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Automated Calibration of the GSSHA Watershed Model:
A Look at Accuracy and Viability for
Routine Hydrologic Modeling

by
Kayson M. Shurtz

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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Department of Civil and Environmental Engineering
Brigham Young University
December 2009

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ABSTRACT

Automated Calibration of the GSSHA Watershed Model: A Look at Accuracy and Viability for Routine Hydrologic Modeling

Kayson M. Shurtz

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Master of Science

The goal of hydrologic models is to accurately predict a future event of a given magnitude. Historic data are often used to calibrate models to increase their ability to forecast accurately. The GSSHA model is a distributed model that uses physical parameters and physics based computations to compute water flow from cell to cell based on a 2 dimensional grid. The goal of calibration is to obtain good estimates for the actual parameters of the watershed. These parameters should then transfer to other storm events of different magnitudes more easily than an empirical model.

In conducting this research three watersheds were selected in different parts of the United States and the required data were collected to develop and run single event hydrologic models. The WMS software was used to preprocess digital spatial data for

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model creation before calibrating them with the GSSHA model. A calibrated HEC-HMS model was also developed for each watershed for comparative purposes. Establishing GSSHA's usability in routine hydrologic modeling is the primary objective of this research. This has been accomplished by developing guidelines for GSSHA calibrations, assisted by WMS, testing model accuracy in the calibration and verification phases, and comparing results with HEC-HMS, a model widely accepted for routine hydrologic modeling.

As a result of this research, the WMS interface has become well equipped to set up and run GSSHA model calibrations. The focus has been on single event, or routine hydrologic model simulations, but continuous simulation calibrations, an important strength of GSSHA, can also be developed.

Each of the model simulations in the study calibrated well in terms of matching peak and volume. However, the verification for two out of the three watersheds used in the study was less than ideal. The results of this research indicate that the physical factors, which GSSHA should represent well, are particularly sensitive for single event storms. The use of calibration of single events is therefore difficult in some cases and may not be recommended. Further research could be done to establish guidelines for situations (e.g. watershed conditions, storm type, etc.) where single event calibration is plausible.

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1 Introduction

Engineers will often use computer models to try and mimic physical processes that are vital to design work. Unfortunately perfect models do not exist. However, good hydrologic models have proven to be useful tools when they are constructed carefully. The challenge lies in that careful construction. There have been many programs that have been created to assist in hydrologic modeling.

The two programs I will be using for my analysis are Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) (USACE 2000) and Gridded Surface Subsurface Hydrologic Analysis (GSSHA) (Downer et al. 2002). These two programs were both developed by the US Army Corps of Engineers. HEC-HMS is a lumped parameter model while GSSHA is a fully distributed model. I will be using the Watershed Modeling System (WMS) (Nelson 2006) as the interface for setting up the models from digital spatial data.

The increase in computer technology has increased computational power and efficiency. This increased ability has created more possibilities to use distributed and physically based two dimensional models that require more data and computational resources (like GSSHA). The relative difficulty of producing a model that accurately depicts the physical conditions of the watershed remains a concern. In order to have

confidence in their use, these models often need calibration, which is the goal of this research.

The motivation of this research is an interest in determining if distributed models have a place in routine hydrologic modeling. This research is a part of a larger study that is interested in the use of distributed models for routine hydrologic modeling. Distributed models are generally not used in practice. The usability of such models has limited their use in the past. Increases in computer processing abilities has increased data availability and decreased computational times. These two problems have been restriction to using distributed models in the past. Have the advances in technology been significant enough to make distributed models a viable option for routine hydrologic modeling?

The main emphasis of this research will be on the GSSHA model. I will examine how to calibrate a GSSHA model as well as describe trends in my datasets and recommendations for efficiently calibrating the GSSHA model. I will also describe the process of setting up and running a GSSHA model calibration within the WMS interface. A detailed description of the process used to set up and run a calibration of a GSSHA model is included in the appendix.

I will focus on what I will call “routine hydrologic modeling”. This statement simply refers to single event storms that are often used in engineering design. The GSSHA model has a vast number of options that can be included in the model. For the purposes of this research the model will be kept simple in an effort to keep things closer to what would be done in more routine situations. I would also like to examine whether or not GSSHA can or should be used in “routine hydrologic modeling”. The HMS model

is included for comparative reasons because of its widespread use and familiarity within the hydrological modeling community.

Every model requires input that describes actual conditions of the watershed. In my study I will be using Green and Ampt parameters (Green and Ampt 1911) in both GSSHA and HMS. The Green and Ampt equation describes how water infiltrates different soil types based on different parameters such as hydraulic conductivity. This input can be difficult to estimate because of the wide variation in field conditions and the need to simplify real world conditions into simpler, effective parameter values. There have been many tables and guidelines established over time that can help with initial estimates. Often observed data are used to increase the accuracy of our estimates, and it can give us more confidence when we try to predict results for a particular watershed.

Digital data for hydrologic computer models are becoming easier to access. In the US, there are many websites which offer the type of data that is needed for hydrologic models free of charge. Most hydrologic models derive input parameters from digital elevation models (DEMs), and also land use and soil type data that is available in GIS format (i.e. shapefiles).

1.1 Model Calibration

Model Calibration is the process of matching simulated outputs with observed outlet hydrographs by adjusting model parameters. Frequently, watershed models have large numbers of parameters which are not directly measurable. It then becomes necessary to estimate these parameters through model calibration.

The accuracy of a model and what it predicts depends largely on the parameters selected to represent the area of interest. A cost function is a number used to describe how well the calibration of a model matches the observed data. The goal of a model calibration becomes a minimization or maximization (where appropriate) of a specified cost function (Duan et al. 1994).

1.2 Lumped Modeling

We refer to a model as “lumped” when the computer model ignores spatial variation, and instead assigns an average value that represents the area as a whole. Lumped models are typically empirical in nature and the model parameters take on effective values that describe the watershed as a whole. For example, if I want to model a watershed using Green and Ampt parameters I would need to come up with some sort of average value for hydraulic conductivity for the whole watershed even though I might have gravel and clay within the bounds of my watershed. While hydraulic conductivity itself has physical meaning, averaging hydraulic conductivity values takes away the temporal distribution that exists in the model.

Lumped parameter modeling is by far the most commonly used type of model. The advantages of lumped parameter modeling are what make them so popular. Since the parameters become lumped together, the number of variables generally is few in number as compared to a distributed model. In order to describe a watershed in every detail there could be an infinite number of parameters to define. This is not a practical approach. Changing the model to have very few parameters makes building and running the model

much easier. Computational effort and time is minimal because the number of parameters is so few.

Even though this type of modeling is popular there are a few fundamental problems. One of the problems with lumped parameter models is they are often over parameterized with interdependent parameters (Uhlenbrook et al. 1999). Since the model parameters in lumped models have effective parameter values, calibration is necessary, and yet the calibrated parameters are often unique to a given storm and not applicable in general. It has been shown that many times it is not possible to find a unique ‘best’ parameter set. Many sets of different parameters yield equally good results (Uhlenbrook et al. 1999).

Since the lumped parameter models do not yield a unique ‘best’ set of parameters, there is inherent uncertainty when using the calibrated model parameters on a different storm (an important purpose of calibration). This parameter uncertainty makes lumped parameter models less reliable outside the calibration period/data (Uhlenbrook et al. 1999). It is generally best to use a calibrated lumped parameter model to predict an event that is similar in magnitude and conditions to the calibration storm.

1.3 Distributed Modeling

Distributed models are typically based on physical processes that try to incorporate the spatial variability of watersheds. Including the spatial variability makes distributed models unique. These types of models are set up by creating a 2-D grid where infiltration and roughness parameters are assigned to each grid cell based on the underlying soil type and land use. Therefore, a distributed model is partially lumped in a way because each

grid cell has a representative area however large or small. The difference ultimately lies in the size of the discretization. The assumption that change in the area of the grid cell is minimal is made in all distributed models. A time step is chosen and calculations made for each grid cell and the movement of water is tracked from cell to cell based on infiltration, roughness, and elevation change.

The accuracy of a distributed model largely depends on key parameters that are assigned to each grid cell by the modeler. The difficulty with this type of model is the large numbers of parameters required for the model. Determining appropriate parameters and measuring their accuracy is a challenge. The number of parameters used in a model that incorporates spatial variability can easily be 5-10 times more than a lumped parameter model that averages a value for the whole watershed.

There are certain parameters that the model is more sensitive to than others. The process of testing which parameters in the model are most sensitive is called a sensitivity analysis. The sensitive parameters are ultimately the most important parameter sets within the model. These are the parameters that should be focused on during the calibration process.

The idea of a calibrated distributed model is that parameters should represent all field conditions. These parameters should be able to validate well on other storms even if they are not similar to the one that was used during calibration. The actual physical nature of the site is obtained through the calibration so any type of storm should be well described in a simulation.

The distributed model has some challenges that come with it. While modern tools and data have improved significantly, the computation time and effort to set up the model

is more intensive than a lumped parameter model. The computation time required for calibration is significantly greater than the lumped parameter models. Another difficulty is estimating the initial moisture of the soil for a given storm event.

2 Literature Review

One of the goals of my research is to establish guidelines to calibrate hydrologic models, particularly GSSHA. In this section I would like to describe some of this research along with how each of the programs work that I am going to be using. Through my research I have found that calibration is done either manually, by an automated process, or a combination of the two.

2.1 Manual Calibration

Manual calibration is the process of changing model parameters by hand to try and match the computed and observed hydrographs. For each successive simulation parameters that are deemed most sensitive are adjusted until the simulated response is within reasonable agreement of observed values. This method is often tedious, labor intensive, and requires a lot of experience, and is only practical when there are a small number of input parameters that need to be changed. Furthermore, the knowledge acquired by one person working on the project is not easily transferred to another. In general, the “closeness” of a manual calibration of a model is measured using different mathematical techniques as well as visually comparing the computed against the observed flow (Boyle et al. 2000).

The manual calibration of a model is highly dependent on the person that performs the calibration. Due to the nature of manual calibration and its dependence on the modeler it will always be a subjective exercise (Eckhardt and Arnold 2001). Manual calibration is most valuable when used before any automated techniques to test the sensitivity of certain parameters and for the modeler to learn the overall behavior of the system modeled.

2.2 Automated Calibration

Calibration of models can be automated through the use of computer algorithms. Since manual calibration is subjective, the results are difficult to assess explicitly. However, the results of automated calibration can be stated explicitly and automated calibration is often faster than manual calibration (Madsen 2000). The results of an automated calibration are largely dependant on the algorithm used.

Considerable research has been done to decide which automated calibration algorithm is the fastest and most robust. Shuffled Complex Evolution (SCE) is regarded and accepted by many as a robust and efficient optimization algorithm (Boyle et al. 2000). Biftu and Gan described how the SCE method has been shown to overcome five common problem areas found in automated calibration. (1) regions of attraction, where there is more than one region of convergence; (2) minor local optima, where small “pits” exist in each region; (3) roughness, when there is a rough surface with discontinuous derivatives; (4) sensitivity, the surface has varying sensitivity in the region of optimum with nonlinear parameter relationships; and (5) shape, the surface has long and curved ridges and is nonconvex (Biftu and Gan 1996).

In my research I will be using the SCE optimization algorithm with GSSHA, but the HMS software uses different techniques of optimization. The two optimization algorithms used in HMS include uni-variate gradient and Nelder Mead. These two algorithms are more commonly used to solve single-optimum problems and most of the time they require some preliminary manual calibration (Duan et al. 1994). I did not choose these algorithms myself. They are being used because they are the algorithms the program developers decided to implement in their particular programs.

2.3 Shuffled Complex Evolution

The Shuffled Complex Evolution algorithm is used for calibration with GSSHA. There are four key concepts which the algorithm is based on: (1) the combining of deterministic and probabilistic approaches; (2) the evolution of a group or ‘complex’ of points which move towards a global optimum; (3) competitive evolution; (4) complex shuffling (Duan et al. 1994). The general idea of how the SCE algorithm work is given in the following seven steps:

- Generate sample- A sample of s points is created in the parameter space that is defined using probability distributions to help in generating the sample. The criteria value for each point is computed and compared against all the other points in the same sample.
- Rank points- All of the points are then placed in order of increasing cost function so that the lowest cost function is first and the highest cost function is last (assuming that the goal is to minimize the cost function).

- Partition into complexes- The group of s points is divided into p complexes, each of these complexes should contain m points. The complexes are then divided so the first complex contains every $p(k-1) + 1$ ranked point, the second complex contains every $p(k-1) + 2$ ranked point and so on, where $k = 1, 2, \dots, m$.
- Evolve each complex- The complexes are then evolved according to the competitive complex evolution (CCE) algorithm
- Shuffle complexes- All of the evolved complexes are then combined into one sample population; the new sample population is then sorted in order of increasing cost function; shuffle this new population into p complexes the same way that is described in Step 3.
- Check Convergence- A check is performed to see if the pre-specified convergence criterion is met. If it has been met the process will end; otherwise, the process will continue until convergence is reached or maximum iterations have been surpassed.
- Check the reduction in the number of complexes- The minimum number of complexes required in the population is p_{\min} . If p_{\min} is less than p then the lowest ranked points need to be removed; set $p= p-1$ and $s= p_{\min}$; then the complexes need to be evolved again as described in Step 4.

In terms of hydrologic modeling a sample of points is generated randomly over the given ranges of the parameter values. Each point is seen as a unique population of living beings. Each individual of the population has its own genetic make-up (a unique

set of parameter values). As the genetic information (or parameters) changes, the population progresses toward an optimum. This is accomplished by sorting the initial population into “complexes” (which are compiled based on their respective cost functions). These “complexes” are a compilation of various combinations of parameter values. These “complexes” are allowed to produce new offspring with better cost functions using the downhill simplex procedure of Nelder and Mead (Eckhardt and Arnold 2001). This means that the parameters of each complex are changed to move toward an optimum value using the downhill simplex procedure. When each of the different “complexes” are finished their superior results are then put back into a single population in what is called a “shuffle”. The process is repeated until the established criteria are met or the maximum number of iterations is exceeded. A flowchart for each of the terms and their descriptions is given in Figure 2.1.

The SCE algorithm is not designed to converge quickly. The algorithm is robust and has been shown to avoid key problems other algorithms seem to have. I found in my research that this algorithm searches the entire possible parameter space. This exhaustive search is designed to ensure that a global optimum is reached. For this reason the algorithm takes some time to run through. A single event calibration in this study generally took anywhere from overnight to a couple of days.

