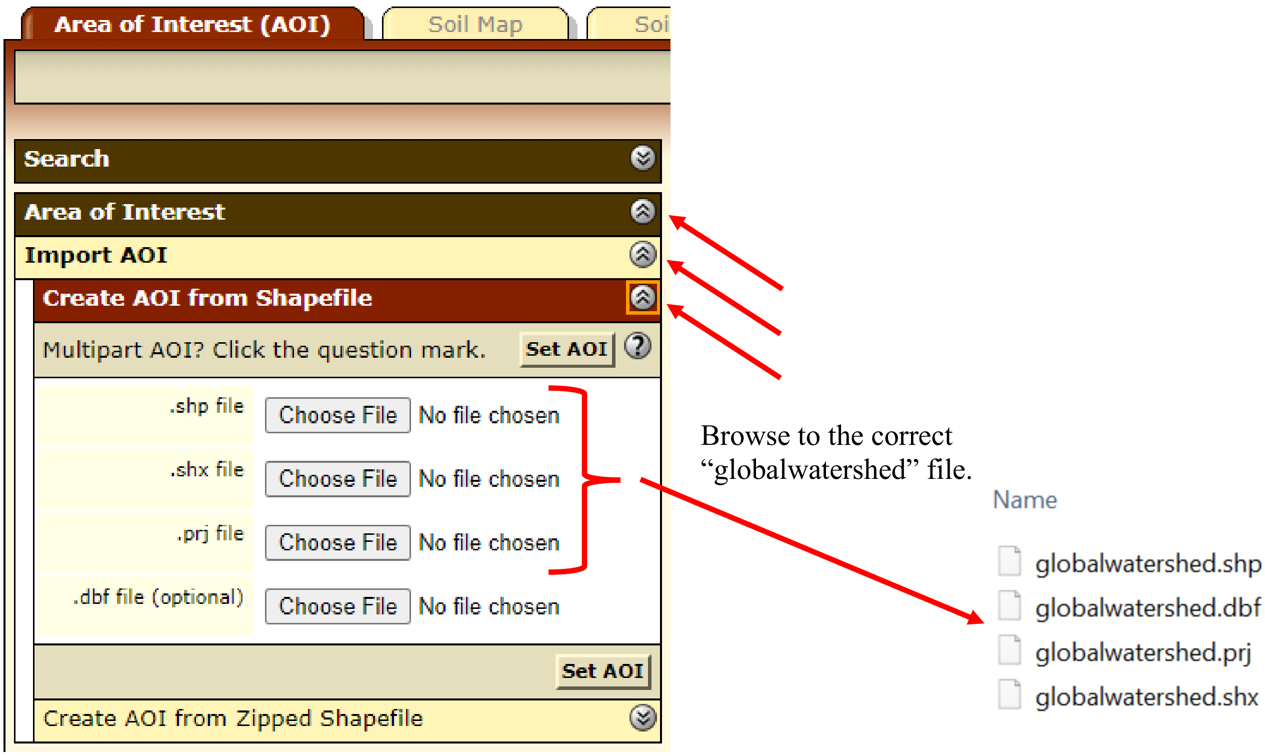
3. The WSS allows you to manually delineate an area of interest, but it is much easier to upload the shapefile of the watershed you delineated in StreamStats.
    a. The StreamStats watershed is downloaded as a zipped folder. WSS allows upload of either (i) the full zipped folder or (ii) the unzipped .shp, .shx, and .prj files. Both options are simple and produce the same results.
        i. Full Zipped Folder: Note that StreamStats creates shapefiles for both your basin and the delineation point you selected, so if uploading a zipped file, you must delete the shapefiles for the delineation point. That is, you must upload the shapefiles for only the watershed basin.



Open the main dropdown menu for "Area of Interest," then open the dropdown menus for "Import AOI" and "Create AOI from Zipped Shapefile." Select "Choose File" and navigate to the zipped folder from which you have deleted the "point" files. Click "Set AOI."

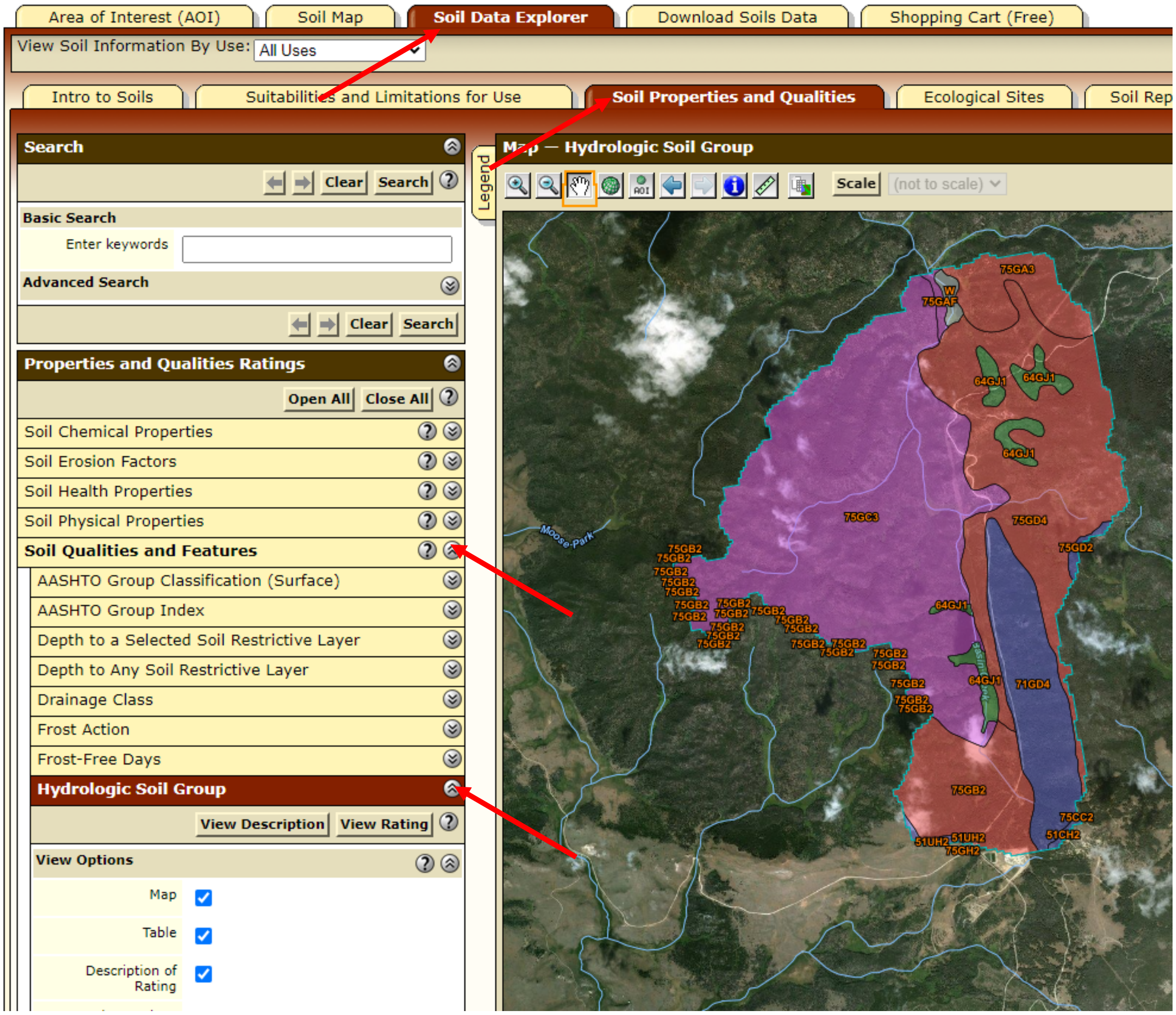


ii. Unzipped Individual Files: Unzip the StreamStats watershed folder using the Windows command, 7-Zip, etc. Open the main dropdown menu for "Area of Interest," then open the dropdown menus for "Import AOI" and "Create AOI from Shapefile." Browse individually to the appropriate .shp, .shx, and .prj files by selecting "Choose File," as shown below. Make sure that you select the watershed files without "point" in their file name (those with "point" in the file name are for your delineation point only).

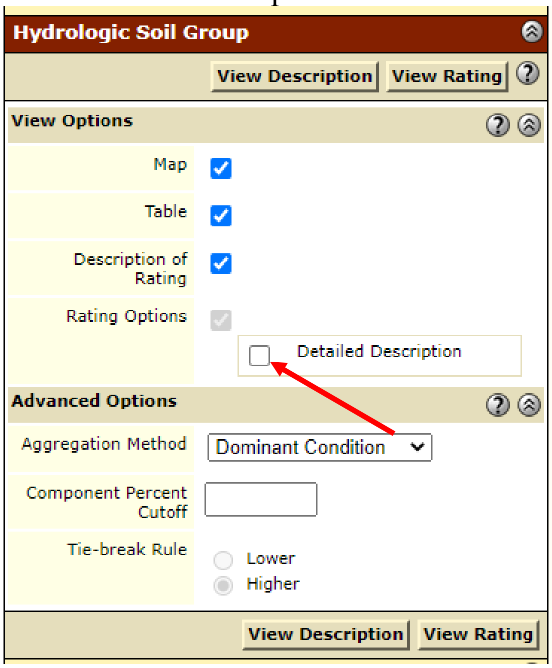


b. Once you have uploaded your shapefile, it should display on the map. By default, it displays the map unit name and symbol and the acreage.

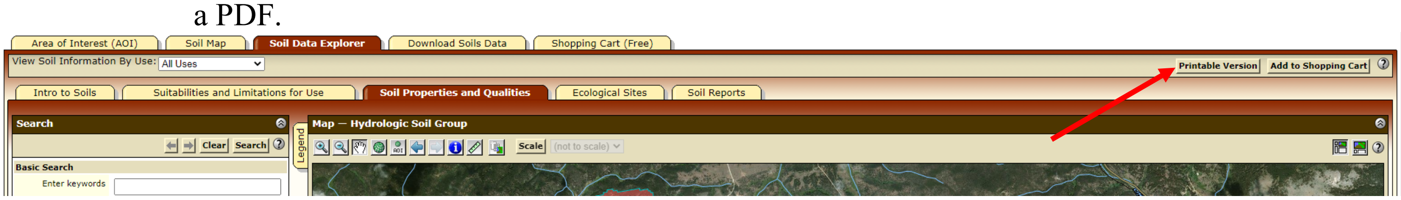
4. To obtain the hydrologic soil group, click on “Soil Data Explorer,” then on “Soil Properties and Qualities.” Under the “Soil Qualities and Features” drop-down menu, select “Hydrologic Soil Group” from the drop-down menu.