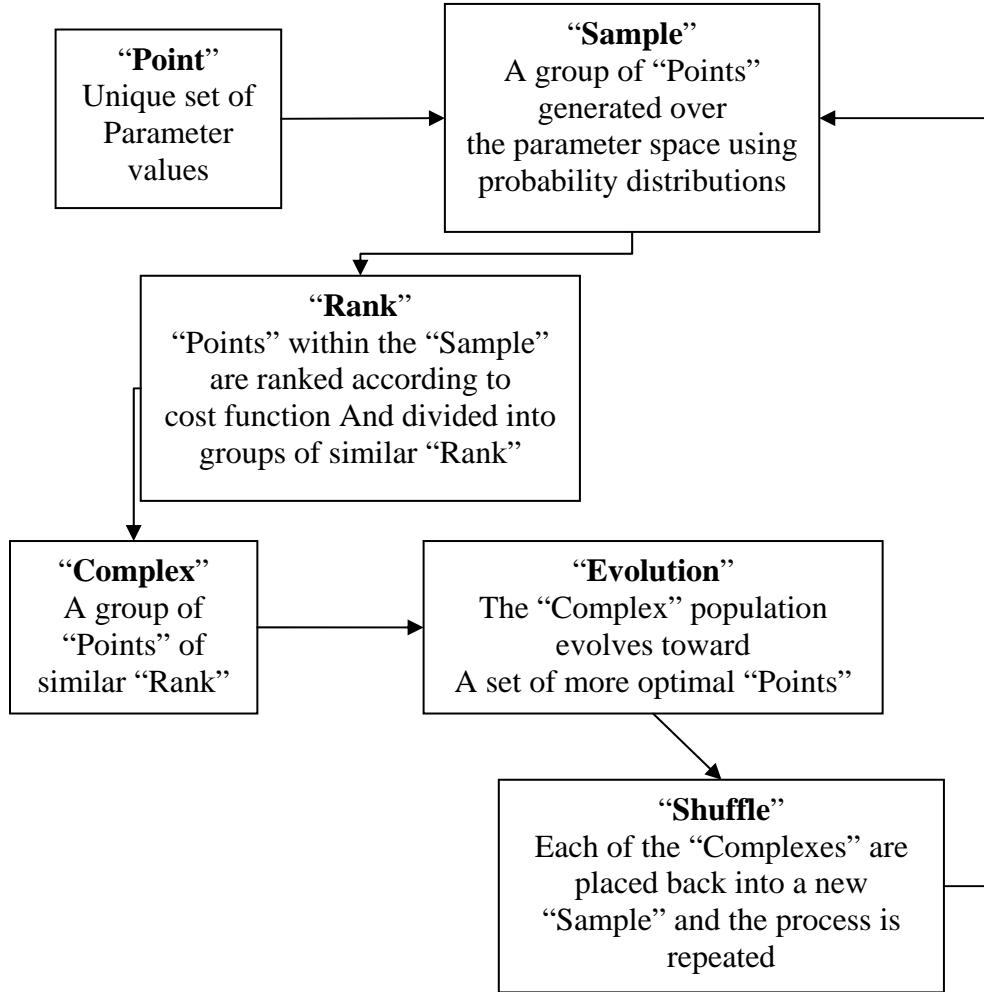


Figure 2.1: SCE algorithm flowchart.

2.4 HMS Calibration

Since the HMS model is a lumped model approach it becomes important to understand that lumped models when calibrated only work well for similar storms (USACE 2000). The guidelines are given in the HMS technical manual to identify what type of event you want to predict and find a similar storm like it to calibrate to.

The calibration procedure in HMS requires the selection of an objective function.

The objective function is a measure of how well the model is calibrating. HMS offers

several different objective functions which emphasize different things like peak, volume, etc. The objective functions offered by HMS are explained in detail below. The functions are given below in Table 2.1(USACE 2000).

Objective Functions

- Sum of absolute errors- When this objective function is used every ordinate of the computed hydrograph and the observed hydrograph are compared and weighted equally. The absolute value of the difference of the two is summed together over the whole hydrograph. The absolute value is used to ensure that the positive and negative differences don't artificially make the objective function small.
- Sum of squared residuals- This method also compares each of the ordinates, but the differences are squared treating larger differences as worse.
- Percent error in Peak- This only compares the peak of the observed against the computed peak. It does not compare multiple ordinates. This method is a good choice if the main focus of the study is peak flow.
- Peak-weighted root mean square error- All of the ordinates are compared and the differences are squared and then weighted according to the magnitude of each ordinate the peak having a weighting factor of one.

Table 2.1: HMS Objective Functions

Criterion	Equation ¹
Sum of absolute errors	$Z = \sum_{i=1}^{NQ} q_O(i) - q_S(i) $
Sum of squared residuals	$Z = \sum_{i=1}^{NQ} [q_O(i) - q_S(i)]^2$
Percent error in peak	$Z = 100 \left \frac{q_S(\text{peak}) - q_O(\text{peak})}{q_O(\text{peak})} \right $
Peak-weighted root mean square error objective function	$Z = \left\{ \frac{1}{NQ} \left[\sum_{i=1}^{NQ} (q_O(i) - q_S(i))^2 \left(\frac{q_O(i) + q_O(\text{mean})}{2q_O(\text{mean})} \right) \right] \right\}^{\frac{1}{2}}$

¹ Z = objective function; NQ = number of computed hydrograph ordinates; $q_O(t)$ = observed flows; $q_S(t)$ = calculated flows, computed with a selected set of model parameters; $q_O(\text{peak})$ = observed peak; $q_O(\text{mean})$ = mean of observed flows; and $q_S(\text{peak})$ = calculated peak

HMS has two different search algorithms available which are used to minimize the objective function.

- The univariate gradient method (UG). The UG method uses first and second derivatives of a selected objective function to minimize that objective function. This method also only allows one parameter to vary while holding all the others constant.
- The Nelder and Mead method (NM). The NM method evaluates all of the parameters at the same time and determines which parameter to adjust using a downhill Simplex. A Simplex is a set of alternate parameter values. These alternate parameters are used in an iterative process where good estimates are kept and bad estimates are rejected. The good

estimates are used to generate better estimates on the next iteration until the objective function is minimized.

3 Scope

The purpose of this research is to find out how well the GSSHA model calibrates and then validates to different storms. The commonly used HMS model will also be calibrated and validated to the same storms for comparative purposes. The models will first be set up in WMS using generally available digital data sources and then the calibration data will be applied to each of the models. The calibration and validation storms will be kept the same for both of the models for the purpose of comparison. I will also outline guidelines for setting up and running a successful calibration in both models. The viability of using the GSSHA model for routine hydrologic modeling will also be a point of emphasis.

3.1 Case Study watersheds and obtaining data

The watersheds and data that were used for this research were obtained from a website maintained by the Agricultural Research Service (ARS) an organization within the United States Department of Agriculture (USDA). The ARS had performed several experiments on multiple watersheds in the past and as a result had large quantities of high resolution data. Three watersheds were selected. The main type of data obtained from this website was rainfall data which included location of each rain gage and rainfall

distribution. Other data found through this website included stream flow data and the location of the outlet for the watershed.

Digital data that was needed for the preparation of the model domain and parameterization of runoff parameters was a DEM, land use, and soil type data. The DEM was obtained from the USGS seamless server (<http://seamless.usgs.gov/index.php>). The DEM is necessary for the delineation of the watershed for both models and the elevations of individual grid cells for the distributed model. The land use data were obtained from the webGIS website (<http://www.webgis.com>). These data are used in the GSSHA model to determine the surface roughness of different land use types. SSURGO soil data was taken from the USDA Soil Data Mart (<http://soildatamart.nrcs.usda.gov>). This data is useful in determining infiltration of specific soil types that are found in the watershed.

This digital spatial data is then assigned to corresponding grid cells which are assigned parameter values that represent the soil type or land use they cover. The parameters needed for a typical GSSHA model with Green and Ampt for infiltration include: Hydraulic Conductivity, Capillary Head, Porosity, Field Capacity, Wilting Point, Initial Moisture, Overland Roughness, and Channel Roughness. The Hydraulic Conductivity, Capillary Head, Porosity, Field Capacity, and Wilting Point are all estimated using standard tables (Rawls et al. 1982).

3.1.1 Case Study 1

The first watershed that was analyzed is Reynolds Creek and it is located near Boise, Idaho. A map of the area and graphic of the watershed is shown in Figure 3.1. The

graphic of the watershed includes the location of the rain gages and stream network. Thiessen polygons were used to divide the rain gages over the watershed.

I used three precipitation gages for this watershed. In order to give a general idea of the depth and intensity of rainfall that was used for the calibration of this watershed, I have included a graph, shown in Figure 3.2, which shows cumulative precipitation for one gage in the watershed that is representative of the whole.

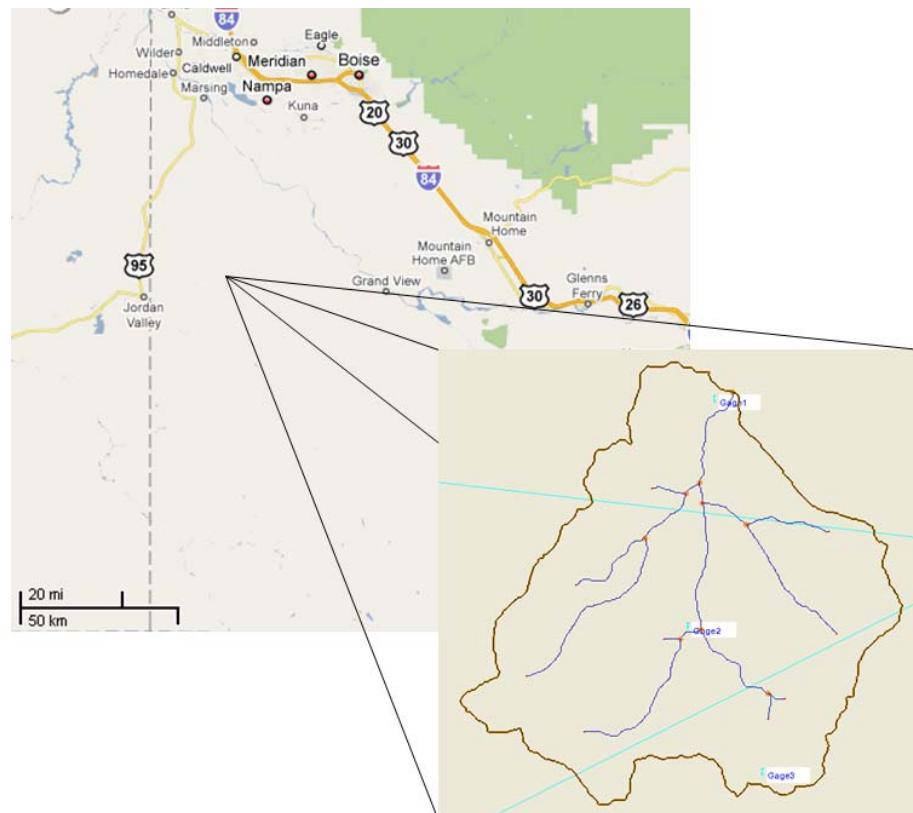


Figure 3.1: Location of the Reynolds Creek Watershed.

This watershed was described by the ARS as almost entirely sagebrush rangeland. The shapefile data for this watershed (both land use and soil type data) was downloaded from webGIS and the Soil Data Mart websites. The watershed is about 21 square miles

and WMS computed the percentage of each land use and soil type that existed in the bounds of the watershed according to the shapefile data. The results of the WMS computations are given in Table 3.2.

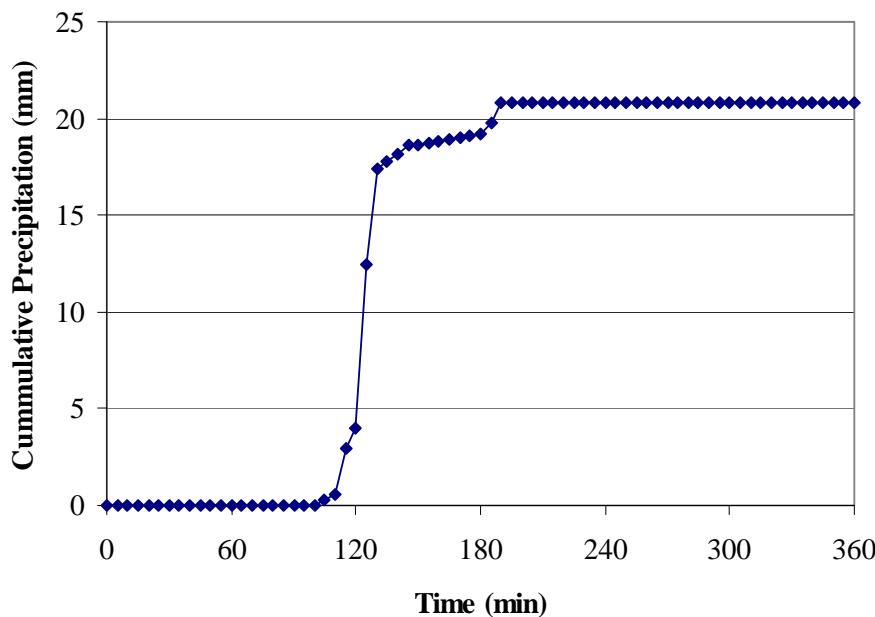


Figure 3.2: Cumulative precipitation for Reynolds Creek Watershed calibration.

Table 3.1: Land Use and Soil Type distribution for Reynolds Creek Watershed

Land Use	Coverage of Basin (%)
Mixed Rangeland	44
Evergreen Forest Land	56

Soil Type	Coverage of Basin (%)
Loam	50
Silt Loam	24
Coarse Sandy Loam	22
Bedrock	2
Organic	2

3.1.2 Case Study 2

The second watershed included in this study was the Tifton watershed found in Georgia. A map indicating the location of the watershed along with an image of the watershed shape is given in Figure 3.3. The graphic of the watershed includes the location of the rain gages and stream network. Thiessen polygons were used to divide the rain gages over the watershed.

I used four precipitation gages for this watershed. In order to give a general idea of the depth and intensity of rainfall that was used for the calibration of this watershed, I have included a graph, shown in Figure 3.4, which shows cumulative precipitation for one gage in the watershed that is representative of the whole.

This watershed is approximately 44 square miles and the same WMS computations were performed using the land use and soil type data to find out what percentages of each land use and soil type this watershed had. The results of these computations are given in Table 3.2.

3.1.3 Case Study 3

The last watershed that was used for this study is named Goodwin Creek and is found in Mississippi. A map indicating the location of the watershed along with an image of the watershed shape is given in Figure 3.5. The graphic of the watershed includes the location of the rain gages and stream network. Thiessen polygons were used to divide the rain gages over the watershed.



Figure 3.3: Location of the Tifton Watershed.

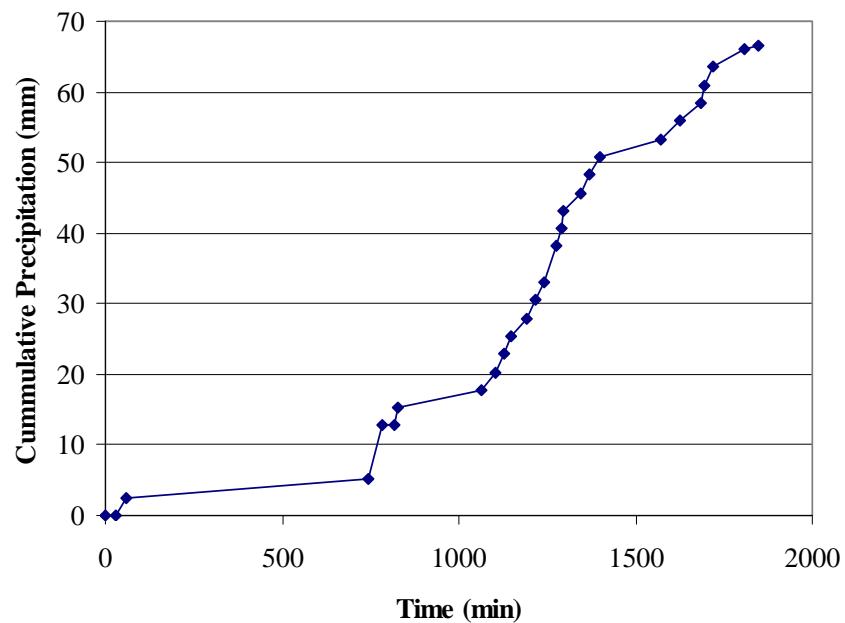


Figure 3.4: Cumulative precipitation for Tifton Watershed calibration.

Table 3.2: Land Use and Soil Type distribution for Tifton Watershed

Land Use	Coverage of Basin (%)
Cropland and Pasture	65
Evergreen Forest	22
Forested Wetlands	13

Soil Type	Coverage of Basin (%)
Loamy Sand	84
Sandy Loam	7
Fine Sandy Loam	7
Sand	2

I used three precipitation gages for this watershed. In order to give a general idea of the depth and intensity of rainfall that was used for the calibration of this watershed, I have included a graph, shown in Figure 3.6, which shows cumulative precipitation for one gage in the watershed that is representative of the whole.

This watershed has been used by others in testing the functionality of the GSSHA model (Senarath et al. 2000). The watershed is approximately 8 square miles and the same WMS computations were performed using the land use and soil type data to find out what percentages of each land use and soil type this watershed had. The results of these computations are given in Table 3.3.



Figure 3.5: Location of the Goodwin Creek Watershed.

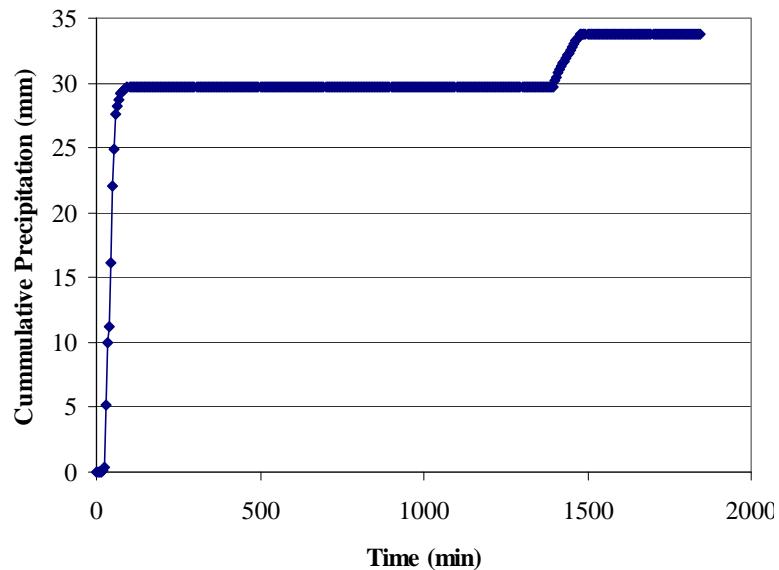


Figure 3.6: Cumulative precipitation for Goodwin Creek Watershed calibration.

Table 3.3: Land Use and Soil Type distribution for Goodwin Creek Watershed

Land Use	Coverage of Basin (%)
Cropland and Pasture	71
Mixed Forest Land	29
Strip Mines and Gravel Pits	<1

Soil Type	Coverage of Basin (%)
Silt Loam	99
Fine Sandy Loam	1

4 Results

4.1 Reynolds Creek Results

4.1.1 HMS Analysis

The preprocessing for the Reynolds Creek watershed was performed within the WMS interface. Green and Ampt parameters along with the Clark unit hydrograph (Clark 1945) were used for the analysis. The parameters that were required for an HMS simulation of this type were: Initial Losses, Moisture Deficit, Capillary Suction, Conductivity, Percent Impervious, Time of Concentration, and Storage Coefficient. Initial values were estimated using tables and equations from a hydrology textbook (Wanielista et al. 1997). A simulation was then run to see how closely the initial values predicted the observed runoff. Manual calibration was performed when needed to get the computed hydrograph closer to the observed hydrograph before turning to the automated calibration algorithms.

The values assigned to the model for initial loss and moisture deficit are a function of how saturated the soil is when a given event takes place. A model can be calibrated to different levels of soil saturation. Each simulation was initially calibrated to a mid-level saturation level. It was desired to establish a range of hydraulic conductivity

values that could be used for the watershed if the soil saturation had been different. The time of concentration and storage coefficient were held constant and a calibration for both fully saturated and fully dry soil was computed to establish the range of possible conductivities for the watershed. The initial loss was adjusted along with the moisture deficit because when a soil is saturated there are less initial losses than when the soil is completely dry. I have included the calibrated parameters below in Table 4.1.

Table 4.1: Calibration parameters for Reynolds Creek Watershed (HMS)

Parameter	Run 1	Run 2	Run 3
Initial Loss (in)	0.2	0.4	0.6
Moisture Deficit (in/in)	0	0.25	0.5
Suction (in)	6	17	28
Conductivity (in/hr)	3.17	0.135	0.0143
Time of Concentration (hr)	1.85	1.85	1.85
Storage Coefficient (hr)	2.45	2.45	2.45

Each of the three runs shown above yielded the same hydrograph. The graphical representation of the results is given in Figure 4.1. The table is an effort to show that these parameters are interrelated and can be adjusted in different ways to get similar results. This table shows how the hydraulic conductivity might vary depending on how saturated the soil was when the event began. It ranges from completely saturated to completely dry with a value in the middle.

The simulated hydrograph matches the peak well, but spreads out a little wider than the observed hydrograph giving it a little more volume than it should have. This result could be attributed to many different things. I think the biggest contributions to

this are the use of the Clark unit hydrograph and only using the temporal distribution of one rain gage. The time of concentration helped to match the time to peak and the storage coefficient was able to match the receding limb fairly well. Most of the excess volume accumulated in the rising limb which can be attributed to the use of a unit hydrograph and the program not being able to model some of the subtleties of the watershed response. The overall summary of the simulated and observed data in terms of peak and volume is given below in Table 4.2.

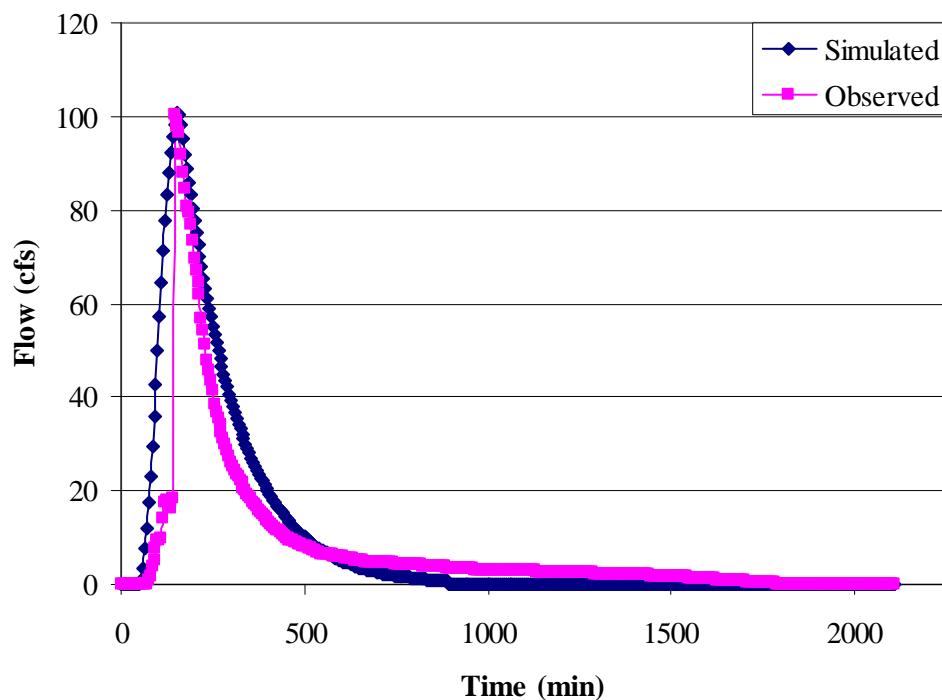


Figure 4.1: Optimization hydrograph for Reynolds Creek Watershed (HMS).

Table 4.2: Summary of Calibration Results Reynolds Creek Watershed (HMS)

Measure	Simulated	Observed	Difference	Percent Difference
Volume (IN)	0.05	0.04	0.01	21.31
Peak Flow (CFS)	100.9	100.2	0.7	0.7

4.1.2 HMS Validation

The parameters from the calibration runs were then held constant and a new storm and observed flow where input into the model to see how well the calibrated parameters validated. A straight translation of the calibrated parameters to the validation storm did not produce any runoff. In order to compare the HMS validation with the GSSHA validation the soil moisture parameter in the HMS model was changed proportional to how the moisture of the GSSHA model was changed for the validation storm. These graphs along with the validation storm hydrograph are given below in Figure 4.2.

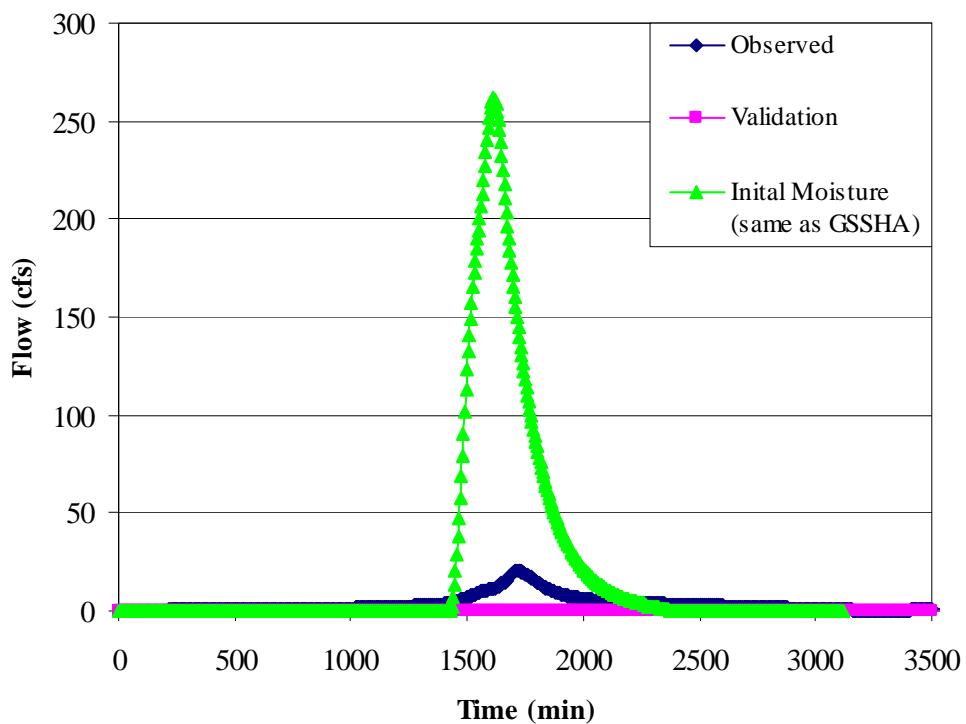


Figure 4.2: Validation storm hydrograph for Reynolds Creek (HMS).

This graph gives insight into how sensitive the parameters that describe soil moisture can be when trying to model a smaller storm with parameters that were

calibrated to a larger storm. The zero flow corresponds to the validation run where the calibrated parameters were used. The validation storm created a peak outlet flow of about 20 cfs. The HMS model was then brought to the same initial moisture as the GSSHA to compare the two. In this case, it meant completely saturating the soil which then made the hydrograph go from no flow to overestimating the peak by a large margin. As noted in the HMS technical manual the practice of using a storm dissimilar to the calibration storm is not recommended (USACE 2000). The reasoning for this is evident from the results of this graph.

4.1.3 GSSHA Analysis

The same data that was used in the HMS analysis was then used to perform a calibration with GSSHA. The WMS interface was used to set up the GSSHA model and calibration parameters. Green and Ampt parameters were used in the GSSHA analysis and no unit hydrograph was necessary because GSSHA is a distributed model. The program requires the use of metric units so they will be used to describe the parameters as well as the results. There are guidelines established on the GSSHAWiki (<http://www.gsshwiki.com>) that list in order the most important parameters that should be included for calibration. They include: Hydraulic Conductivity, Initial Moisture, Overland Roughness, and Channel roughness. All of these parameters were allowed to vary for each of the different soil types and land uses for individual simulations. The results of the calibration are presented in Table 4.3.

The values displayed in bold are the values that were adjusted during calibration. The other values were taken from a table developed by Rawls and Brakensiek for the respective soil types found in the watershed. This watershed had two soil types that were

not found in this table (organic and bedrock). The values for the organic soil were estimated while the bedrock was treated as an impervious area. These two soil types made up about 4 % of the total watershed and should not have a significant effect on the overall result.

Table 4.3: Calibrated values Reynolds Creek Watershed (GSSHA)

Soil Type	Coarse sandy loam	Loam	Silt loam	Organic
Hydraulic Conductivity (cm/hr)	0.860	1.599	1.368	9.450
Capillary Head (cm)	11.01	8.89	16.68	5.50
Porosity (m ³ /m ³)	0.453	0.463	0.501	0.475
Field Capacity (m ³ /m ³)	0.207	0.270	0.330	0.100
Wilting Point (m ³ /m ³)	0.095	0.117	0.133	0.050
Initial Moisture	0.389	0.217	0.409	0.349

The roughness parameters are important to help get the volumes of the simulated and observed hydrograph to match. The calibrated parameters for the overland roughness as well as channel roughness are given below in Table 4.4.

Table 4.4: Calibrated roughness values Reynolds Creek Watershed (GSSHA)

Land Use	Mixed Rangeland	Evergreen Forest
Surface Roughness	0.393	0.724
Channel Roughness	0.148	

These values are high in comparison to the values that are given in established tables for roughness values. In my calibration efforts I tried to restrict these values to a small range close to the estimates I found in tables only to find that the calibration did not converge. The volume was far too small when the roughness values were restricted. When I allowed them to vary to higher values the convergence was much better. I hypothesize that this is because GSSHA does not have a mechanism to account for storage in a watershed when using the simplistic approach I am taking. Thus I believe the high values can be attributed to accounting for the watershed storage.

The resulting hydrograph using the calibrated parameters along with the observed hydrograph is shown in Figure 4.3.

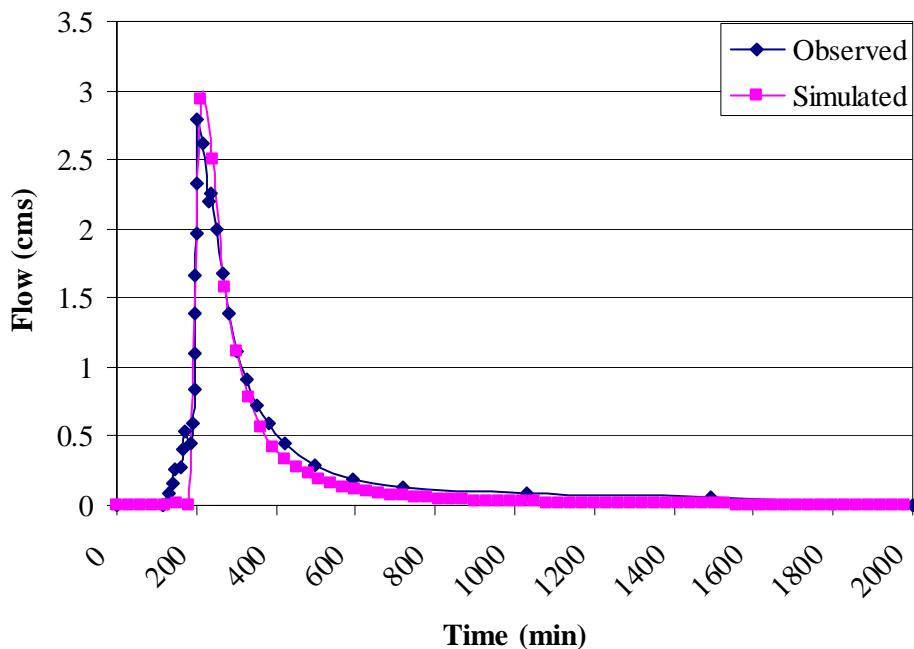


Figure 4.3: Optimization hydrograph for Reynolds Creek Watershed (GSSHA).