5. **Option 1: Download your results – PDF summary**
   a. Leave the default options as shown below; optionally, also check “Detailed Description”



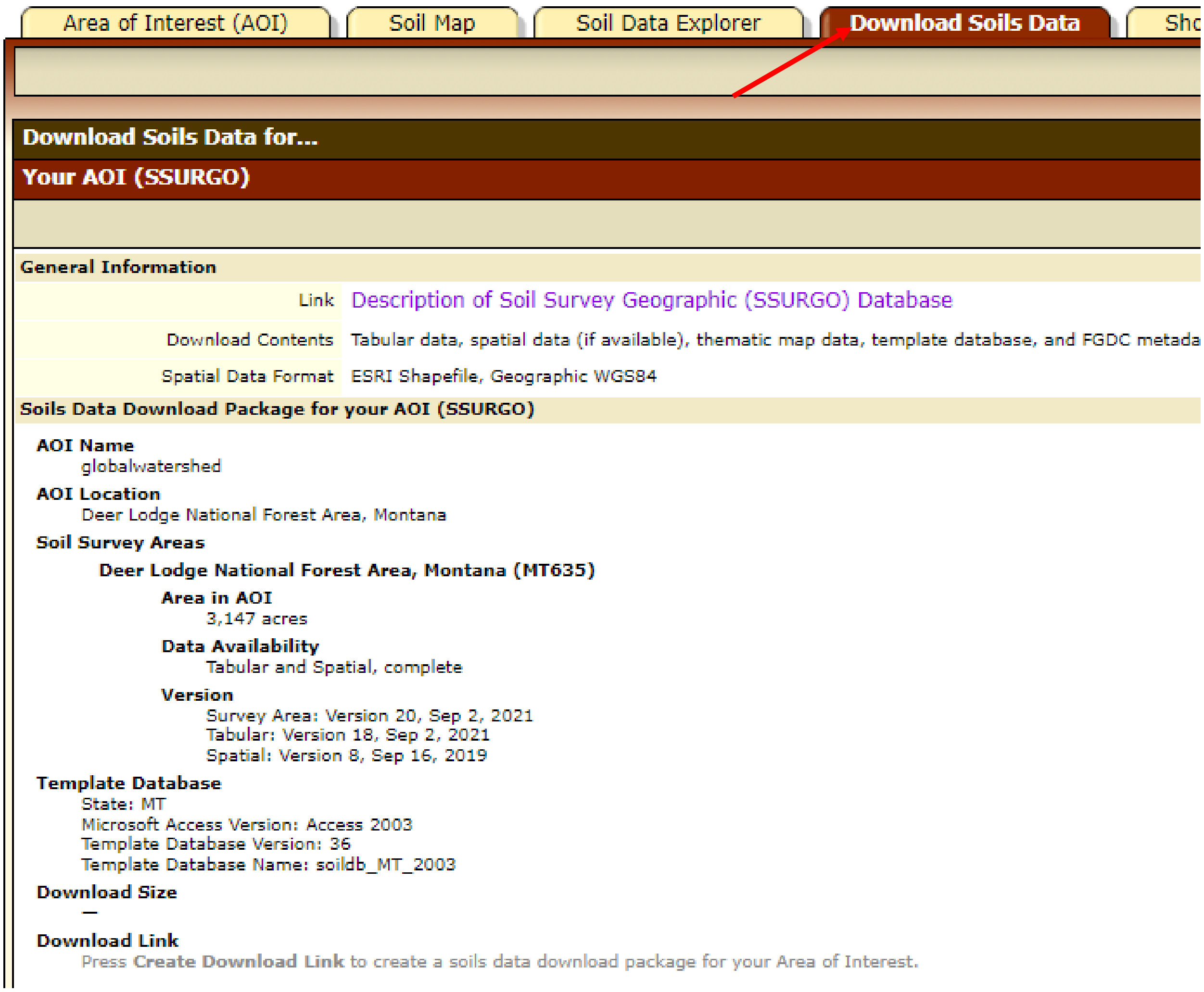
   b. On the far-right side of the screen, click on “Printable Version” and download as a PDF.



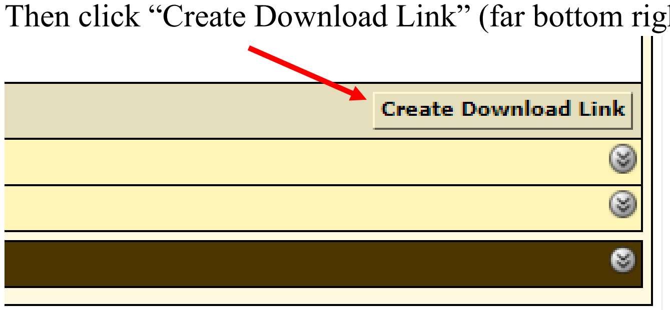
   c. Export your PDF to a spreadsheet to calculate a weighted curve number. In Adobe Acrobat Pro, choose “File” → “Export to” → “Spreadsheet.”

6. Option 2: Download your results – GIS

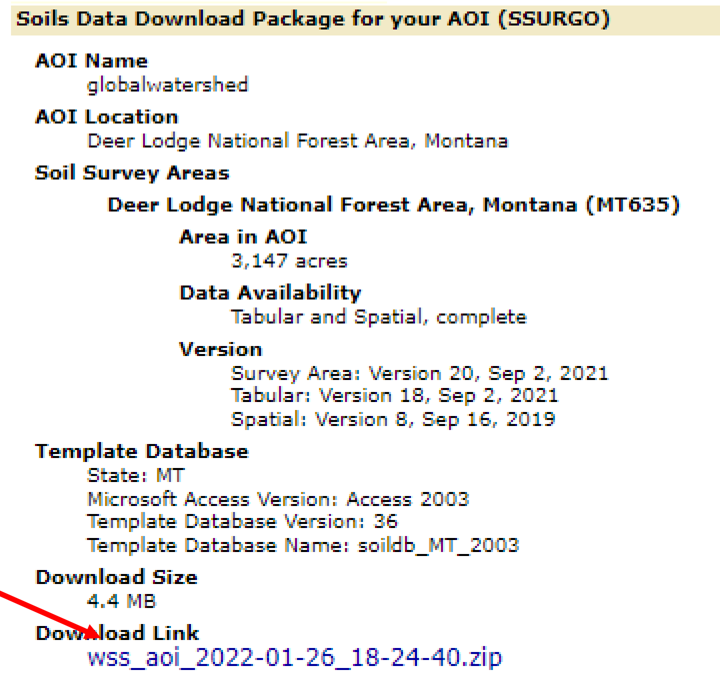
a. Click on the "Download Soils Data" tab



b. Then click "Create Download Link" (far bottom right of screen)



c. Download the zip file that appears under “Download Link”



Soils Data Download Package for your AOI (SSURGO)

AOI Name
globalwatershed

AOI Location
Deer Lodge National Forest Area, Montana

Soil Survey Areas

Deer Lodge National Forest Area, Montana (MT635)

Area in AOI
3,147 acres

Data Availability
Tabular and Spatial, complete

Version
Survey Area: Version 20, Sep 2, 2021
Tabular: Version 18, Sep 2, 2021
Spatial: Version 8, Sep 16, 2019

Template Database
State: MT
Microsoft Access Version: Access 2003
Template Database Version: 36
Template Database Name: soildb_MT_2003

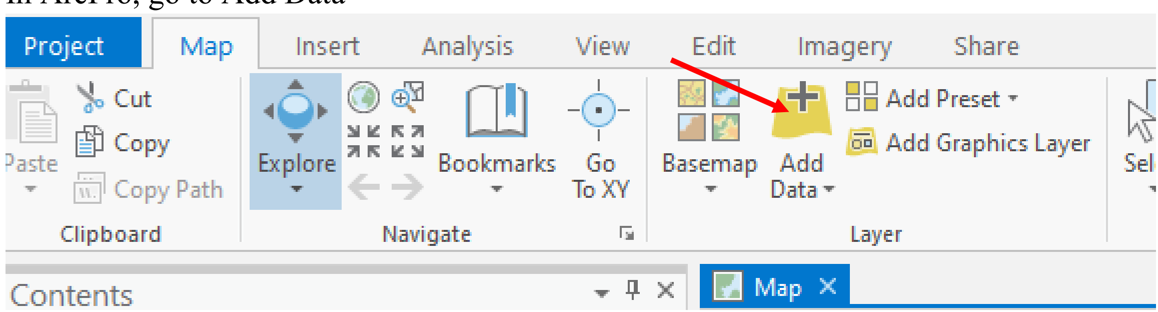
Download Size
4.4 MB

Download Link
wss_aoi_2022-01-26_18-24-40.zip

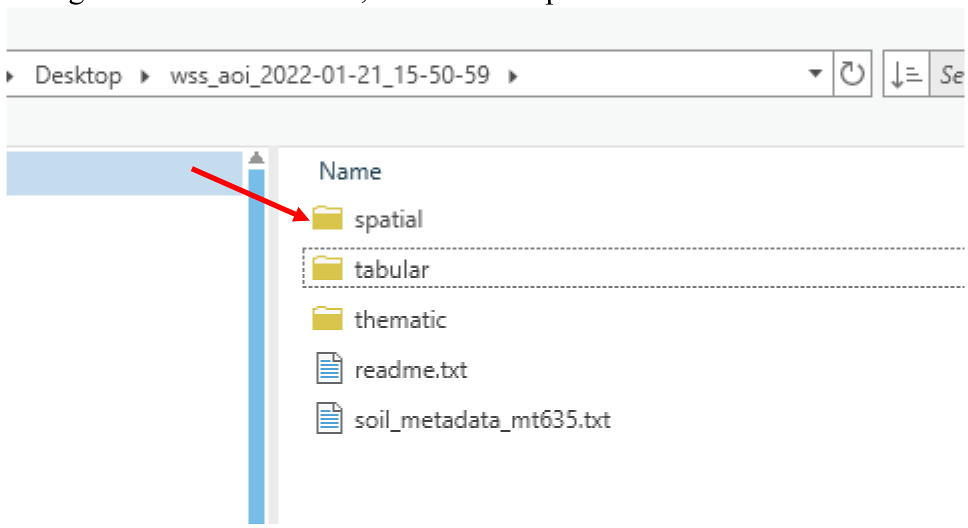
d. Unzip the file and import it into ArcPro (or GIS software of choice)

i. The file name will be “wss_aoi_YYYY-MM-DD-HH-MM-SS”

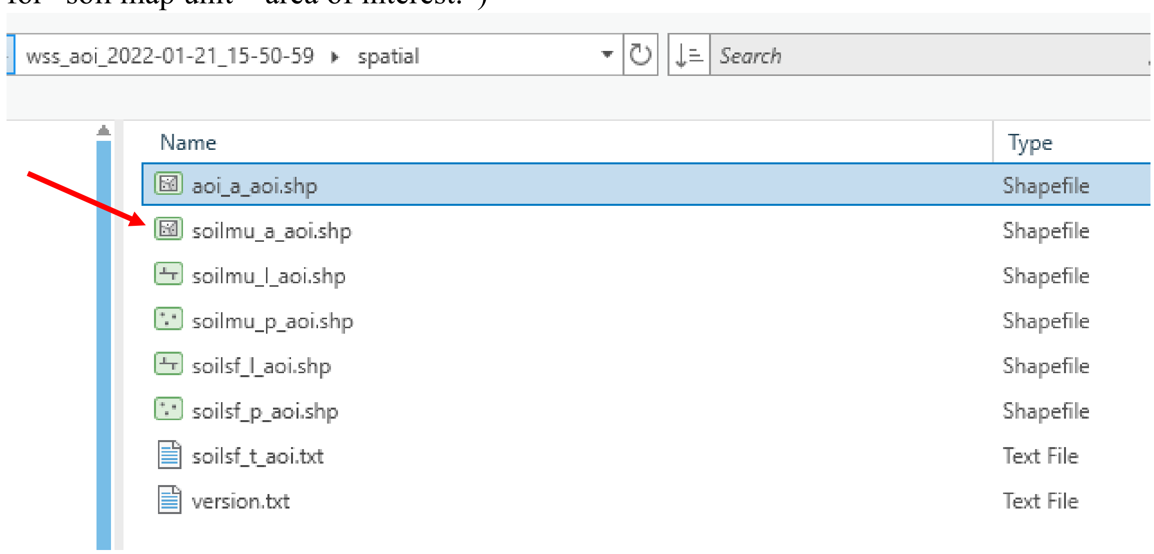
ii. In ArcPro, go to Add Data



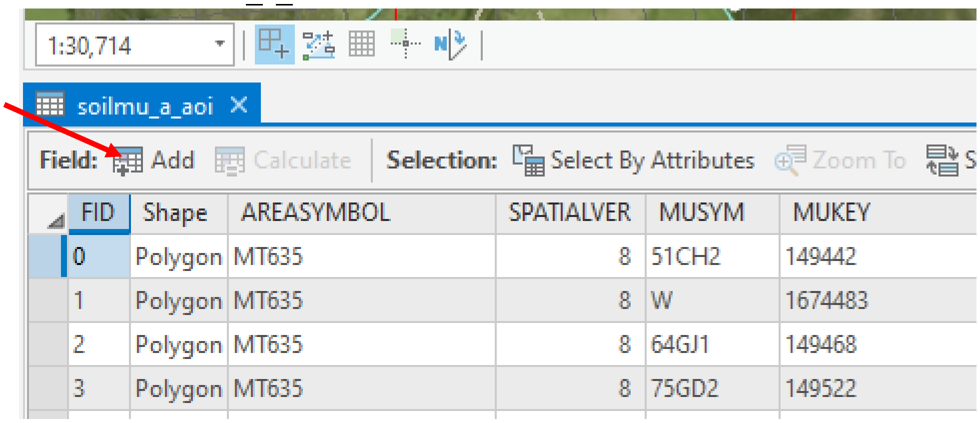
iii. Navigate to the WSS folder, then to the “spatial” sub-folder.