The simulated graph follows the rising and falling limbs quite well. The time to peak is almost right on, but the peak is overestimated. The volume is underestimated. It appears that the simulation does not respond quickly enough to account for the initial volume of the observed hydrograph and the falling limb of the simulated graph goes down a little more sharply than the observed hydrograph. The overall summary of the simulated and observed data in terms of peak and volume is given in Table 4.5.

Table 4.5: Summary of Calibration Results Reynolds Creek Watershed (GSSHA)

Measure	Simulated	Observed	Difference	Percent Difference
Volume (m ³)	22,764	27,228	-4464	-16.4
Peak Flow (CMS)	2.95	2.78	.17	6.1

4.1.4 GSSHA Validation

In doing a GSSHA validation all the parameters from the calibration effort will be held constant except for the initial moisture of the soil. The validation conditions of how moist the soil is could be different than the calibration event. The initial moisture of the soil can be adjusted in the validation phase since this parameter is unknown and changes from event to event.

For the case of Reynolds Creek the validation was unsuccessful. I tried different soil moisture conditions up until the soil was completely saturated and still did not produce any runoff with the parameters from the calibrated simulation. This type of result indicates that the initial calibration failed to capture the true values for the parameters. It is most likely that the initial moisture in this case is very sensitive and the

validation storm conditions did not match because the calibration parameters “matched” but did not capture the “real” parameters for the watershed. It is also possible that a few sensitive parameters for this watershed were neglected from the calibration and were erroneous from the beginning. The result was the same as the HMS trial in that the simulation predicted no runoff in the validation phase. The observed flow of the validation event is given below in Figure 4.4.

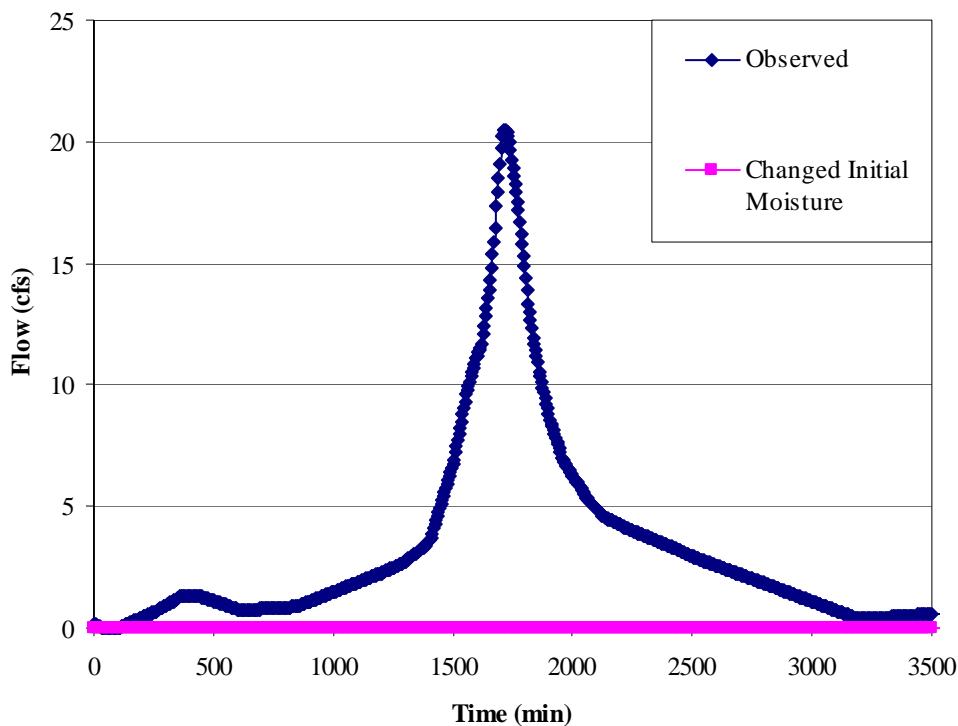


Figure 4.4: Validation storm hydrograph for Reynolds Creek (GSSHA).

The calibration parameters did not yield any runoff with the validation storm. The soil moisture was changed until the soil was completely saturated. Even after completely saturating the soil, no runoff was computed for this simulation.

4.2 Tifton Results

4.2.1 HMS Analysis

The Tifton watershed was prepared and calibrated using the same methods described in the HMS analysis section for the Reynolds Creek watershed. The results of three calibration efforts of varying soil moisture are shown below in Table 4.6.

Table 4.6: Calibration parameters Tifton Watershed (HMS)

Parameter	Run 1	Run 2	Run 3
Initial Loss (in)	0.2	0.58	0.75
Moisture Deficit (in/in)	0	0.25	0.5
Suction (in)	2.15	6.13	6.22
Conductivity (in/hr)	0.639	0.141	0.060
Time of Concentration (hr)	22.37	22.37	22.37
Storage Coefficient (hr)	44.19	44.19	44.19

Each of the three calibration runs produced equally good results and they give a range of possible values that describe the watershed response to the given storm under varying soil moisture conditions. The HMS manual suggests against calibrating a watershed where the time of concentration is greater than the length of the storm. This is the case for this watershed, but it is desired to see what the results are for a comparison to how the GSSHA model handles such situations. The results of the calibration are shown below in Figure 4.5.

This watershed is the largest of the three and it is evident that spatial variation is not being taken into account with this calibration. The rising limb matches really well,

but the falling limb does not match as well. The peak is overestimated in this case to help produce more volume to account for water produced by the second peak. The temporal distribution in this case was unable to produce the double peak that occurs in the observed hydrograph. The overall summary of the simulated and observed data in terms of peak and volume is given below in Table 4.7.

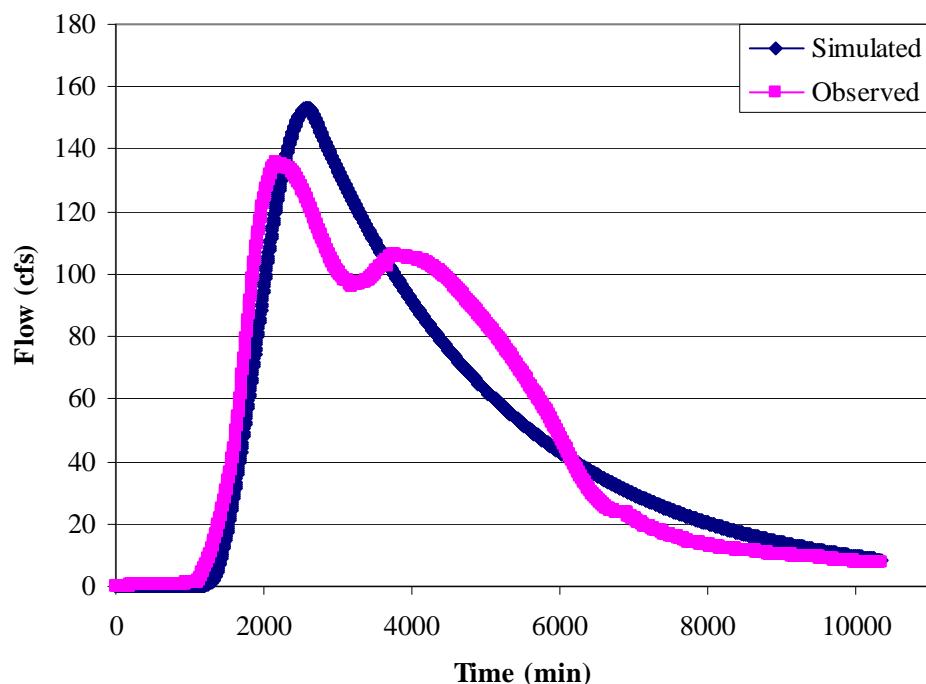


Figure 4.5: Optimization hydrograph for the Tifton Watershed (HMS).

Table 4.7: Summary of Calibration Results Tifton Watershed (HMS)

Measure	Simulated	Observed	Difference	Percent Difference
Volume (IN)	0.29	0.30	<0.01	-1.53
Peak Flow (CFS)	152.7	135.6	17.1	12.6

4.2.2 HMS Validation

The conditions of the watershed were likely to change between the calibration time period and the validation time periods. In this particular case, there is a four month lapse between the calibration and validation storms. During this amount of time the watershed conditions can change drastically. Therefore, the soil moisture was allowed to change to get the best match to the observed flow and also changed proportional to the GSSHA soil moisture change for that simulations validation run for comparative purposes. The results of the validation runs are given in Figure 4.6.

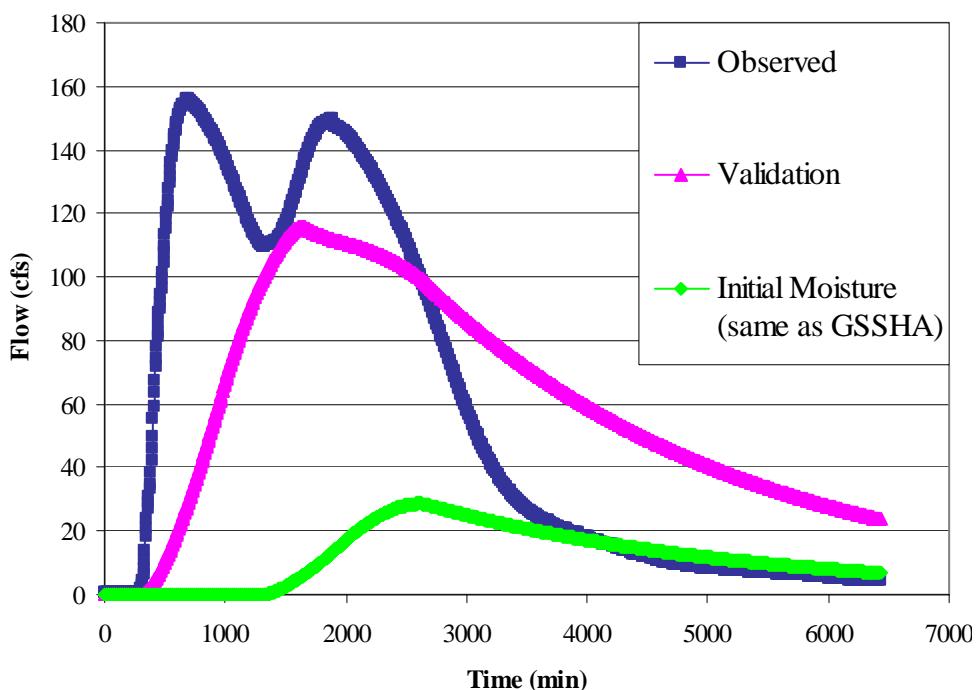


Figure 4.6: Validation for the Tifton Watershed (HMS).

The results of the validation run show that the temporal distribution of the rainfall was unable to produce the double peak and the storage coefficient and time of concentration seem to be too high for the validation conditions. The watershed response

to this storm seems to happen much more quickly than the calibration storm. The rising limb of the simulated hydrograph rises much slower than the observed hydrograph. The falling limb of the observed hydrograph also is at a much steeper angle than the simulated hydrograph. It is likely that in the calibration the model calibrated to a time of concentration and storage coefficient that did not transfer well to this validation storm and therefore did not perform very well. The hydrograph that compares with the moisture content of the GSSHA hydrograph produced runoff that underestimated peak and volume by more than the HMS model. This shows that the GSSHA model over predicted while the HMS model under predicted in the case of this watershed.

4.2.3 GSSHA Analysis

The same data that was used in the HMS analysis was then used to perform a calibration with GSSHA. The WMS interface was used to set up the GSSHA model and calibration parameters. The results of the calibration run produced the parameter values given in Table 4.8.

Table 4.8: Calibrated values Tifton Watershed (GSSHA)

Soil Type	Sand	Loamy Sand	Sandy Loam	Fine Sandy Loam
Hydraulic Conductivity (cm/hr)	1.255	0.095	0.678	0.219
Capillary Head (cm)	4.95	6.13	11.01	11.01
Porosity (m^3/m^3)	0.437	0.437	0.453	0.453
Field Capacity (m^3/m^3)	0.091	0.125	0.207	0.207
Wilting Point (m^3/m^3)	0.033	0.055	0.095	0.130
Initial Moisture	0.239	0.239	0.209	0.209

This simulation was calibrated in a similar fashion allowing the hydraulic conductivity of all the different soils to vary while assuming values for the rest of the parameters from the Rawls and Brakensiek table. An estimate for the initial moisture was assumed and held constant for this simulation.

The overland roughness was assumed to be constant for the three different land use types. The overland roughness and the channel roughness were both included as calibration variables and the results are shown below in Table 4.9.

Table 4.9: Calibrated Roughness values Tifton Watershed (GSSHA)

Land Use	Cropland and Pasture	Evergreen Forest	Forested Wetlands
Surface Roughness	0.794	0.794	0.794
Channel Roughness	0.418		

Once again the values for roughness are much higher than expected according to literature values. This trend was seen in each of the watersheds that I analyzed.

The resulting hydrograph using the calibrated parameters along with the observed hydrograph is shown in Figure 4.7.

For the calibration of this watershed with GSSHA, both peak and volume match quite well with a low cost function. However, the visual fit is not as good as the metrics provided for peak and volume would lead you to believe. The time to peak is off by approximately 20 hours. Even though the peak and volume match really well it does not make the calibration precise. The precipitation distribution does not produce the second peak. Since this watershed is larger than the other two in this study perhaps more rain

gages were needed to obtain the necessary rainfall distribution to produce a second peak and match the time to peak better. Another possibility is the influence groundwater could be playing and which is not being taken into account in my model. The overall summary of the simulated and observed data in terms of peak and volume are given in Table 4.10.

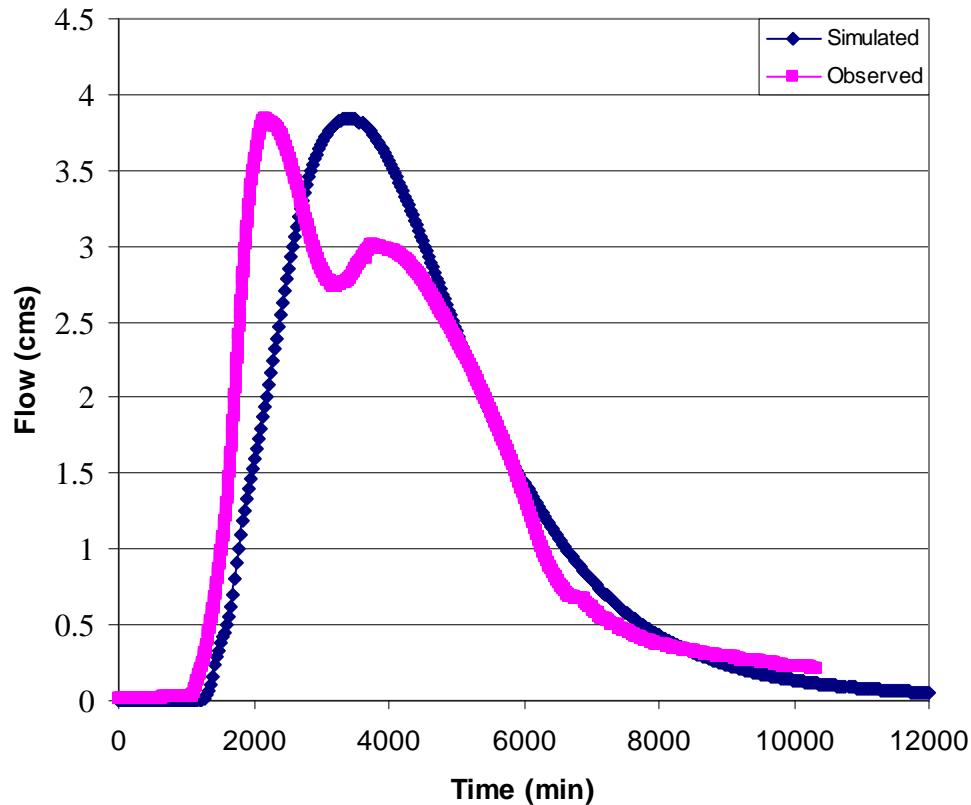


Figure 4.7: Optimization Hydrograph for the Tifton Watershed (GSSHA).

Table 4.10: Summary of Calibration Results Tifton Watershed (GSSHA)

Measure	Simulated	Observed	Difference	Percent Difference
Volume (m^3)	859,313	856,689	2624	0.3
Peak Flow (CMS)	3.84	3.84	0.004	0.1

4.2.4 GSSHA Validation

The validation storm and observed hydrograph were then applied to the same watershed holding all of the parameters from the calibration run constant. After an initial run the soil moisture was adjusted to match the simulated and observed hydrographs. The results of this effort are shown below in Figure 4.8.

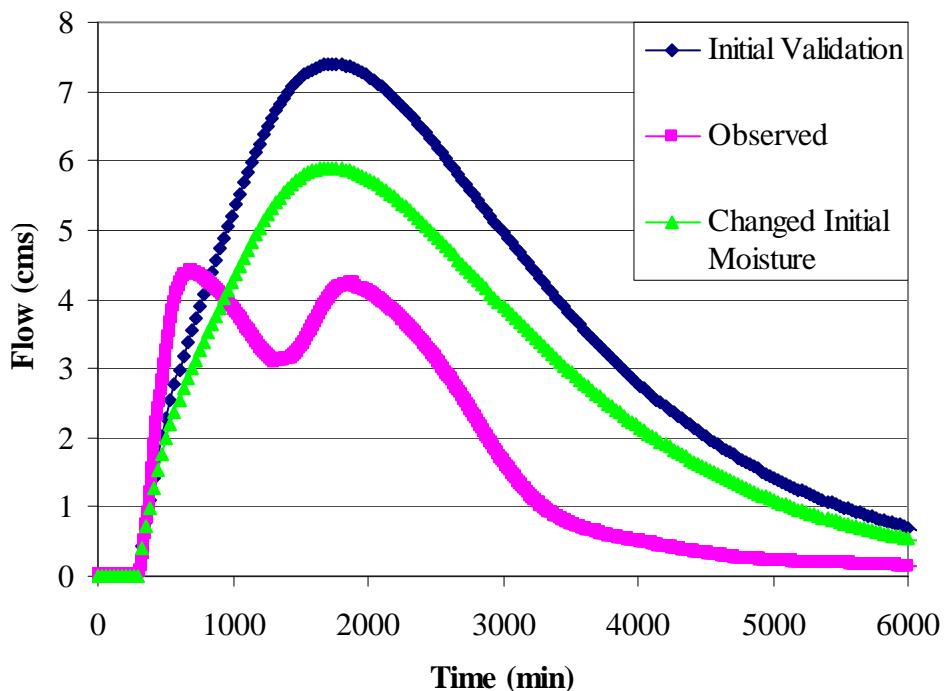


Figure 4.8: Validation result for the Tifton Watershed (GSSHA).

The peak and volume were both over-predicted. Once again I tried changing the initial moisture to get a better match, and I changed it until the soil was completely dry. The changing of the soil moisture was only able to bring the peak down by about 1.5 cms when it needed to come down about twice that. The two storms for this watershed produced similar looking outlet hydrographs with double peaks. The calibration effort yielded a result that matched the peak and volume well but didn't match the shape of the

outlet hydrograph. It is not surprising that similar results are obtained in the validation effort.

There are many different factors that could be causing the results I am getting. The original calibration might have calibrated to incorrect soil moisture which created the problem in the verification period. This watershed could also have more complexity than I am trying to model. There could be groundwater flow contributing throwing the results off. It appears that more work needs to be done with this watershed to find out what other factors are influencing how it reacts to different storm events.

4.3 Goodwin Creek Results

4.3.1 HMS Analysis

The Goodwin Creek watershed was prepared and calibrated using the same methods described in the HMS analysis section for the Reynolds Creek watershed. The results of three calibration efforts of varying soil moisture are shown below in Table 4.11.

Table 4.11: Calibration parameters Goodwin Creek Watershed (HMS)

Parameter	Run 1	Run 2	Run 3
Initial Loss (in)	.15	0.5	.7
Moisture Deficit (in/in)	0	.25	.5
Suction (in)	2.47	14.08	17.72
Conductivity (in/hr)	0.490	0.0458	0.0027
Time of Concentration (hr)	1.502	1.502	1.502
Storage Coefficient (hr)	0.974	0.974	0.974

Each of the three calibration runs shown in the table produced equally good results and they give a range of possible values that describe the watershed under varying soil moisture conditions. The results of the calibration are shown in Figure 4.9.

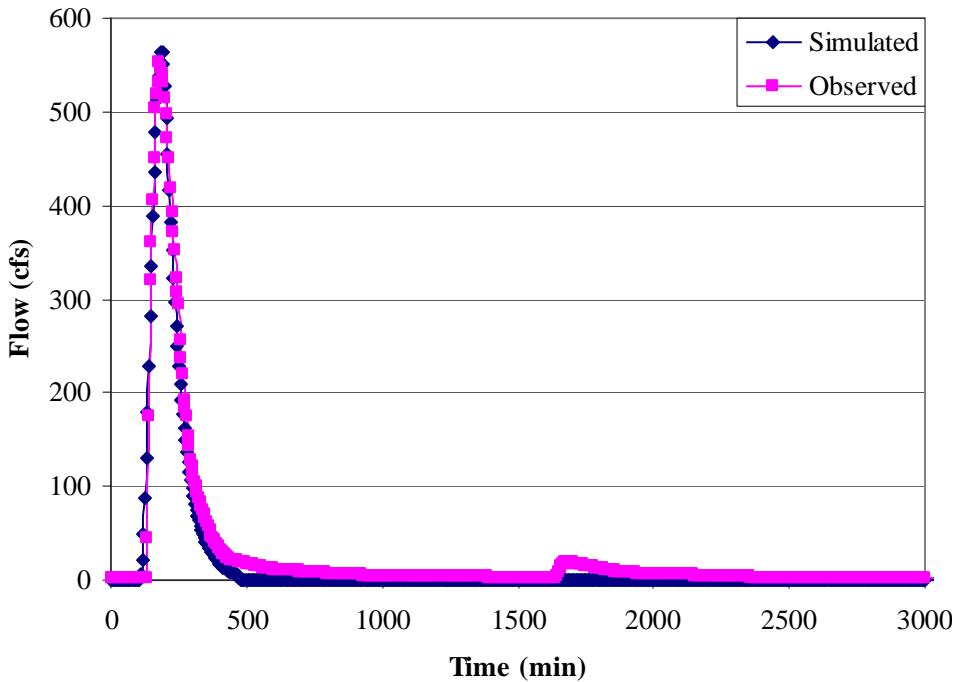


Figure 4.9: Optimization hydrograph for the Goodwin Creek Watershed (HMS).

The first peak matches well for both the rising and falling limbs as well as the peak. The simulated hydrograph does not produce a second peak like the observed hydrograph has. This is most likely due to the HMS model normalizing the rainfall. The temporal distribution of the closest gauge is taken to represent the whole watershed. The GSSHA model incorporates the spatial variability of the rainfall better and should do a better job at picking up second peaks like the one seen in Figure 4.9. Since the simulated hydrograph does not have a second peak it has a lower volume than the observed hydrograph. In this case it was more important to match the largest hydrograph. The

overall summary of the simulated and observed data in terms of peak and volume is given below in Table 4.12.

Table 4.12: Summary of Calibration Results Goodwin Creek Watershed (HMS)

Measure	Simulated	Observed	Difference	Percent Difference
Volume (IN)	0.21	0.25	-0.05	-18.48
Peak Flow (CFS)	579	553.9	25.1	4.5

4.3.2 HMS Validation

The conditions of the watershed were likely to change between the calibration time period and the validation time periods. Therefore, the soil moisture was allowed to change to get the best match to the observed flow and also changed proportional to the GSSHA soil moisture change for that simulations validation run for comparative purposes. The results of the validation runs are given in Figure 4.10.

The validation results were surprising because the peaks of the calibration and validation phases were so similar. The validation run was unsuccessful as the simulated hydrograph over predicted by more than 100%. The simulated hydrograph where the soil moisture was changed proportionally to the GSSHA model for comparative purposes also overestimated both peak and volume by more than 100%. The results being this different from what was expected points towards a possible data error. It is possible that I made an error in the data reduction or that in the compilation of the data there was some kind of error. Another possible reason for the large discrepancy lies in the soil moisture

of the original calibration. If this value was not correct then the other values would be incorrect making predictions outside the calibration time period impossible.

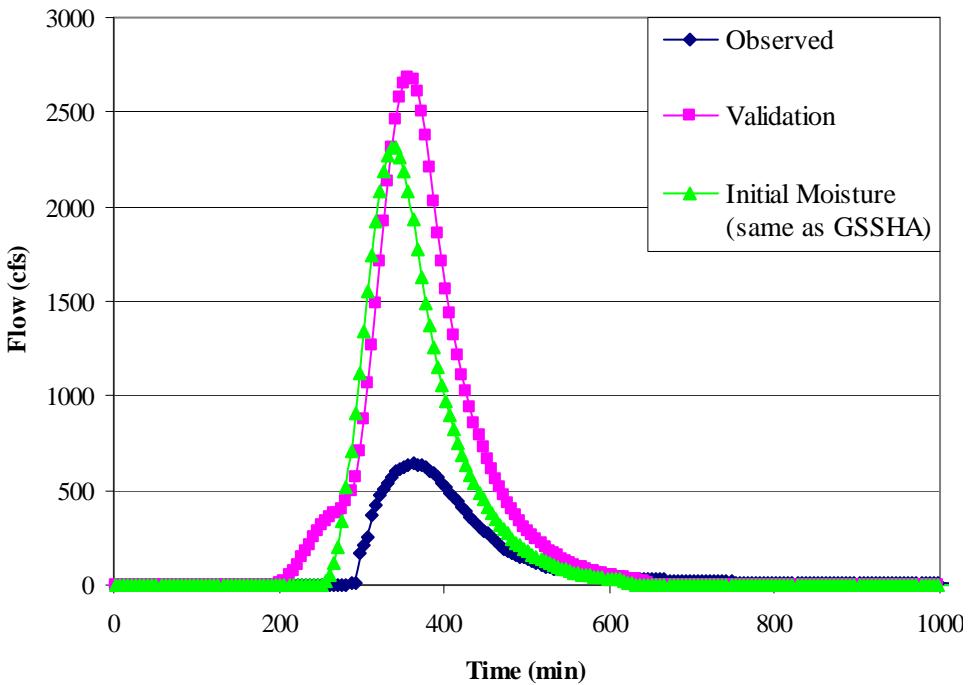


Figure 4.10: HMS validation for the Goodwin Creek Watershed (HMS).

4.3.3 GSSHA Analysis

The same data that was used in the HMS analysis was then used to perform a calibration with GSSHA. The WMS interface was used to set up the GSSHA model and calibration parameters. The results of the calibration run produced the parameter values given in Table 4.13.

Table 4.13: Calibrated values Goodwin Creek Watershed (GSSHA)

Soil Type	Fine Sandy Loam	Silt Loam
Hydraulic Conductivity (cm/hr)	5.370	0.194
Capillary Head (cm)	11.01	16.68
Porosity (m ³ /m ³)	0.453	0.501
Field Capacity (m ³ /m ³)	0.207	0.330
Wilting Point (m ³ /m ³)	0.095	0.133
Initial Moisture	0.287	0.491

This simulation was also calibrated allowing hydraulic conductivity and initial moisture to vary while holding the other Green and Ampt parameters constant according to the estimates given in the Rawls and Brakensiek table.

The overland roughness and the channel roughness were included for this simulation and the results of the calibration are given below in Table 4.14.

Table 4.14: Calibrated Roughness Values Goodwin Creek Watershed (GSSHA)

Land Use	Cropland and Pasture	Mixed Forest	Strip Mines and Gravel Pits
Surface Roughness	0.217	0.350	0.669
Channel Roughness	0.049		

This watershed produced smaller roughness values than the previous two watersheds. The values are more reasonable but still high. One possible explanation for why this watershed had lower values is it is the smallest of the three watersheds that were analyzed. The size difference could mean there is less storage and therefore higher roughness values are not needed to simulate the effects of storage.

The resulting hydrograph using the calibrated parameters along with the observed hydrograph is shown below in Figure 4.11.

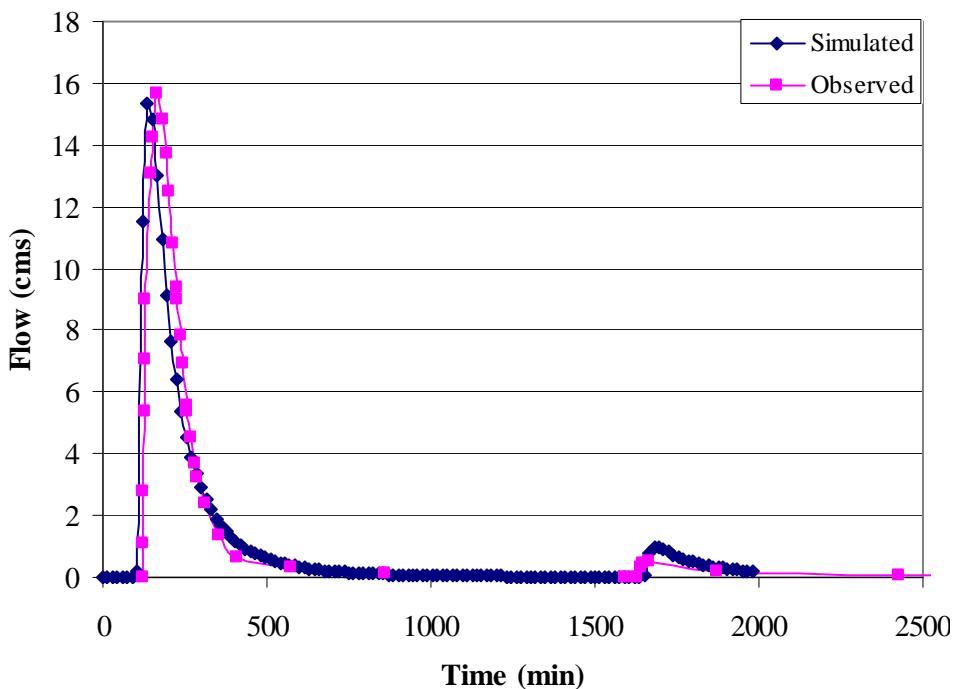


Figure 4.11: Optimization hydrograph for the Goodwin Creek Watershed (GSSHA).