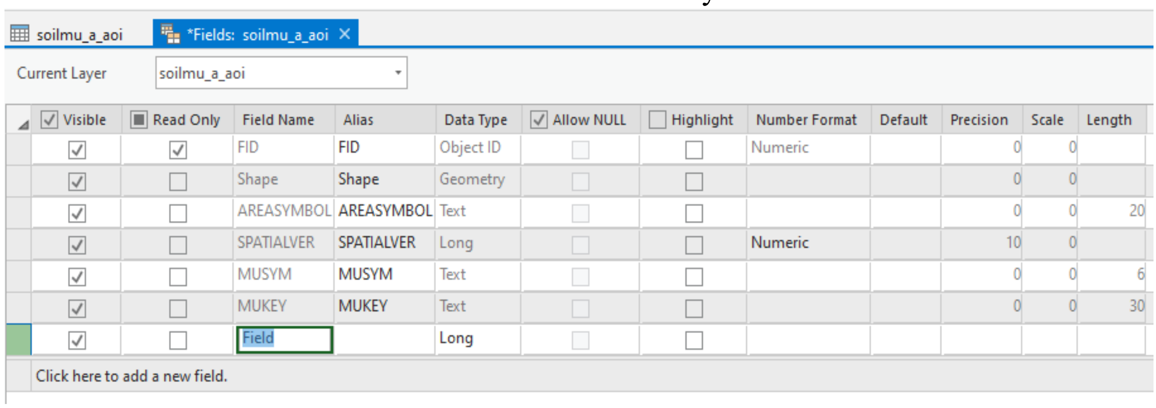
iv. The data we are interested in are “soilmu_a_aoi” (This is an abbreviation for “soil map unit – area of interest.”)



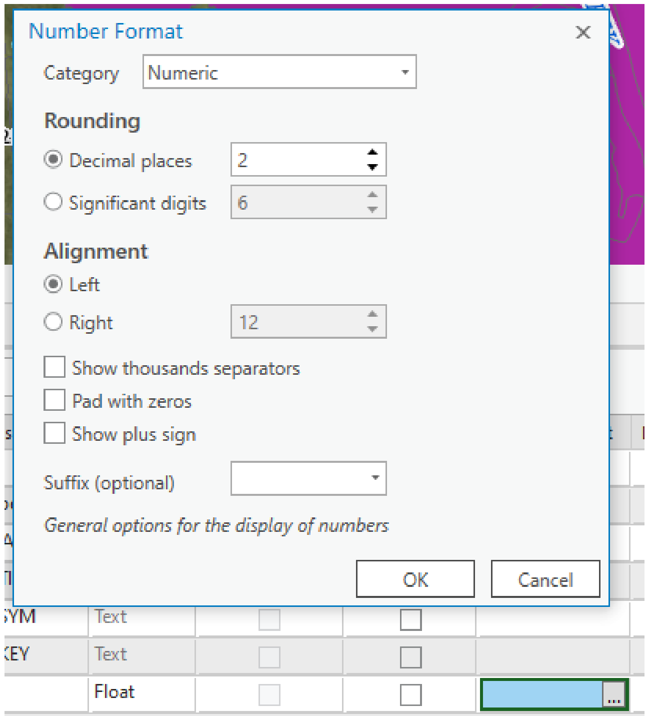
v. Right click on the shapefile in your Contents pane and open the Attribute Table for "soilmu_a_aoi." Add a field for area.



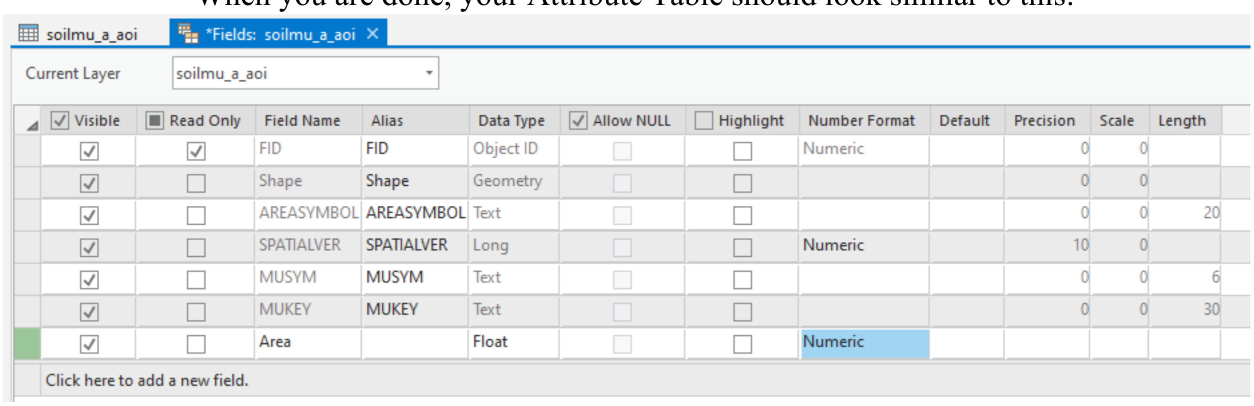
vi. Your Attribute Table should look similar to this when you start



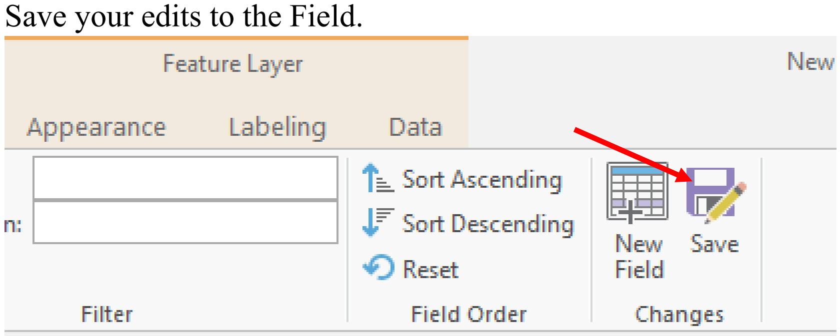
vii. Name the field “Area” and change the data type to “Float,” change the number format to “Numeric,” and select a reasonable number of decimal places (two decimal points should be sufficient). The “Numeric” pop-up is shown below:



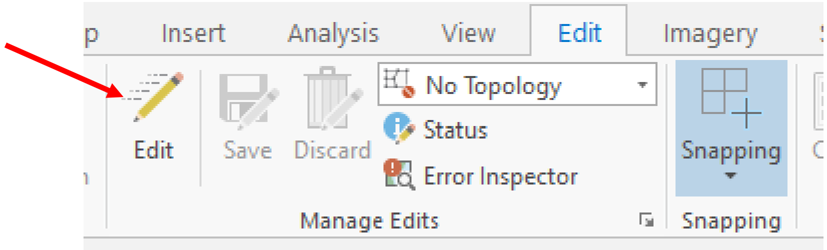
When you are done, your Attribute Table should look similar to this:



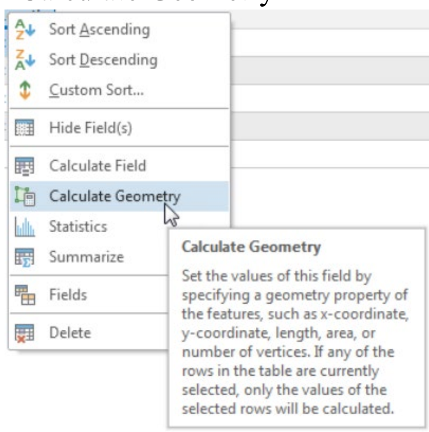
viii. Save your edits to the Field.



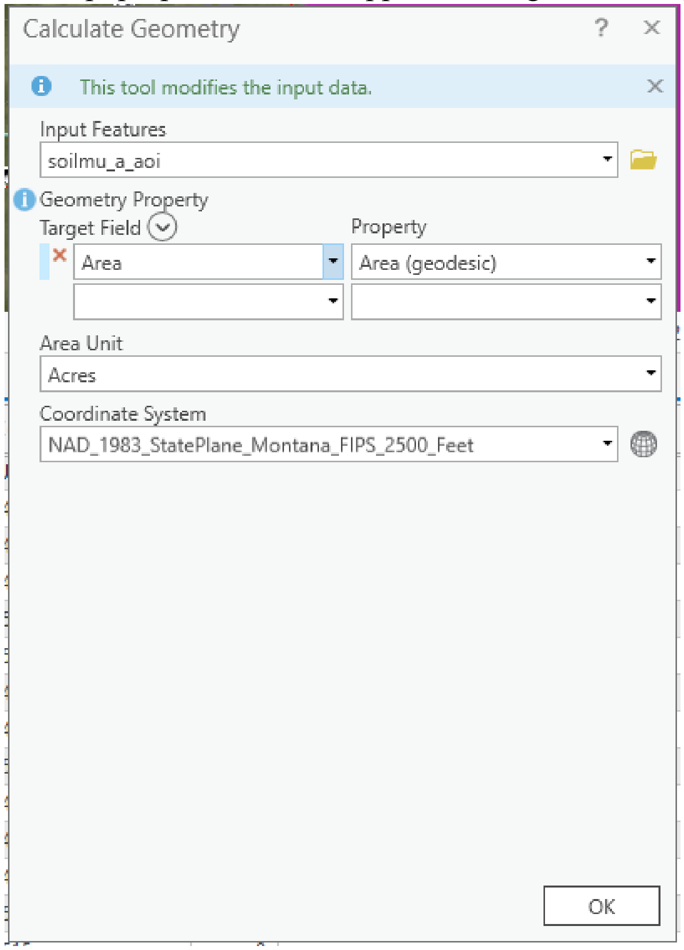
ix. Make sure you turn editing on – in the Edit Tab, click the “Edit” icon



x. Return to the main Attribute Table, right click on “Area,” and choose “Calculate Geometry”