The simulated hydrograph has a very similar slope of the rising and falling limb of the observed hydrograph. The time to peak is off by about 30 minutes. This time difference is not that significant for an event like this. The second small peak occurs with good timing but the simulated hydrograph overestimates that peak by about 40 percent. This simulation was an excellent example of how the GSSHA model incorporated the spatial variability of the rainfall and captured the second small peak. Recall, the HMS model for the same storm (displayed in Figure 4.9) was unable to produce any runoff where the second small peak occurred. The overall summary of the simulated and observed data in terms of peak and volume is given below in Table 4.15.

Table 4.15: Summary of Calibration Results Goodwin Creek Watershed (GSSHA)

Measure	Simulated	Observed	Difference	Percent Difference
Volume (m^3)	131,374	131,353	21	<0.1
Peak Flow (CMS)	15.34	15.69	-0.35	-2.23

4.3.4 GSSHA Validation

The validation storm and observed hydrograph were then applied to the same watershed holding all of the parameters from the calibration run constant. After an initial run the soil moisture was adjusted to match the simulated and observed hydrographs. The results of this effort are shown below in Figure 4.12.

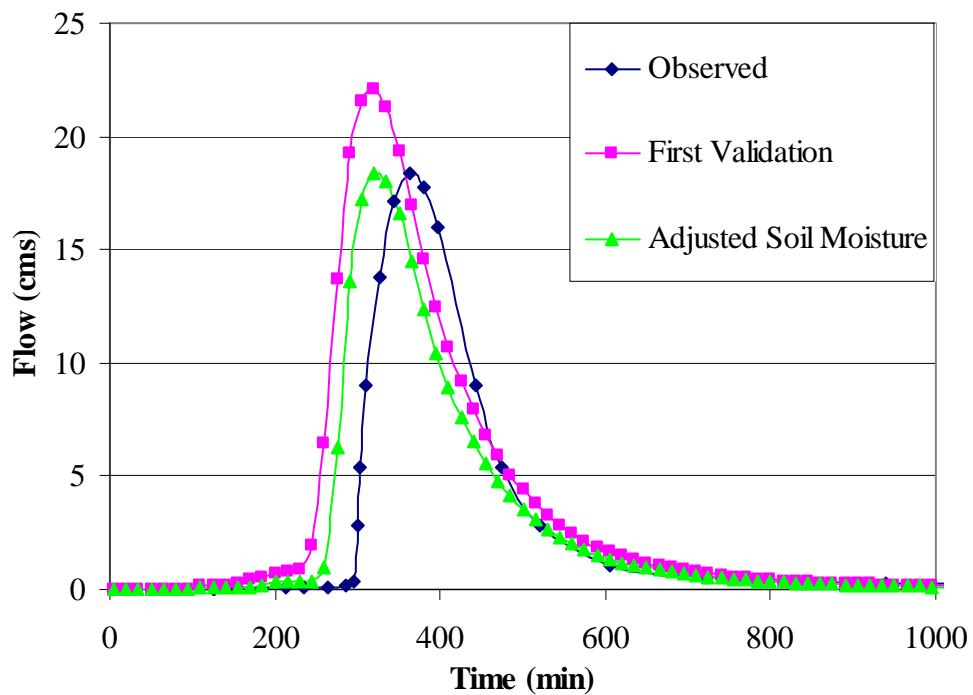


Figure 4.12: Validation results for the Goodwin Creek Watershed (GSSHA).

These hydrographs indicate the initial validation holding everything constant from the calibration effort over predicts the peak. When the initial moisture is adjusted the peak matches right on and volumes are close to the same. The one thing that is not matching really well is the time to peak. In this case it is off by about 40 minutes. This is most likely a result of the precipitation data not lining up perfectly with the stream flow data because of the intervals which the precipitation data were recorded.

4.4 Comparison of HMS vs. GSSHA Results

4.4.1 Reynolds Creek

The calibration results of Reynolds Creek watershed were different for HMS and GSSHA. A graph which includes the results of both models is given in Figure 4.13.

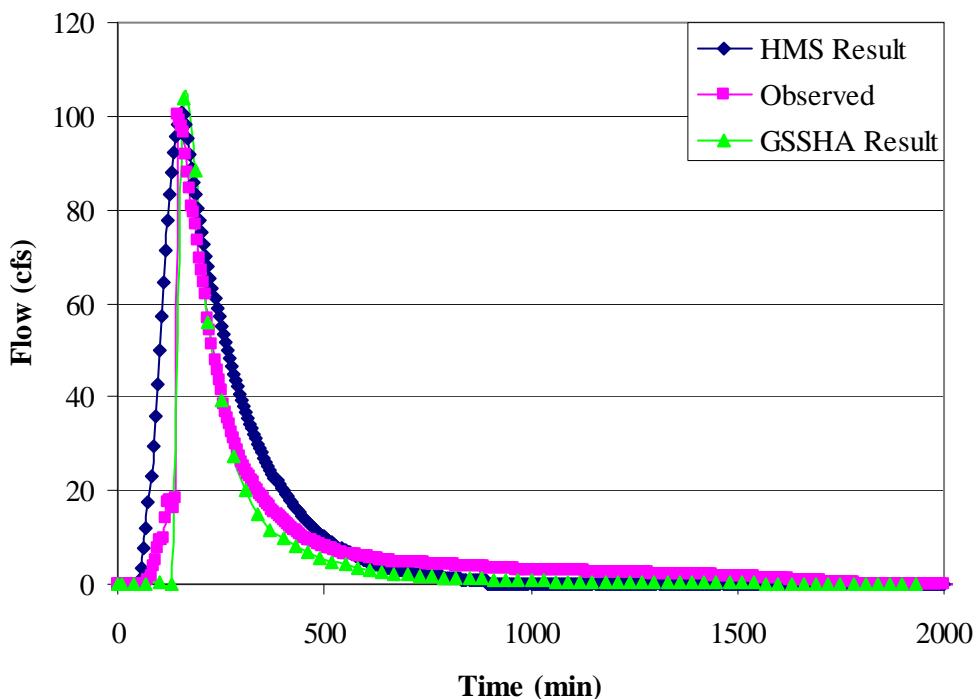


Figure 4.13: HMS and GSSHA calibration results for the Reynolds Creek Watershed.

The visual conclusion that can be drawn from this graph is that both models calibrated well for this particular storm. The HMS result over predicted the peak by 0.7% and the GSSHA result over predicted the peak by 6.1%. The HMS result also over predicted the volume by 21.3% and the GSSHA result under predicted the volume by 16.4%. So the HMS result was better for matching the peak and the GSSHA results did better matching the volume.

The most important measure of a model calibrating well is whether or not the model can validate using a different storm and stream flow data. Neither model was able to validate well. When the validation storm was applied neither model produced runoff. This was most likely due to the difficulty in estimating the soil moisture and also the large discrepancy between the two events peak runoff and volume.

4.4.2 Tifton

The results of the calibration of both models for the Tifton Watershed are shown in Figure 4.14.

Neither the HMS nor GSSHA results visually fit match the observed data. The GSSHA results had remarkably good matches to both peak and volume (both off by less than 0.35%), but the shape and time to peak were not close. The HMS result produced a hydrograph that matched the rising limb fairly well, but over predicted the peak by 12.6%. It was fairly close to matching the volume, under predicting by about 1.5%. It is hard to say which is better when neither one was able to simulate the double peak.

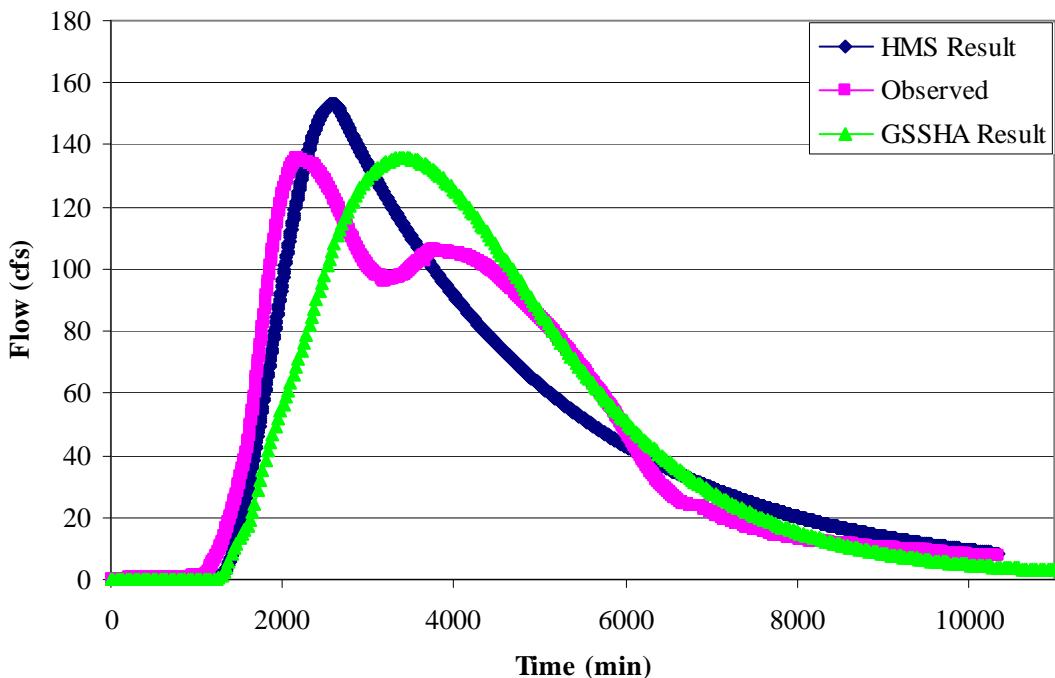


Figure 4.14: HMS and GSSHA calibration results for the Tifton Watershed.

The validation results have been graphed together with the observed outlet hydrograph and are shown in Figure 4.15.

The HMS result under predicts while the GSSHA event over predicts. Neither of the results validates the model, which tells us that the initial calibration does not transfer well to this new storm. A summary of how well the peak and volume are predicted in the validation run are given below in Table 4.16.

If the measures of peak and volume are used the HMS result seems to have the better validation result. The conditions of the watershed such as soil moisture and initial losses are hard to predict and likely are playing a part in the model not validating. The models are also simple and neglect things such as groundwater which could be a strong factor in the watershed response.

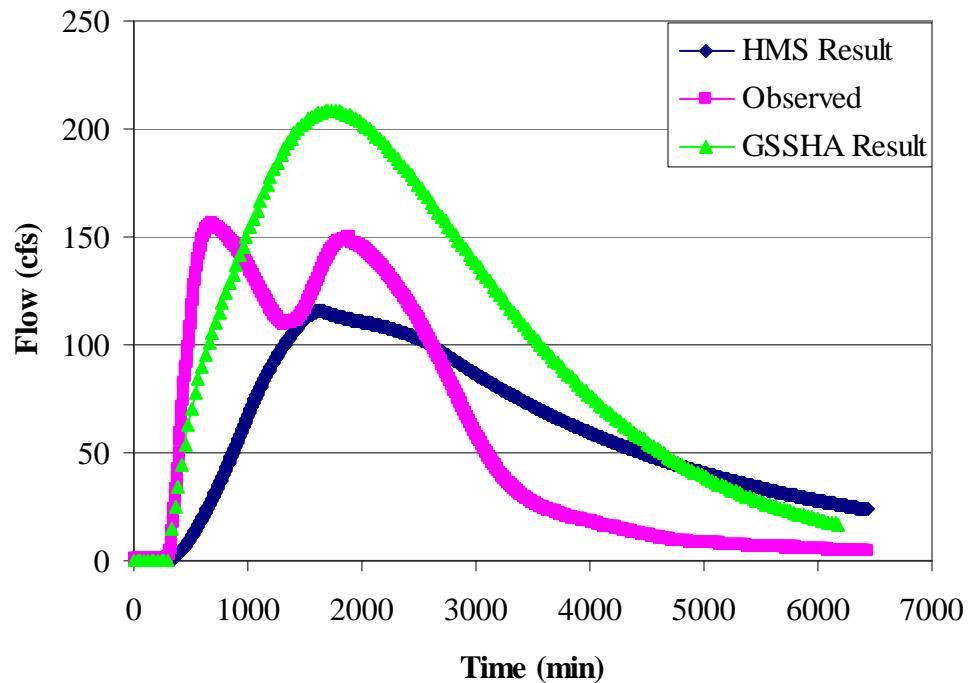


Figure 4.15: Validation results of HMS and GSSHA for the Tifton Watershed.

Table 4.16: Summary of Validation results Tifton Watershed

	Peak	Volume
HMS	-25.9%	4.6%
GSSHA	33.2%	67.3%

4.4.3 Goodwin Creek

The results of both models for the Goodwin Creek Watershed are shown in Figure 4.16.

The HMS model seems to follow the observed data a little better on the first peak, but generates no runoff on the second peak. The GSSHA model does a better job of producing runoff at the time of the second peak. The HMS model over predicts the peak by 4.5% while the GSSHA model under predicts the peak by about 2.2%. The HMS

model under predicts the volume by about 18.5% while the GSSHA model predicts the volume almost exactly (<0.1% off). The GSSHA model by these measures is the better of the two.

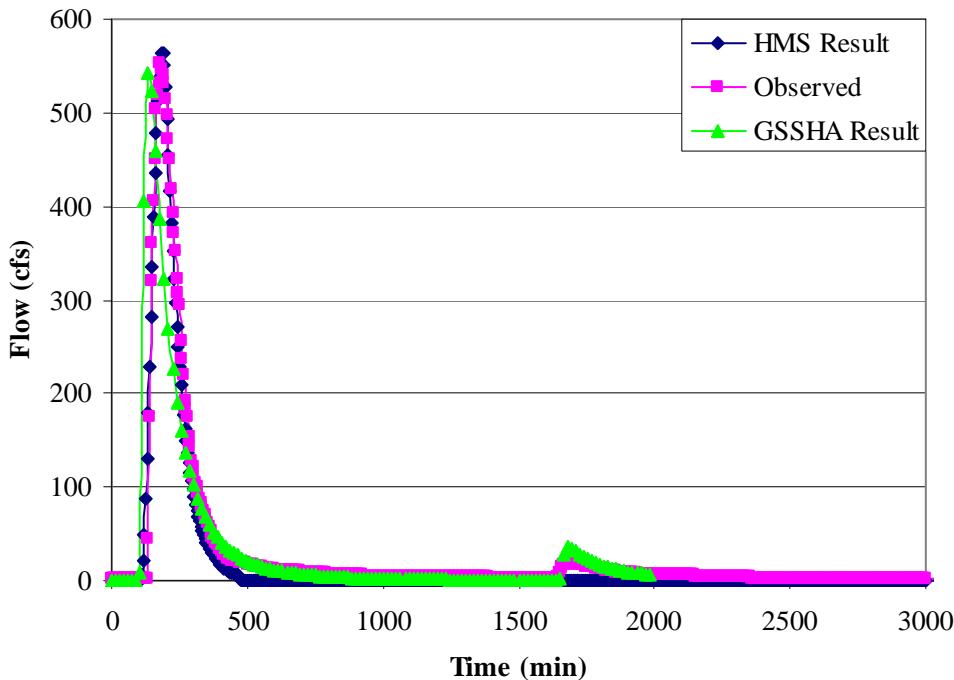


Figure 4.16: HMS and GSSHA calibration results for the Goodwin Creek Watershed.

The validation of this model yielded some interesting results. The graph of the two different models with the observed data is shown below in Figure 4.17.

The GSSHA validation result on this watershed is clearly superior. The summary of how well the validation runs performed is given below in Table 4.17.

The GSSHA model validates very well for this watershed. The timing is off a little bit but the peak and volume match closely with the observed data. The HMS results are not close and the parameters obtained for that model could not be used reliably for predicting runoff events.

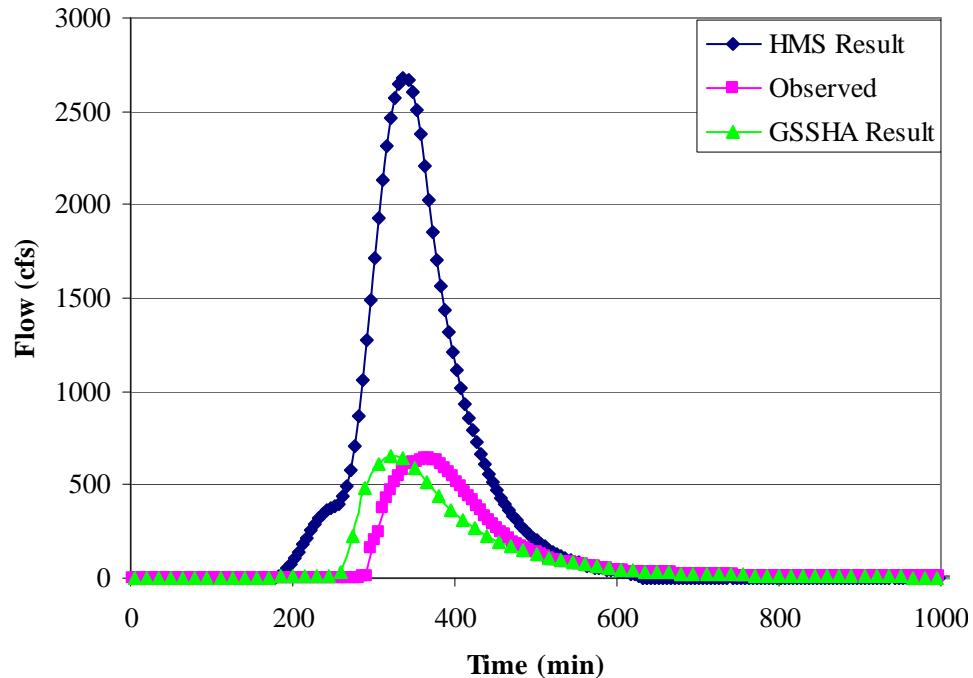


Figure 4.17: Validation results of HMS and GSSHA for the Goodwin Creek Watershed.

Table 4.17: Summary of Validation Goodwin Creek Watershed

	Peak	Volume
HMS	316%	218%
GSSHA	<1%	2.3%

4.4.4 Observations Concerning GSSHA calibration with SCE algorithm

There were a few important questions I wanted to answer in regards to the calibration of the GSSHA model using the SCE algorithm. These questions included: is there a way to speed up the calibration computation time, what affect does the min/max range the user specifies have on accuracy and computation time, and how important is it that I get my initial guesses close to the real answer. I have answered these questions by researching literature and running tests on my own models.

The computational time of the original model has a significant impact on overall calibration time. There are a couple of ways to decrease computational time before you begin the calibration process. The first is selecting the right grid cell size. The larger the grid cells are in the model the faster the computations can be. When you first create your model you should chose a grid cell size and set up a very basic model and run it to see how long it takes for the model to run. If you notice the model taking longer than a couple of minutes you should start over and increase the size of the grid cells you are using. I have included Table 4.18 that shows the size of the watersheds and their corresponding grid cell sizes to give a general idea of where to start.

Table 4.18: Watershed sizes and corresponding grid cell sizes

Watershed Name	Area (mi ²)	Grid Cell Size (m ²)
Reynolds Creek	21	100
Tifton	44	150
Goodwin Creek	8	120

There is no explicit rule to follow here, but it is important to test your watershed and try to come up with a grid size that promotes fast computational time (I would recommend under one minute) and also retains the spatial variability you are trying to capture in the watershed. The second way to increase computational time would be to increase the time step used in each computation. The best way to do this would be to run the model with a small time step (good initial value would be 10 seconds) and run the model and observe the hydrograph. The model could then be run multiple times increasing the time step each time. The outlet hydrograph should be observed each time

and when there is a change the last time step before the change occurred should be used for the calibration.

The convergence criterion is an important part of how quickly a model converges. Only two things will stop a calibration: exceeding the set number of iterations and convergence criterion being met. If the convergence criterion is less stringent the computational times can be significantly decreased. In the models that were calibrated in this study the convergence criterion was very stringent (0.1%) and the max iterations were often exceeded without reaching convergence. One study suggested a convergence criterion of 1%. They also surmised increasing this value to 2% significantly decreases computational times (Lin and Radcliffe 2006). The only thing to remember when changing the convergence criterion is the fact that accuracy of the calibration could decrease the more the convergence criteria are relaxed. The key is to find a good value where the computational time is not excessive and the calibration results are within acceptable limits. This could vary for project to project depending on what is most important.

The SCE algorithm performs a search which is resistant to converging to local optima. This means the search in the parameter space, which the user defines, is very thorough. In order to test this out I tried taking the best results from one simulation and using them as the initial parameters for a new simulation without changing the max/min range. The computational time was the same and the best results for the model were the same. This shows that the algorithm searches the entire parameter space and it doesn't matter what the initial estimates are. The computational time does not decrease with

better initial estimates. However, the best results need to be within the range set up for each of the parameters.

The best results from the same model were then used as the initial guess for a new model where the parameter space was narrowed down. The result from this simulation was similar computational time, and the cost function was lower. The cost function was able to be lower because none of these simulations reached the convergence criterion. If the convergence criterion had been met the results of each simulation should be the same. If it is possible to narrow the parameter space down it will give better results, but it is not guaranteed to converge faster than a larger parameter space.

4.4.5 Changes to parameters from initial estimates

The parameters all started with some initial estimates which of course changed over the course of calibration. I will present the changes to the parameters from this research and try to identify any patterns I see in how the parameters changed. The changes in the parameters for the Reynolds Creek watershed are shown in Table 4.19.

This table shows the initial estimates first followed by the calibrated value in bold. The hydraulic conductivity does not seem to have a specific pattern for every soil type. They are not all consistently higher or lower than the initial estimates. In the case of Reynolds Creek the soil type that is supposed to have the highest conductivity value (coarse sandy loam) ended up calibrating to the lowest value of all the soil types in the watershed. One explanation of this would be the land use interaction with that soil type is not being taken into account in the model that was calibrated. The Tifton Watershed each soil type consistently calibrated to a lower value than the initial estimate. The silt loam soil type was the only soil type that showed up in two different watersheds. These

two values did not compare well with each other. In fact they were different by about an order of magnitude.

Table 4.19: Changes to Soil Parameters for each of the Research Watersheds

Reynolds Creek Watershed

Soil Type	Coarse sandy			
	loam	Loam	Silt loam	Organic
Hydraulic Conductivity (cm/hr)	2.18/ 0.860	1.32/ 1.599	0.68/ 1.368	20.0/ 9.450
Initial Moisture	0.207/ 0.389	0.27/ 0.217	0.33/ 0.409	0.20/ 0.349

Tifton Watershed

Soil Type		Loamy	Sandy	Fine Sandy
	Sand	Sand	Loam	Loam
Hydraulic Conductivity (cm/hr)	23.56/ 1.255	5.98/ 0.095	2.18/ 0.678	2.18/ 0.219

Goodwin Creek Watershed

Soil Type	Fine Sandy Loam	Silt Loam
Hydraulic Conductivity (cm/hr)	2.18/ 5.370	0.68/ 0.194
Initial Moisture	0.207/ 0.287	0.33/ 0.491

The initial moisture estimates come from the field capacity estimates for each of the different soil types. This is generally a good rule of thumb for estimating the initial moisture. Almost all of the initial moistures that were included in the calibration ended up at a higher value than the initial estimate of field capacity. The calibrated moisture content values seemed to stay in the middle of the established range of wilting point to fully saturated (soil moisture = porosity).

The changes in the overland roughness and channel roughness parameters are given in Table 4.20. Each one of the roughness values increased to a value much higher than the original estimates obtained from standard tables. This pattern was consistent with each one of the watersheds included in this research. One possible explanation for this increase in roughness is the possibility that it represents the inherent watershed storage. The roughness values were larger in the larger watersheds which would support the theory that part of the roughness value corresponds to watershed storage because larger watersheds have more storage capacity in general. The GSSHA model has other components that can be added that help account for storage like retention depth and interception, but they were not explored because the focus of the research is on simplistic routine modeling.

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Table 4.20: Changes to Roughness Parameters for each of the Research Watersheds

Reynolds Creek Watershed

Land Use	Mixed Rangeland	Evergreen Forest
Surface Roughness	0.04/ 0.393	0.15/ 0.724
Channel Roughness	0.035/ 0.148	

Tifton Watershed

Land Use	Cropland and Pasture	Evergreen Forest	Forested Wetlands
Surface Roughness	0.080/ 0.794	0.080/ 0.794	0.080/ 0.794
Channel Roughness	0.035/ 0.418		

Goodwin Creek Watershed

Land Use	Cropland and Pasture	Mixed Forest	Strip Mines and Gravel Pits
Surface Roughness	0.035/ 0.217	0.10/ 0.350	0.011/ 0.669
Channel Roughness	0.035/ 0.049		

4.5 Long Term Calibration (Tifton)

The experience from the single event calibration indicated the most difficult parameter to get correct was the initial moisture. One benefit of a long term simulation is the soil moisture stabilizes over time. In an effort to account for the soil moisture better I obtained data needed for a long term simulation for the Tifton watershed.

A calibration run over an extended period of time has the benefits of multiple events to calibrate to as well as the soil moisture stabilizing to more precise values. The storms near the beginning of the dataset are used to “wet” the watershed. They are generally not included in the calibration, but are there to establish better soil moisture values to start the calibration off better. The calibration variables were left unchanged except for the initial moisture values. The model was run a couple of times and the results are given in Figure 4.18.

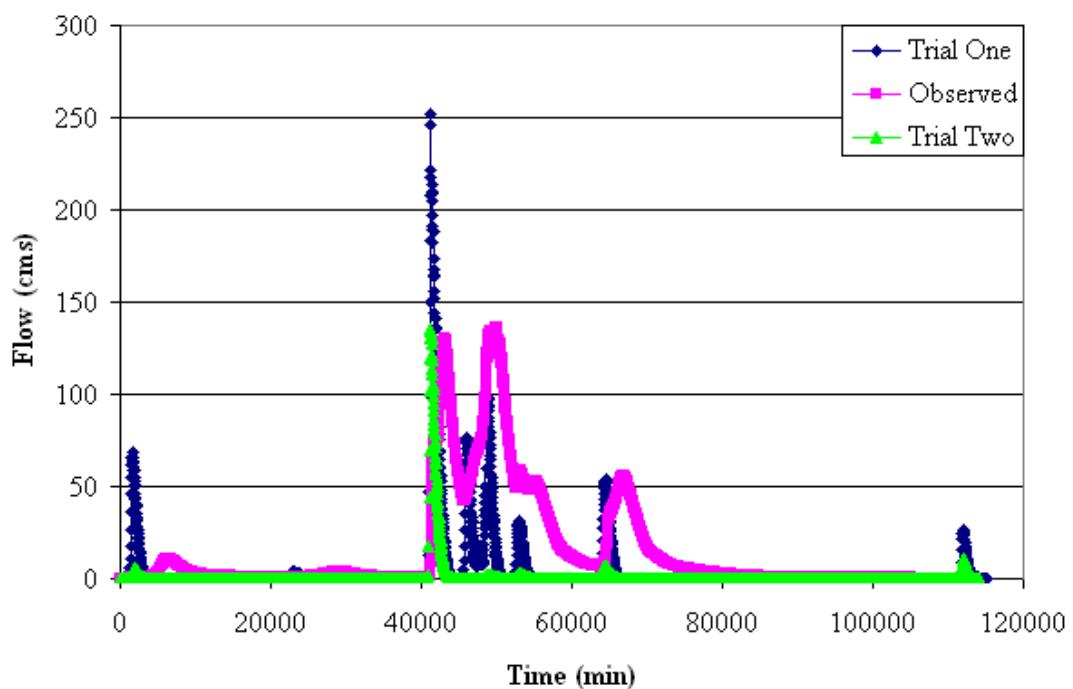


Figure 4.18: Results of a long term calibration (Tifton).

This particular simulation is clearly not calibrating well to this dataset. The reason for the inability of this simulation to calibrate is not clear. The response of this watershed is likely more complex than the current model is set up to handle. In order to effectively model this watershed more complex components would need to be included. The

GSSHA model does have the ability to include more complex scenarios, but that is beyond the scope of this research. The simulation was not able to produce enough volume even when the hydraulic conductivities were much lower than initial estimates found in tables. This result implies that groundwater is active in this area and is increasing the volume of the hydrograph.

5 Conclusions

The main goals of this research were: to establish guidelines and a systemic process for calibrating the GSSHA model (within the WMS interface), establishing whether or not GSSHA can be used to calibrate single event storms, and how well does the GSSHA model calibration results compare to the widely accepted HEC-HMS.

Throughout the course of the research guidelines and steps for setting up a model for calibration were outlined. A detailed outline of the steps needed to set up and run a GSSHA calibration using the WMS interface has been provided in the appendix. All of the files that are needed are described in detail and how they can be edited in order to obtain successfully run a calibration with the GSSHA program. The process is repeatable and can be applied to various watersheds.

I would like to summarize a few things I learned through my GSSHA calibration work. First, the cost function should add up to one. Second, the calibration files will be written to the same folder where the GSSHA executable is located. In order to have the calibration files in the same location as the project you must make a copy of the GSSHA executable and select that particular executable to use for the calibration. Third, the precipitation gages need to all have a value for every time step (even if it is zero). Fourth, if you have base flow it needs to be subtracted off. Fifth, the cost function does not

always go down for every simulation. This is a direct result of the SCE algorithm and its ability to search the entire parameter space.

The calibration of single event storms using GSSHA was a success. The model is now easy to set up and calibrate within the WMS interface. The SCE algorithm is quite robust and works well to produce a peak and volume close to the observed values. This research was not able to definitively conclude on whether single event calibration is good or bad in every case.