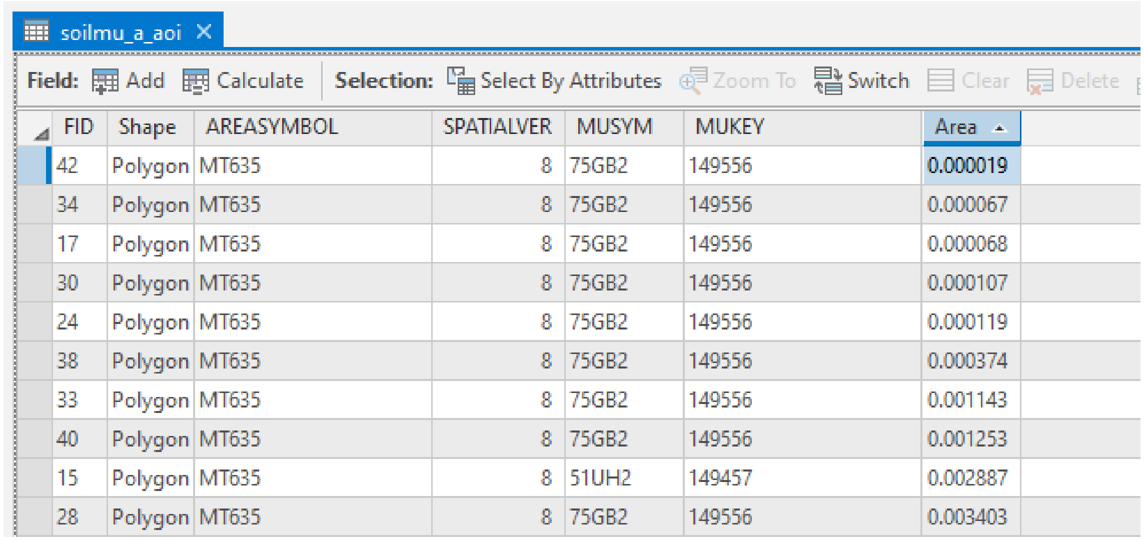


xi. In the pop-up window that appears, change the settings to be as follows:



For the coordinate system, it is recommended to use the same coordinate system as the rest of your map (this should be the first option, labeled "Current Map [Map]"). Click "OK."

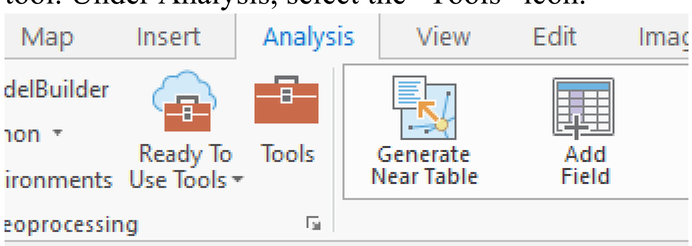
xii. Calculate Geometry will run, and it should populate the attribute table with the area in each row.



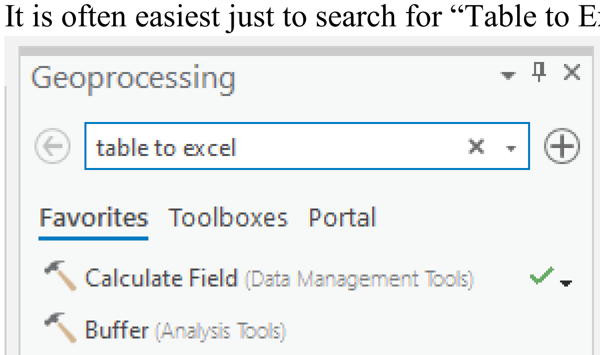
FID	Shape	AREASYMBOL	SPATIALVER	MUSYM	MUKEY	Area
42	Polygon	MT635	8	75GB2	149556	0.000019
34	Polygon	MT635	8	75GB2	149556	0.000067
17	Polygon	MT635	8	75GB2	149556	0.000068
30	Polygon	MT635	8	75GB2	149556	0.000107
24	Polygon	MT635	8	75GB2	149556	0.000119
38	Polygon	MT635	8	75GB2	149556	0.000374
33	Polygon	MT635	8	75GB2	149556	0.001143
40	Polygon	MT635	8	75GB2	149556	0.001253
15	Polygon	MT635	8	51UH2	149457	0.002887
28	Polygon	MT635	8	75GB2	149556	0.003403

xiii. At this point, you can save your work and turn off "Edit." Those comfortable with GIS analysis may prefer to continue working in ArcPro. An easier option at this stage is to export your results to a spreadsheet program like Excel and continue your analysis there.

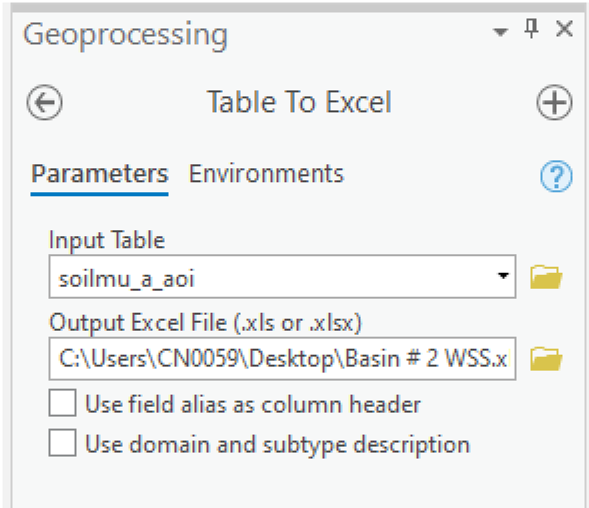
xiv. As with anything in GIS, there are multiple ways to accomplish the same result. One way to export your table is the "Table to Excel" Geoprocessing tool. Under Analysis, select the "Tools" icon.



It is often easiest just to search for "Table to Excel" in the search box.



Once in the “Table to Excel” tool, choose the “soilmu_a_aoi” Attribute Table that we’ve been working with as the input, then choose where you’d like to export the Excel file.

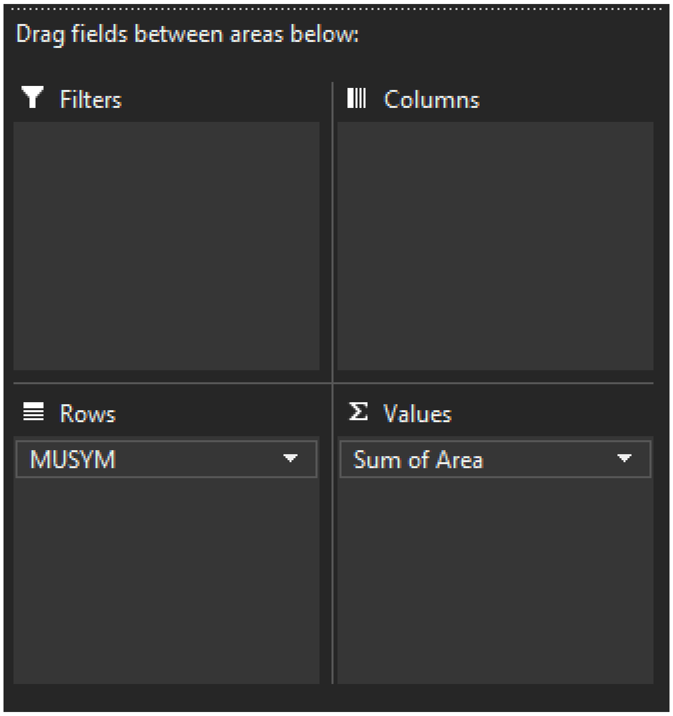


Click “Run” at the bottom, and you’re done!

7. Open the resulting Excel file. You will have one row for each individual area, but we want to group these together to calculate the total area of each soil type. Note that “MUSYM” and “MUKEY” are abbreviations for Map Unit Symbol and Map Unit Key, respectively. Your table will look something like this:

	A	B	C	D	E	F	G	H
1	FID	AREASYMBOL	SPATIALVER	MUSYM	MUKEY	Area		
2	0	MT635	8	51CH2	149442	5.391370053		
3	1	MT635	8	W	1674483	16.92539878		
4	2	MT635	8	64GJ1	149468	27.85364999		
5	3	MT635	8	75GD2	149522	11.16342438		
6	4	MT635	8	75GA3	149514	155.5740454		
7	5	MT635	8	64GJ1	149468	5.660503997		
8	6	MT635	8	64GJ1	149468	18.63811539		
9	7	MT635	8	75CC2	149511	0.098684623		
10	8	MT635	8	64GJ1	149468	26.72266288		
11	9	MT635	8	71GD4	149489	316.2732409		
12	10	MT635	8	64GJ1	149468	23.93997356		
13	11	MT635	8	75GC3	149518	1494.075671		
14	12	MT635	8	75GAF	149515	11.92099839		
15	13	MT635	8	75GD4	149523	743.9326854		
16	14	MT635	8	75GH2	149526	0.012811222		
17	15	MT635	8	51UH2	149457	0.002886906		
18	16	MT635	8	51UH2	149457	8.293287027		
19	17	MT635	8	75GB2	149556	6.79989E-05		
20	18	MT635	8	75GB2	149556	0.036107345		
21	19	MT635	8	75GB2	149556	0.801002255		
22	20	MT635	8	75GB2	149556	0.088648676		
23	21	MT635	8	75GB2	149556	0.036235708		
24	22	MT635	8	75GB2	149556	0.01151999		

a. A quick way to group your data is by using a Pivot Table. Select all your data (including headers), then choose "Insert" → "Pivot Table." Use "MUSYM" (or rename it to something more meaningful, such as "Map Unit") as your Rows, then use the Pivot Table function "Sum" for the Area.



This groups all Map Unit Symbols together, as shown below.

Sum of Area	
MUSYM	Total
51CH2	5.391370053
51UH2	8.296173933
64GJ1	102.8149058
71GD4	316.2732409
75CC2	0.098684623
75GA3	155.5740454
75GAF	11.92099839
75GB2	280.4073195
75GC3	1494.075671
75GD2	11.16342438
75GD4	743.9326854
75GH2	0.012811222
W	16.92539878
Grand Total	3146.886729

You can now match the Hydrologic Soil Group rating from the PDF results printout to each Map Unit Symbol. For example, our first row 51CH2 corresponds to group B; 51UH2 corresponds to group B; and so on. You will have to manually assign the Group to each Map Unit Symbol.

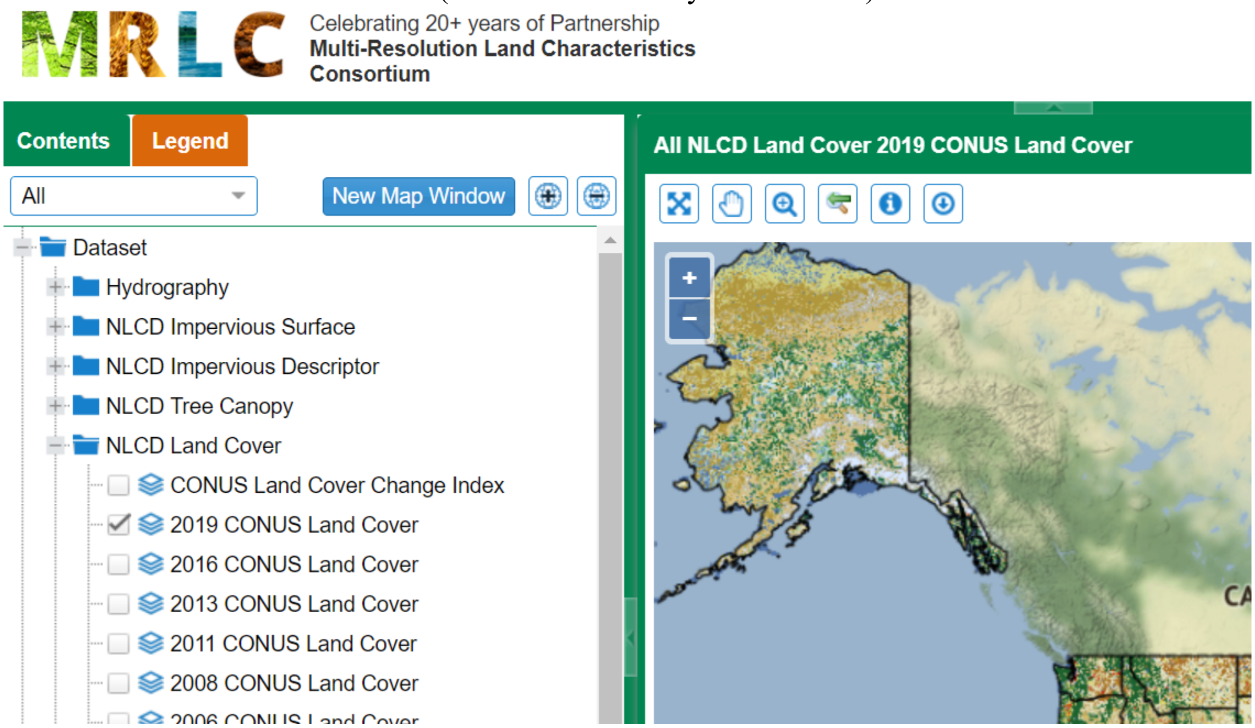
Hydrologic Soil Group

Map unit symbol	Map unit name	Rating	Acres in AOI	Percent of AOI
51CH2	Hanson-Tiban families-Rubble land complex, steep ridges and mountain slopes	B	5.4	0.2%
51UH2	Sebud-Libeg-Marcetta families, complex, steep ridges and mountain slopes	B	8.3	0.3%
64GJ1	Cryofluvents-Finn family-Water complex, rolling stream terraces and flood plains	A/D	102.8	3.3%

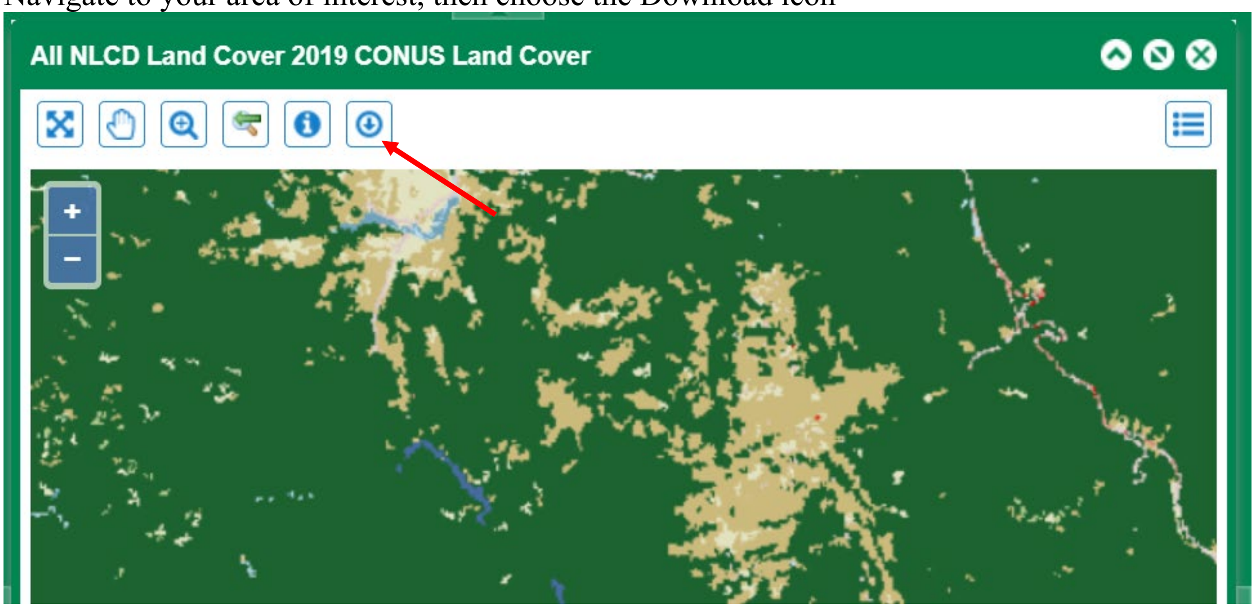
b. This allows you to compute the percentage of your watershed that is rated A, B, C, or D.

B.2 HOW TO OBTAIN LAND COVER FROM NATIONAL LAND COVER DATASET

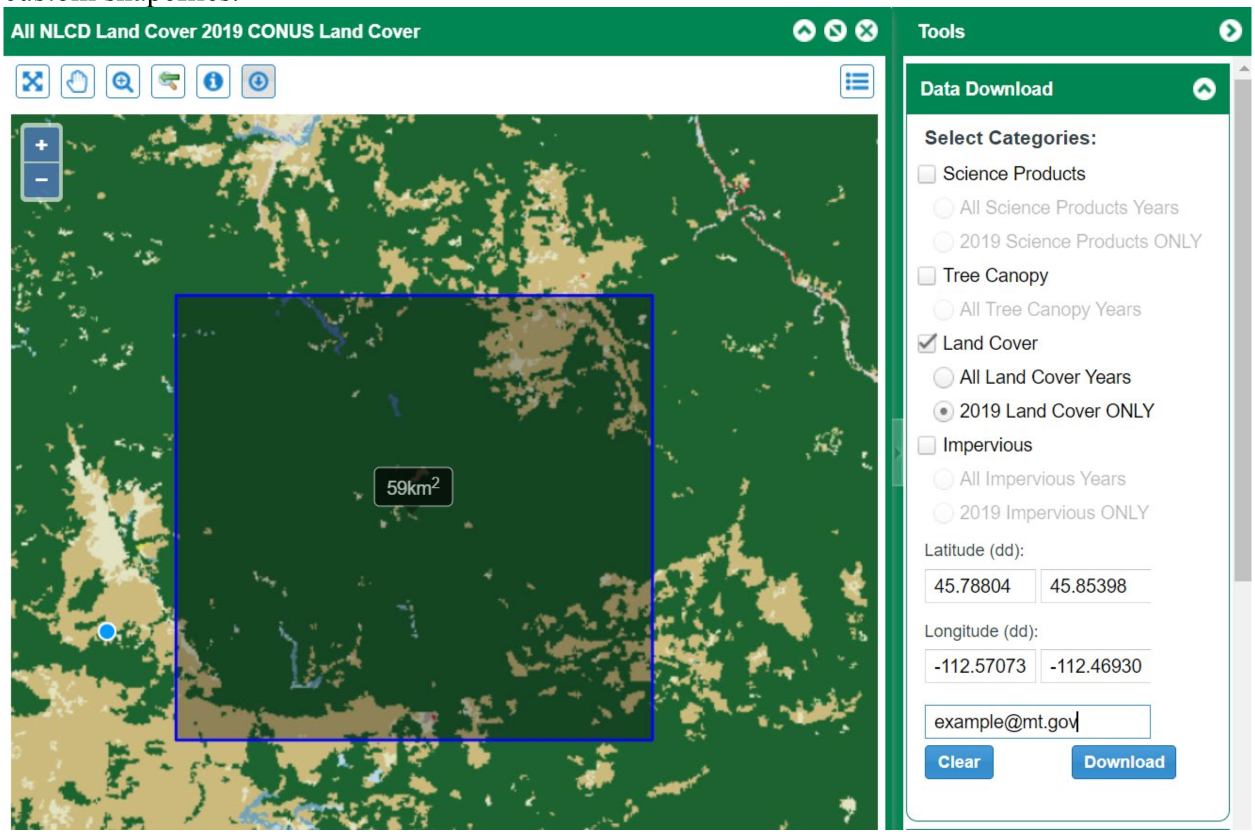
1. Much of the GIS process is the same for the NLCD as what was previously outlined for the WSS. Navigate to the NLCD viewer, at https://www.mrlc.gov/viewer/.
2. Select 2019 CONUS Land Cover (or the most recent year available)



3. Navigate to your area of interest, then choose the Download icon



4. Draw a box around the area of interest, then make the appropriate selections under "Data Download," shown below. Unlike WSS, NLCD does not currently support upload of custom shapefiles.

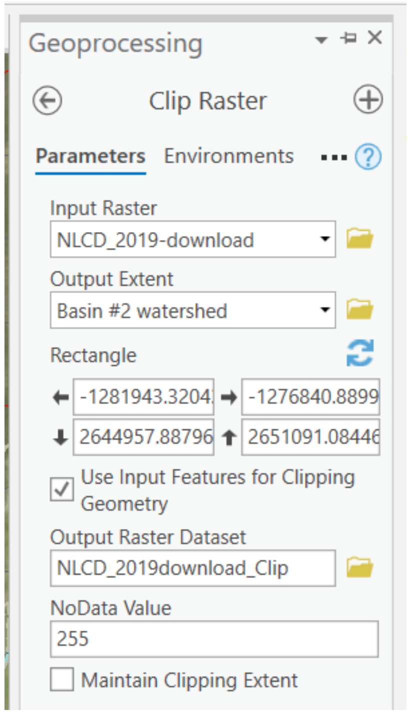


5. Click "Download" – you will receive an email link within 24 hours. For smaller projects, it is usually less than a minute.
6. Download and unzip your data. Add your data to ArcPro. You want to add the TIFF file with a name like "NLCD_2019_Land_Cover" – <u>not</u> the land cover change index.
7. Note that NLCD does not support upload of a shapefile for your area of interest (like we did with the WSS); you must download a rectangular area of interest and then trim it to the boundaries of your watershed. When trimming, be sure to use the actual delineated watershed boundary and not the buffered watershed that you used to set the extents of your DEM in Appendix A.
8. The NLCD downloads as a raster. Trim the NLCD raster to the extents of watershed shapefile.
   a. On the Analysis tab in the upper left corner of ArcPro, select the Tools button. This will open a search bar on the right-hand side of the page. Search for Clip Raster and select the Clip Raster (Data Management Tools) tool.
   b. A form will display on the right-hand side of your window:
      i. Input Raster – select your NLCD file
      ii. Output Extent – select your watershed shapefile
      iii. Below Rectangle, **Check** the Use Input Features for Clipping Geometry
      iv. Output Raster Dataset – click the folder icon to the right and navigate to where you would like to save your clipped NLCD file

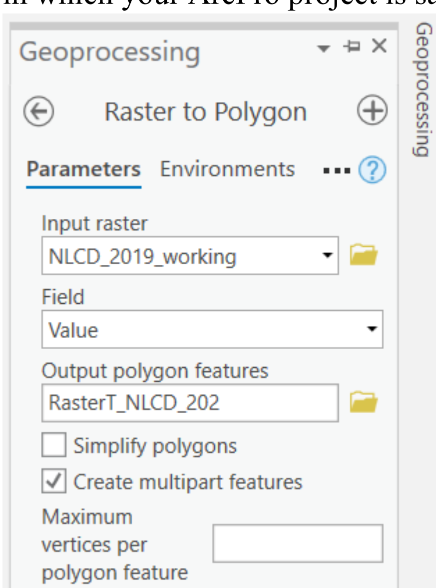
v. NoData Value – leave as is

vi. Press "Run"

vii. Once the tool has finished running, the clipped NLCD file will show up in the table of contents on the left-hand side



9. You now need to convert the NLCD from a raster to a vector before analysis.
    a. In ArcPro, under the main "Analysis" tab, click the "Tools" icon, then under the Geoprocessing menu, select "Conversion Tools" and finally "From Raster to Polygon"
    b. Your input is the NLCD file you just clipped, and the output location is the folder in which your ArcPro project is saved. Other suggested settings are below:



10. Open the Attribute Table for the layer you just created (named "NLCD_2019_working" in the example below). It should look something like this:

NLCD_2019_working

Field: Add Calculate Selection

FID	Shape *	Id	gridcode
0	Polygon	1	11
1	Polygon	2	21
2	Polygon	3	22
3	Polygon	4	23
4	Polygon	5	24
5	Polygon	6	31
6	Polygon	7	41
7	Polygon	8	42
8	Polygon	9	43
9	Polygon	10	52
10	Polygon	11	71
11	Polygon	12	81

Each unique gridcode corresponds to a different type of land cover.

11. As needed or desired, you can update the symbology of each field – note the overwhelming predominance of evergreen forest (green) in our example:

12. Use the same GIS procedures as with the WSS data to do the following:
    a. Add a field
    b. Compute geometry to find the total acreage of each land cover layer
    c. Export your results to Excel
    d. Create a Pivot Table that groups each land cover type together and sums the total acreage for each type
    e. Sort your table by land cover type (or gridcode; unique gridcodes correspond to land cover type), then assign a CN to each land cover type for all four possible soil groups, using values from TR-55. An example is below (note that this is an example for illustrative purposes, so the acreages do not necessarily match the rest of this document):

Sum of Acres			CURVE NUMBER				
NLCD Code	Total		A	B	C	D	
11	7.3	Open Water	98	98	98	98	
21	0.7	Developed, Open Space	39	61	74	80	For "good" condition, grass cover >75%
22	0.4	Developed, Low Intensity	49	69	79	84	For "fair" condition, grass cover 50 - 75%
23	0.1	Developed, Medium Intensity	49	69	79	84	For "fair" condition, grass cover 50 - 75%
24	0.2	Developed, High Intensity	68	79	86	89	For "poor" condition, grass cover <50%
31	8.1	Barren Land (Rock/Sand/Clay)	77	86	91	94	For fallow, bare soil
41	1.2	Deciduous Forest	43	65	76	82	For woods-grass combinarion (orchard or tree farm), "fair" condition
42	7247.9	Evergreen Forest	36	60	73	79	For woods, "fair" condition
43	0.4	Mixed Forest	35	56	70	77	For brush-brush-forbs-grass mixture with brush the major element, "fair" condition
52	449.1	Shrub/Scrub	48	67	77	83	For brush-brush-forbs-grass mixture with brush the major element, "poor" condition
71	42.8	Grasslands/Herbaceous	30	58	71	78	For meadow-continuous grass, protected from grazing and generally mowed for hay, "good" condition
90	14.3	Woody Wetlands	30	58	71	78	For meadow-continuous grass, protected from grazing and generally mowed for hay, "good" condition
95	15.7	Emergent Herbaceous Wetlands	30	58	71	78	For meadow-continuous grass, protected from grazing and generally mowed for hay, "good" condition
Grand Total	7788.3						

B.3 PUTTING IT ALL TOGETHER – WEIGHTING YOUR CN

1. To weight your CN by land cover type and hydrologic soil rating, one methodology is as follows:
   a. Weight once based on the CN
   b. Weight again based on the percentage of each hydrologic soil group in the basin
   c. An example for a simplified basin is shown below. Note that, while this basin was simplified to only three land cover types, these three types make up over 95 percent of the actual basin, so this would be a reasonable simplification to make. The land cover types are open water (the reservoir), evergreen forest, and shrub/scrub. The basin has soil groups A, B, and D (no group C).

	A	B	C	D	E	F	G	H	I
1					Curve Number				
2	NCLD Code	Acreage	Percent	Description	A	B	C	D	NOTES
3	11	7.3	0.1%	Open Water	100	100	100	100	Use CN = 100 for open water
4	42	7247.9	94.1%	Evergreen Forest	45	66	77	83	For woods, "poor" condition
5	52	449.1	5.8%	Shrub/Scrub	48	67	77	83	For brush-brush-forbs-grass mixture with brush the major element, "poor" condition
6	Total =	7704.4							
7									
8				NCLD Code		Weighted CN			
9				11	734	734	734	734	
10				42	326156	478362	558089	601577	
11				52	21556	30089	34580	37275	
12				Weighted average =	45	66	77	83	
13									
14					Web Soil Survey results (%) for hydrologic soil rating				
15					A	B	C	D	
16				Percentage =	48%	11%	0%	41%	
17									
18									
19				Weighted average x percentage =	21.7	7.3	0.0	34.0	
20				Final answer =	63.0				

From our GIS work, 94.1% of the basin is evergreen forest. From Table 2-2c (TR-55), we entered the CN values for woods in "poor" condition for all four hydrologic soil groups (cells E4:H4). Poor condition was chosen because this basin has extensive beetle kill and dead trees.

A weighted CN is calculated as:
326156 (cell E10) = 45 (CN from cell E4) x 7247.9 (acreage from cell B4)

	A	B	C	D	E	F	G	H
1						Curve Number		
2	NCLD Code	Acreage	Percent	Description	A	B	C	D
3	11	7.3	0.1%	Open Water	100	100	100	100
4	42	7247.9	94.1%	Evergreen Forest	45	66	77	83
5	52	449.1	5.8%	Shrub/Scrub	48	67	77	83
6	Total =	7704.4						
7								
8				NCLD Code		Weighted CN		
9				11		734	734	734
10				42	=E4*$B4	478362	558089	601577
11				52	21556	30089	34580	37275
12				Weighted average =	45	66	77	83

326156

The weighted average of all CNs for group A is calculated as:
45 (cell E12) = SUM(cells E9:E11) / 7704.4 (total acreage from cell B6)

	A	B	C	D	E	F	G	H
1						Curve Number		
2	NCLD Code	Acreage	Percent	Description	A	B	C	D
3	11	7.3	0.1%	Open Water	100	100	100	100 U
4	42	7247.9	94.1%	Evergreen Forest	45	66	77	83 F
5	52	449.1	5.8%	Shrub/Scrub	48	67	77	83 F
6	Total =	7704.4						
7								
8				NCLD Code		Weighted CN		
9				11	734	734	734	734
10				42	326156	478362	558089	601577
11			45	52			34580	37275
12				eighted average =	=SUM(E9:E11)/B6		77	83

From the WSS, 48% of our basin is group A, 11% is group B, etc.

	Web Soil Survey results (%) for hydrologic soil rating			
	A	B	C	D
Percentage =	48%	11%	0%	41%

The percent of each soil group is multiplied by the weighted average CN. A sample calculation for group A is:
21.7 (cell E19) = 48% (cell E16) x 45 (weighted average CN from cell E12)

	A	B	C	D	E	F	G	H
1						Curve Number		
2	NCLD Code	Acreage	Percent	Description	A	B	C	D
3	11	7.3	0.1%	Open Water	100	100	100	100 U
4	42	7247.9	94.1%	Evergreen Forest	45	66	77	83 F
5	52	449.1	5.8%	Shrub/Scrub	48	67	77	83 F
6	Total =	7704.4						
7								
8				NCLD Code		Weighted CN		
9				11	734	734	734	734
10				42	326156	478362	558089	601577
11				52	21556	30089	34580	37275
12				Weighted average =	45	66	77	83
13								
14					Web Soil Survey results (%) for hydrolog			
15					A	B	C	D
16			21.7	Percentage =	48%	11%	0%	41%
17								
18								
19				Weighted average x percentage =	=E12*E16	7.3	0.0	34.0
20				Final answer =	63.0			

Finally, the weighted average x percentage value is summed for all four soil groups. This is the final weighted CN for the basin.

	A	B	C	D	E	F	G	H
1						Curve Number		
2	NCLD Code	Acreage	Percent	Description	A	B	C	D
3	11	7.3	0.1%	Open Water	100	100	100	100 U
4	42	7247.9	94.1%	Evergreen Forest	45	66	77	83 F
5	52	449.1	5.8%	Shrub/Scrub	48	67	77	83 F
6	Total =	7704.4						
7								
8				NCLD Code		Weighted CN		
9				11	734	734	734	734
10				42	326156	478362	558089	601577
11				52	21556	30089	34580	37275
12				Weighted average =	45	66	77	83
13								
14					Web Soil Survey results (%) for hydrolog			
15					A	B	C	D
16				Percentage =	48%	11%	0%	41%
17								
18								
19			Weighted average x percentage =		21.7	7.3	0.0	34.0
20				Final answer =	=SUM(			

63

(While it sounds complicated when written out with screenshots, the calculations are very quick for those with basic spreadsheet experience.)

2. This approach is more complicated than either a basic or intermediate approach, described at the beginning of the appendix, but it has the benefit of using published national data and being defensible if used in a contentious situation, e.g., deciding to implement a reservoir operational restriction. This method would also be helpful in areas with many different land cover types. Furthermore, after following the process described for the example watershed, the rainfall-runoff model calibrated immediately and required very little additional work; the initial weighted CN was very representative. Since the CN is one of the primary parameters changed during calibration, upfront work to choose a representative CN can save subsequent work.

   The weakness in this method is that it assumes the soil types are evenly distributed among the land cover types. From our example above, the method assumes that 48% of evergreen forest is group A, and 48% of the shrub/scrub is group A. This may not be the case – for example, it is likely that certain soil types correspond with certain vegetation types because the vegetation is specifically adapted to grow well in those soil conditions. Despite this, the method produces good estimations on a basin scale and is then refined with calibration.

3. Advanced GIS users could build an ArcPro tool that would calculate a weighted CN based on both WSS and NCLD GIS datasets (and where the data intersect, e.g., which

evergreen land cover types intersect with hydrologic soil group A, and so on), but such an effort is likely only worthwhile for large projects and is outside the scope of this manual.

Even if a full GIS tool is not developed to support these “intersection” calculations, the analyst could quickly review both the WSS and NLCD shapefiles in ArcPro to evaluate any major trends, e.g., if all or most of one soil type was associated with a certain land cover, and then adjust their weighting estimates accordingly.

APPENDIX D

CONSTANT MONTHLY BASEFLOW VALUES

Statistic	Value	Unit
November Mean Flow	1.6	ft^3/s
December Mean Flow	1.43	ft^3/s
January Mean Flow	1.26	ft^3/s
February Mean Flow	1.24	ft^3/s
March Mean Flow	1.72	ft^3/s
April Mean Flow	4.31	ft^3/s
May Mean Flow	10.1	ft^3/s
June Mean Flow	9.99	ft^3/s
July Mean Flow	4.53	ft^3/s
August Mean Flow	2.29	ft^3/s
September Mean Flow	1.62	ft^3/s
October Mean Flow	1.59	ft^3/s

APPENDIX E

10-YEAR STORM DEPTH
SPREADSHEET COMPUTATION

Step-by-Step Procedures for Montana Dam Safety Technical Note 1, Determination of the Inflow Design Flood for High Hazard Dams in Montana (2019)

Step 1 - Determining Basin Size and Location Relative to Tech Note 1

Size

Basins are to be measured for size in square miles.

Methods to accomplish this:
1. Digital tools for delineating basin and having the size automatically determined (AutoCAD®, Google Earth®, other digital tools.
2. Using StreamStats® (USGS) Click here to go to StreamStats
3. Planimeter (ask an engineer over the age of 40 - they will know)

Total Drainage Basin Size = 4.917 square miles

For drainage basins that overlap into two regions, enter the drainage area in each region in the table below.

Region

Determine the region in which the drainage basin is located.
Use Plate 1 (Locations of annual-maxima precipitation stations) of WRIR 97-4004.
If the basin happens to overlap into two regions, determine locations of basin in each region (see table below).

Location

Determine the location of points in the basin in latitude and longitude. In Montana, longitude ranges from about 104 to 116 degrees. Latitude ranges from about 44 to 49 degrees.The user is required to convert latitude and longitude from degrees, minutes, seconds format to decimal format.

For smaller basins, one location point near the centroid of the drainage area is adequate.
For larger basins, the user may want to use multiple points to provide a more even distribution of points representing locations in which mean annual precipitation and mean storm depths are determined.
Using a grid pattern is recommended to provide even coverage of the basin, without intentional bias.

If the drainage basin is located in two regions, enter the area and location points in both regions.

User enters in the **green** cells only.

Region	Subbasin Area in Region (sq mi)	Point in Basin	Latitude (decimal)	LAT (latitude minus 40)	Longitude (decimal)	LONG (longitude minus 100)
1	4.917	1	45.818032	5.818032	112.525193	12.525193
		2				
		3				
		4				
		5				
		6				
		7				
		8				
		9				
		10				
		1				
		2				
		3				
		4				
		5				
		6				
		7				
		8				
		9				
		10				

Step 2 - Determining Dimensionless Storm Depths

Knowing the region, storm duration, and the storm recurrence interval, determine the dimensionless storm depth

The following information is taken from Equation 2 (page 10) and Table 9 (page 17) of WRIR 97-4004.

User enters in the green cells only.

NOTE: For basins in two regions, make sure the storm duration is the same in regions needed.

For regions not being considered, delete the storm duration value in that region (the appropriate q(F) value should be zero).

FOR REGION 1:

Input storm duration (in hrs) to be used $t_{(2, 6, 24)}$ = 24 Input region 1, 2, or 3 1 Storm Event = 10

q(F) = 1.4514 <----- REGION 1 DIMENSIONLESS STORM DEPTH*

FOR REGION 2:

Input storm duration (in hrs) to be used $t_{(2, 6, 24)}$ = 24 Input region 1, 2, or 3 2 Storm Event = 10

q(F) = 1.5244 <----- REGION 2 DIMENSIONLESS STORM DEPTH*

FOR REGION 3:

Input storm duration (in hrs) to be used $t_{(2, 6, 24)}$ = 24 Input region 1, 2, or 3 3 Storm Event = 10

q(F) = 1.5451 <----- REGION 3 DIMENSIONLESS STORM DEPTH*

$$q(F) = \xi + \alpha(\{1 - (-\log F)^k\}/k), \qquad (2)$$

where

ξ, α, and k are the parameters of the GEV distribution, and

log F is the natural logarithm of non-exceedance probability.

*This is an unprotected sheet with formulas. Green cells are for user input; referenced table is included below for convenience.

Table 9. Parameters for Generalized Extreme Value (GEV) distribution applied to 2- 6-, and 24-hour duration storm depths in Montana

[ξ, α, and **k** are parameters for the GEV distribution]

REGION	Duration, in hours								
	2			6			24		
	ξ	α	k	ξ	α	k	ξ	α	k
1	0.803	0.258	-0.159	0.830	0.242	-0.114	0.839	0.258	-0.047
2	.783	.276	-.176	.79	.275	-.135	.801	.280	-.120
3	.765	.314	-.150	.791	.300	-.109	.799	.304	-.076

OR

Use Figures 12 - 17 below to estimate the dimensionless storm depth for the regions needed.

REGION 1 DIMENSIONLESS STORM DEPTH =

REGION 2 DIMENSIONLESS STORM DEPTH = 3.8

REGION 3 DIMENSIONLESS STORM DEPTH = 3.6

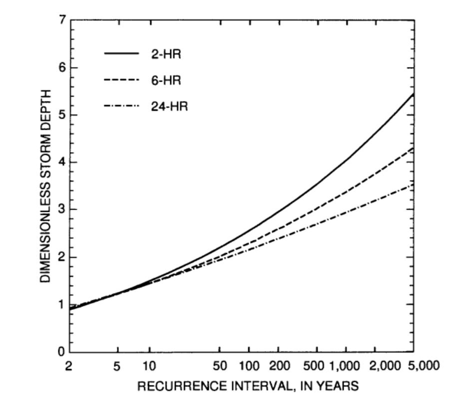


Figure 12. Regional frequency curves for dimensionless annual storm depths in Region 1, Montana.

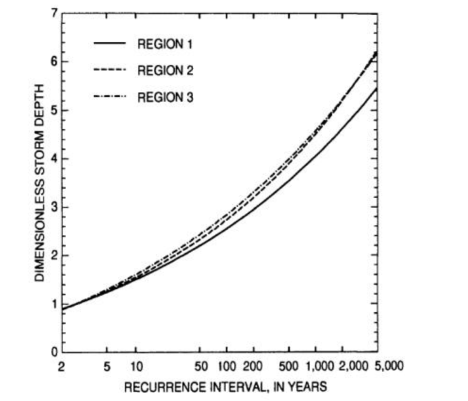


Figure 15. Regional frequency curves for dimensionless 2-hour duration annual precipitation depth, Montana.

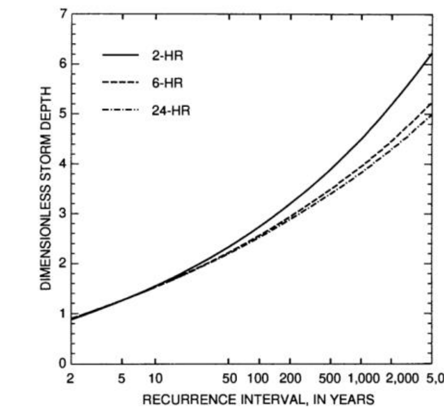


Figure 13. Regional frequency curves for dimensionless annual storm depths for Region 2, Montana.

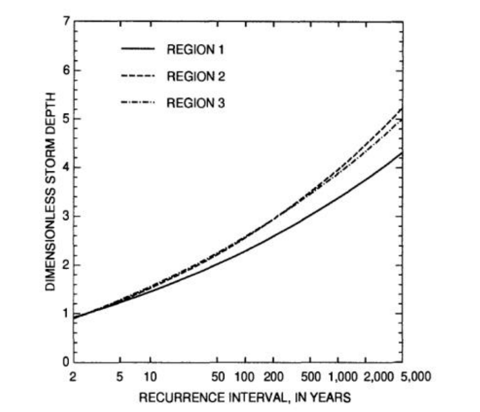


Figure 16. Regional frequency curves for dimensionless 6-hour duration annual precipitation depth, Montana.

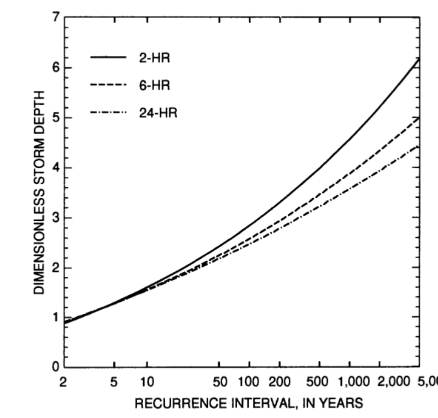


Figure 14. Regional frequency curves for dimensionless annual storm depths for Region 3, Montana.

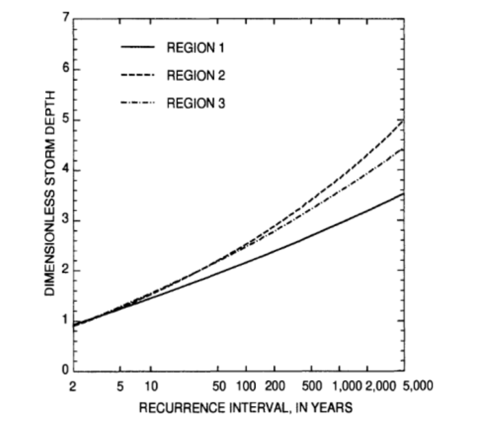


Figure 17. Regional frequency curves for dimensionless 24-hour duration annual precipitation depth, Montana.

Step-by-Step Procedures for Montana Dam Safety Technical Note 1, Determination of the Inflow Design Flood for High Hazard Dams in Montana (2019)

Step 3 - Mean Annual Precipitation

Determine the mean annual precipitation for the basin using Plate 2 (Mean annual precipitation in Montana) of WRIR 97-4004.

User enters in the **green** cells only.

Region	Point in Basin	Mean Annual Precipitation (in)
1	1	22
	2	
	3	
	4	
	5	
	6	
	7	
	8	
	9	
	10	
	1	
	2	
	3	
	4	
	5	
	6	
	7	
	8	
	9	
	10	

Step-by-Step Procedures for Montana Dam Safety Technical Note 1, Determination of the Inflow Design Flood for High Hazard Dams in Montana (2019)

Step 4 - Mean Storm Depth

User enters in the green cells only.

Storm duration (hrs) from Step 2 $t_{(2, 6, 24)}$ = 24

Point in Basin	Region	LAT	LONG	MAP	From Table 11 $P_{max}2$	$P_{max}6$	$P_{max}24$	Dimensionless Depth	Mean Storm Depth (in)
1	1	5.818032	12.52519	22	0.00	0.00	1.26	1.45	1.84
2	1				0.00	0.00	#VALUE!	1.45	
3	1				0.00	0.00	#VALUE!	1.45	
4	1				0.00	0.00	#VALUE!	1.45	
5	1				0.00	0.00	#VALUE!	1.45	
6	1				0.00	0.00	#VALUE!	1.45	
7	1				0.00	0.00	#VALUE!	1.45	
8	1				0.00	0.00	#VALUE!	1.45	
9	1				0.00	0.00	#VALUE!	1.45	
10	1				0.00	0.00	#VALUE!	1.45	
1					0.00	0.00	0.00	1.55	
2					0.00	0.00	0.00	1.55	
3					0.00	0.00	0.00	1.55	
4					0.00	0.00	0.00	1.55	
5					0.00	0.00	0.00	1.55	
6					0.00	0.00	0.00	1.55	
7					0.00	0.00	0.00	1.55	
8					0.00	0.00	0.00	1.55	
9					0.00	0.00	0.00	1.55	
10					0.00	0.00	0.00	1.55	

*This is an unprotected sheet with formulas. Green cells are for user input; referenced table is included below for convenience.

Avg at site storm depth, weighted for subbasin sizes (in)	1.84
Area adjustment factor	0.98 From Figure 19 ---->
Basin mean storm depth (in)	**1.80** *

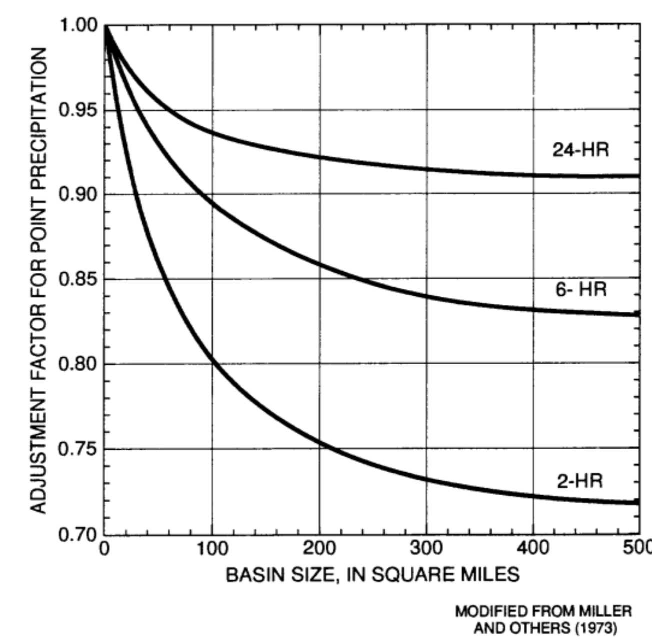


Figure 19. Depth-area adjustment curves for Montana.

Table 11. Regression equations for estimation of mean storm depth for indicated duration in Montana

[Regression equation: *Pmaxt*, storm depth in inches, with t indicating duration in hours; *LAT*, site latitude, in decimal degrees minus 40; *LONG*, site longitude, in decimal degrees minus 100; and *MAP*, mean annual precipitation, in inches, as determined from State maps prepared from digital data from Oregon State University Climate Center (pl. 2)]

Region	Equation	Standard error, inches	Coefficient of determination, R^2
1	$Pmax2 = 0.44 + (0.0027 \times MAP)$	0.05	0.10
	$Pmax6 = 0.60 + (0.0067 \times MAP)$	0.07	0.31
	$Pmax24 = 1.0 + (0.078 \times LAT) - (0.059 \times LONG) + (0.025 \times MAP)$	0.16	0.80
2	$Pmax2 = 0.69 + (0.034 \times LAT) - (0.029 \times LONG)$	0.09	0.16
	$Pmax6 = 0.75 + (0.087 \times LAT) - (0.041 \times LONG)$	0.12	0.30
	$Pmax24 = 1.4 + (0.18 \times LAT) - (0.13 \times LONG) + (0.019 \times MAP)$	0.27	0.52
3	$Pmax2 = 0.70 + (0.031 \times LAT) - (0.040 \times LONG) + (0.0087 \times MAP)$	0.08	0.62
	$Pmax6 = 0.85 + (0.031 \times LAT) - (0.038 \times LONG) + (0.015 \times MAP)$	0.08	0.59
	$Pmax24 = 0.62 + (0.039 \times LAT) - (0.016 \times LONG) + (0.058 \times MAP)$	0.16	0.49

APPENDIX F

10-YEAR STORM HYETOGRAPH SPREADSHEET COMPUTATION

24 hour precipitation hyetograph; 6 hour kernal, 50% exceedance probability for region 1 (USGS WRI 98-4100)

For a 10.000 **year return period storm**

Basin average depth **1.80** inches

ncremental Duratio	Dimensionless depth (Table 13)	Depth-area adjustment (Figure 17)	Adjusted dimensionless depth	Incremental Time	Incremental dimensionless depth	Dimensionless depth per 1 hour period	Depth per 1 hour period	Incremental depth
0	0.000	1	0					
				1	0.14	0.1400	**0.252**	**0.252**
1	0.140	1	0.14					
				1	0.082	0.0820	**0.148**	**0.148**
2	0.222	1	0.222					
				1	0.079	0.0790	**0.142**	**0.142**
3	0.301	1	0.301					
				3	0.136	0.0453	**0.082**	**0.245**
6	0.437	1	0.437					
				3	0.113	0.0377	**0.068**	**0.203**
9	0.550	1	0.55					
				3	0.105	0.0350	**0.063**	**0.189**
12	0.655	1	0.655					
				6	0.21	0.0350	**0.063**	**0.378**
18	0.865	1	0.865					
				6	0.135	0.0225	**0.041**	**0.243**
24	1.000	1	1					
				12	0.073	0.0061	**0.011**	**0.131**
36	1.073	1	1.073					
				12	0.044	0.0037	**0.007**	**0.079**
48	1.117	1	1.117					
				12	0.043	0.0036	**0.006**	**0.077**
60	1.160	1	1.16					
				12	0.04	0.0033	**0.006**	**0.072**
72	1.200	1	1.2					

72 hr sum	**2.160**
24 hr sum	**1.800**

Hour	Incremental Precip Depth (in)	Hour	Incremental Precip Depth (in)	Hour	Incremental Precip Depth (in)
0					
1	0.011	25	0.063	49	0.006
2	0.011	26	0.041	50	0.006
3	0.011	27	0.041	51	0.006
4	0.011	28	0.041	52	0.006
5	0.041	29	0.011	53	0.006
6	0.041	30	0.011	54	0.006
7	0.041	31	0.011	55	0.006
8	0.063	32	0.011	56	0.006
9	0.063	33	0.011	57	0.006
10	0.063	34	0.011	58	0.006
11	0.063	35	0.011	59	0.006
12	0.063	36	0.011	60	0.006
13	0.068	37	0.007	61	0.006
14	0.068	38	0.007	62	0.006
15	0.082	39	0.007	63	0.006
16	0.082	40	0.007	64	0.006
17	0.252	41	0.007	65	0.006
18	0.148	42	0.007	66	0.006
19	0.142	43	0.007	67	0.006
20	0.082	44	0.007	68	0.006
21	0.068	45	0.007	69	0.006
22	0.063	46	0.007	70	0.006
23	0.063	47	0.007	71	0.006
24	0.063	48	0.007	72	0.006

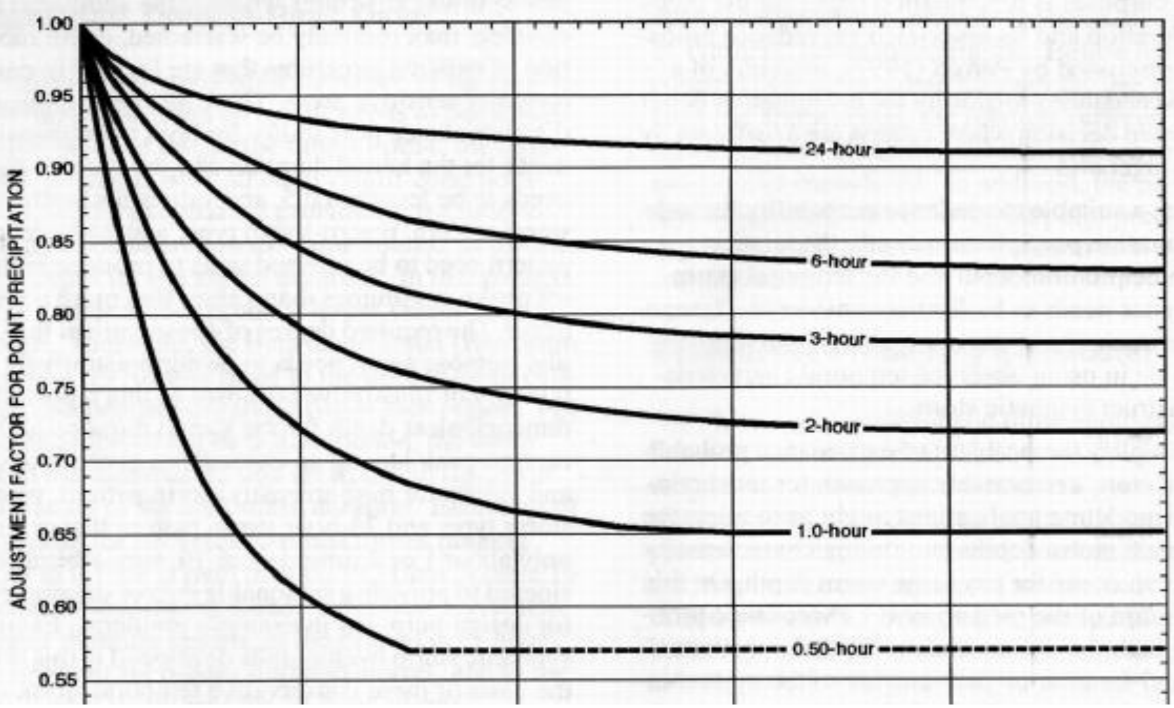
Note:
Time to peak is in accordance with Table 19 (below) with 50% exceedance.

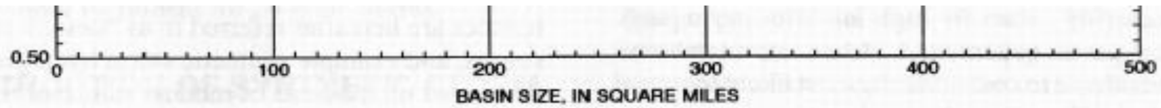
SEE THE PLOTTED HYETOGRAPH

Table 13 Region 1

Dependent duration (hours)	**24-hour independent duration 6-hour kernel duration**								
	Exceedance probability								
	0.9	**0.8**	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**	**0.1**

1	0.094	0.106	0.118	0.128	0.140	0.152	0.165	0.182	0.206
2	.138	.165	.189	.205	.222	.240	.260	.285	.321
3	.180	.220	.250	.275	.301	.325	.352	.386	.433
6	.313	.346	.377	.406	.437	.470	.508	.554	.620
9	.440	.469	.490	.520	.550	.580	.610	.650	.710
12	.561	.586	.609	.632	.655	.680	.709	.745	.795
18	.822	.836	.845	.855	.865	.880	.901	.920	.947
24	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
36	1.113	1.102	1.092	1.083	1.073	1.062	1.054	1.045	1.040
48	1.147	1.139	1.132	1.125	1.117	1.109	1.100	1.089	1.080
60	1.182	1.175	1.172	1.167	1.160	1.150	1.140	1.130	1.120
72	1.211	1.205	1.203	1.201	1.200	1.190	1.180	1.170	1.160





Modified from Miller and others (1973)

Figure 17. Depth-area adjustment curves for Montana.

Table 19. Time-to-peak precipitation for various exceedance probabilities, Montana and northern Wyoming

Exceedance probability	Time-to-peak precipitation, in hours, for indicated independent duration, in hours, and region								
	2			6			24		
	Region			Region			Region		
	1	2	3	1	2	3	1	2	3
0.9	0.0833	0.0833	0.0833	0.25	2	0.25	2	8	4
.8	.0833	.0833	.167	.75	3	.75	5	13	7
.7	.0833	.0833	.25	1.25	4.25	1	8	18	12
.6	.0833	.0833	.417	2	5.25	1.5	12	22	17
.5	.167	.25	.50	3	6.5	2.25	17	27	22
.4	.25	.333	.667	4	7.5	3	24	32	28
.3	.417	.50	.917	5.5	9	4	31	37	35
.2	.75	.833	1.167	7.5	10.25	5	40	44	43
.1	1.167	1.333	1.583	10	12.25	7	52	52	53

To avoid too much conservatism, the following has been incorporated into this spreadsheet:

1) The 50% exceedance probability hyetograph pattern is used to distribute incremental storm depths;

2) 50% exceedance probability storm characteristics have been used.

The user is also cautioned to use the depth-area adjustment in Figure 17 ONLY if it was not used in the basin average depth calculations. If it was already used for the basin average depth, enter a value of 1 in each of the **green** cells in column C.

ON THE NEXT WORKSHEET