The WMS interface underwent a few significant changes that improved its ability to set up and run a GSSHA calibration. I would like to document what changes took place and why they are important. First, the concept of using “key” values for the calibration parameters has enabled users to select almost any parameter they want to include in the calibration. This is significant because it reduces the need to edit the calibration files by hand. Second, the GSSHA executable has been updated to be fully compatible with WMS. This means that instead of using the command prompt to run the simulations it can all be done internally within WMS. Third, input of the calibration data has become easier and more effective. The user can input the peak and volume by hand or allow WMS to make those computations. The weighting function can now be edited within WMS as well.

The calibration of GSSHA models using WMS truly has become easier and more efficient. However, there is always room for improvements to be made to make the calibration process more seamless. The compilation of the rain gage file including multiple gages proved a daunting task. If the program was able to import the raw data and compile the gage file for the user it would be helpful. The computational time for these

runs proved to be significantly long. In running a long term simulation there are no tools to find and download applicable data. Currently, not every parameter is selectable for calibration within WMS. The calibration files are written to the same location as the GSSHA executable file being used for the simulation. It would be nice if those file were written to the same location as the project file so the user did not need to copy the executable file into the same folder as the project file for every new simulation.

It is difficult to compare the relative results of the two models. In one case the GSSHA model could have calibrated to have less error in peak and volume, but at the same time it took much longer to get to those results and perhaps the difference in results is not worth the extra time it took to get them. Each project should carefully weigh what it needs from the model and make a decision from there. This research shows that both models are able to perform calibrations well.

The results from this research give some perspective of the difficulty in calibrating a distributed model. One of the largest challenges lies in getting the initial moisture of the soil correct. When this particular parameter is incorrect other calibration parameters are often incorrect as well leading to inability of the model to validate and ultimately be used for predictive purposes. This particular point was clear in the Reynolds Creek model when the validation run did not produce any run off even when the soil was completely saturated.

The high sensitivity of the initial moisture parameters causes problems when trying to calibrate a single event storm. GSSHA has other components like groundwater interaction that can be added to the model to increase accuracy. GSSHA also has the ability to calibrate over longer periods of time with multiple storms which can help

stabilize the moisture of the soil and theoretically yield better soil moisture results. The calibration will most likely be better with a few more observed values to calibrate to.

I have found from completing this research that calibration for a single event using the GSSHA model is not a practical method of calibration. The high sensitivity of the initial moisture parameter in the GSSHA model makes single event calibrations unreliable. In this research one out of the three watersheds performed well in both calibration and verification. There is more research that should be done to help establish conditions which GSSHA is well suited for single event calibration or if it should be done at all.

The use of calibration algorithms is a powerful tool and can help hydrologic models predict runoff more accurately. The two models considered in this research both have certain conditions which would make them preferable to the other. Either model is capable of performing well if the right conditions are met.

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Appendix A. GSSHA Calibration Setup using WMS

The purpose of this section is to describe how to set up and run an automated calibration for a GSSHA model within the WMS interface.

Initial Setup

It is important for the calibration of a GSSHA model that an initial GSSHA model be built. When building the initial model special care should be taken to make sure water is draining well in the model. This would include the removal of all depressions where ponding might occur in the model known as “digital dams”. There are several tutorials given on the GSSHA wiki which describe how a GSSHA model should be set up. Once you have a functioning GSSHA model it becomes important to define infiltration and roughness parameters that best describe the physical parameters that are found in the watershed. It is also good at this time to select an appropriate time step for your simulation. This can be done by running the model with a time step of about 10 seconds to begin. The same model can then be run multiple times with increasing time step until there is significant change in the shape of the hydrograph. The largest time step which keeps the original shape of the hydrograph should be selected for the calibration of the model.

Calibration Data

In order to perform a calibration you must have a set of observed data. The data required for calibration is precipitation and stream flow. The precipitation data should include a well defined storm with fairly high resolution data (it is recommended that data should have a resolution of 15 minute intervals with a maximum interval of about an hour). The stream flow data should include a well defined hydrograph that is the result of the precipitation event. Generally, it is good to find the a steady flow in the stream before the event and then go forward in time until the stream returns to roughly the same flow that you started with.

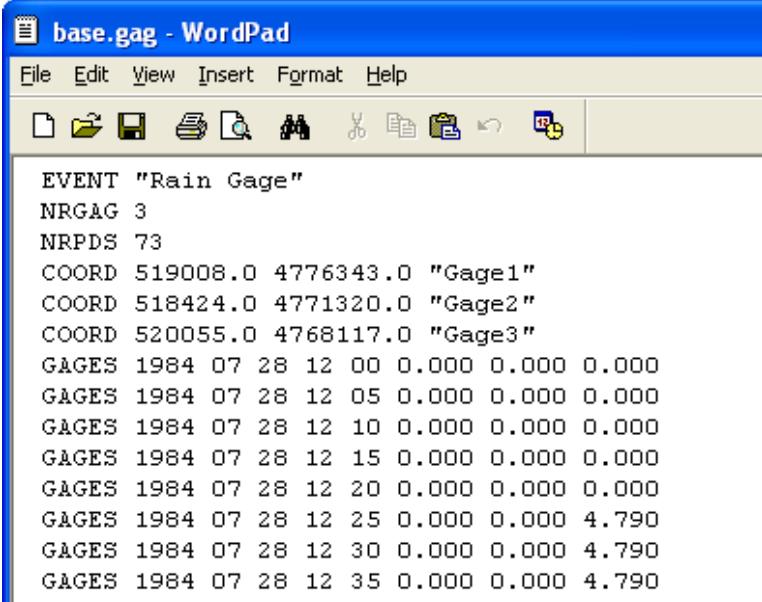
Precipitation Data

For the precipitation data you must decide how many rain gages you want to use. Sometimes the rain gage data for different gages record at different times. For GSSHA it is a requirement that the time steps are the same. So the data needs to be altered so the starting times are equal and the time steps are equal. Here is an example of what a gage file looks like. NRGAG = number of gages, NRPDS = number of rows of rainfall data, COORD = the value of the coordinates of each gage in the project, and the columns after the first few rows first describe the date going from year-month-day-hour-minute this is followed by the precipitation columns for each gage which is always in millimeters. An example of a rain gage file is shown in Figure A.1.

Observed Stream Flow Data

The only alteration needed for the stream flow data is subtracting off the base flow if there is any. The calibration in GSSHA requires a peak and a volume for calibration purposes. This can be calculated independently or WMS will calculate it for

you when you input the observed data. The observed data can be entered in by going into job control and toggling on *Calibrate* and clicking on the *Edit parameter* button. Figure A.2 displays what this window will look like.



```

base.gag - WordPad
File Edit View Insert Format Help
New Open Save Print Find Replace Undo Redo
EVENT "Rain Gage"
NRGAG 3
NRPDS 73
COORD 519008.0 4776343.0 "Gage1"
COORD 518424.0 4771320.0 "Gage2"
COORD 520055.0 4768117.0 "Gage3"
GAGES 1984 07 28 12 00 0.000 0.000 0.000
GAGES 1984 07 28 12 05 0.000 0.000 0.000
GAGES 1984 07 28 12 10 0.000 0.000 0.000
GAGES 1984 07 28 12 15 0.000 0.000 0.000
GAGES 1984 07 28 12 20 0.000 0.000 0.000
GAGES 1984 07 28 12 25 0.000 0.000 4.790
GAGES 1984 07 28 12 30 0.000 0.000 4.790
GAGES 1984 07 28 12 35 0.000 0.000 4.790

```

Figure A. 1: Typical rain gage file format.

At this point you would then click on the *Observed Data* button and then *Define*. This will bring up the Define GSSHA Observation dialogue shown in Figure A.3.

If you have some time series data you can enter it in by toggling on the *Use XY data* button and then clicking on the *Define Series* button where you can copy and paste the hydrograph data. WMS will then compute the peak and the volume and fill it into the boxes on the right side. If you already know what the peak and volume for the event are you can just enter them in by hand into the boxes on the right side. For multiple events this data should be done for each individual event. Once you are done with defining the peak and volume you can click *Done*. Now you are back to the GSSHA Observations

dialogue. You now need to select the rain event that goes with the outlet hydrograph you just defined. This should look something like Figure A.4.

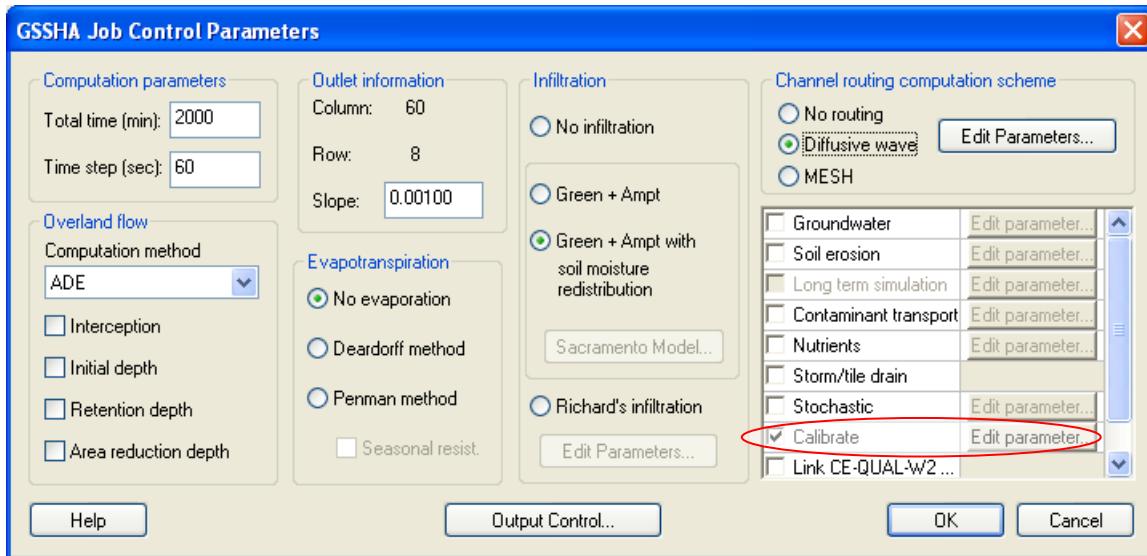


Figure A. 2: Location of calibration parameters and setup menu.

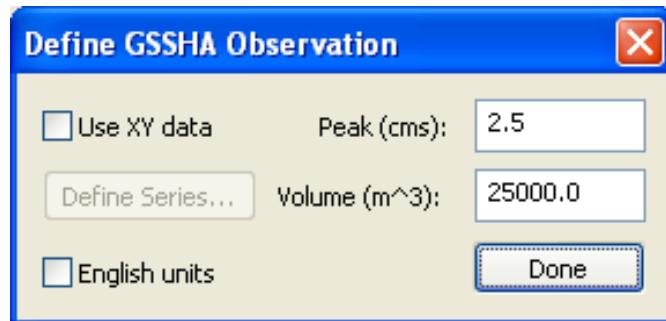


Figure A. 3: Define GSSHA Observation window.

You select the rainfall event by a dropdown box under *Precip Event*. Another thing that you can do is weight the peak or volume to be more important in the calibration. This is done by increasing the weight of one and decreasing the weight of the other. The two weights must add up to one. If there are multiple storm events there

should be an equal number of observations in order of the corresponding storms. The storm should match the peak and volume that was created by that storm. If a particular event is not included in the calibration the weight for both peak and volume should be zero.

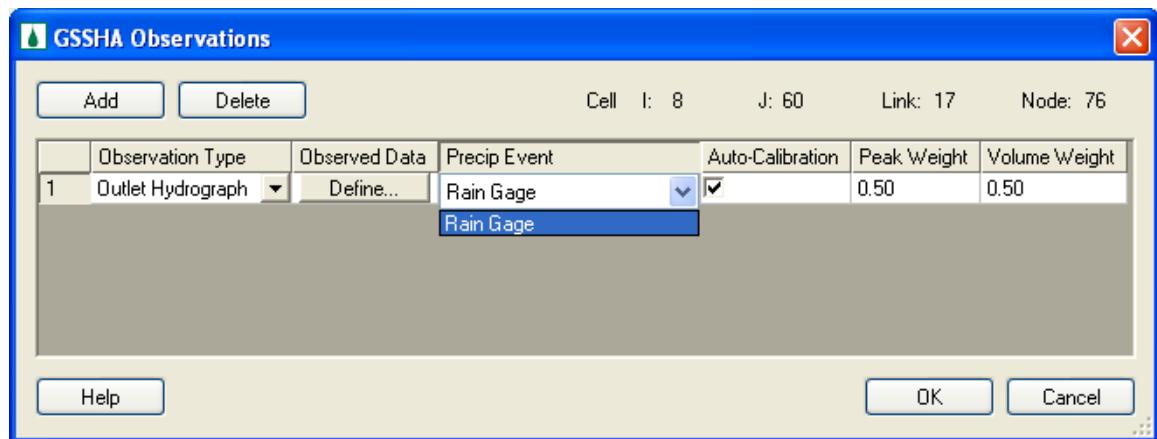


Figure A. 4: GSSHA Observations window.

Selecting the Calibration Variables

You are now ready to enter in the parameters that you want to vary in the calibration. You will need to open the job control dialogue and toggle on the *Calibrate* option and click on *Edit parameter* button. The same way that is shown in Figure A.2.

Now the Parameters dialogue should be open and you can begin to select parameters that you want to include in the calibration. This is done with a dropdown box. You first select the parameter. For example, I might want to allow hydraulic conductivity to vary in my calibration so I select it from the dropdown list. Then the column to the right will fill in a key value. It will be a number with a negative sign in front of it. This dialogue is shown in Figure A.5.

The screenshot shows a software window titled 'Parameters'. It contains a table with columns: Parameter, Key, Start Value, Min, and Max. There are two rows for each of the following parameters: Hydraulic conductivity (-1, -2, -3, -4), Roughness (-5, -6), and Initial moisture (-7, -8). Below the table are several buttons: 'Add Parameter', 'Delete Parameter', 'Delete All', 'SCE Parameters...', 'Observed Data...', and 'Done'.

Parameter	Key	Start Value	Min	Max
Hydraulic conductivity...	-1	2.18	0.44	10.9
Hydraulic conductivity...	-2	1.32	0.264	6.6
Hydraulic conductivity...	-3	0.68	0.136	3.4
Hydraulic conductivity...	-4	20.0	4.0	60.0
Roughness	-5	0.28072	0.01	0.5
Roughness	-6	0.36564	0.05	0.8
Initial moisture	-7	0.376597	0.1	0.452
Initial moisture	-8	0.338231	0.1	0.462

Figure A. 5: Calibration parameter window.

If I have four different soil types in my watershed, and I want to the hydraulic conductivity of each soil type to be included in the calibration I should have four separate rows with separate key values. The column under *Start value* should be filled in with the value that you would be using in the mapping table for that particular parameter. The min and max values are assigned a default that is filled in automatically and should be adjusted to a range that makes sense for the parameter you have selected. A good rule of thumb for most parameters is to go plus or minus five times the number in the *Start value* column. Initial moisture however does not follow this rule. The minimum should be equal to the wilting point and the maximum should be equal to the porosity of that particular soil. It is good to keep the number of parameters under 16 (Senarath et al. 2000).

You will need to go to the mapping table and input the key values for the calibration variables that you just set up. It is important that you keep track of which parameter is associated with what key value. An example of the key values input into the mapping tables is shown in Figure A.6

As the figure shows the first row of the parameters dialogue has now been associated with hydraulic conductivity for ID #9 which is coarse sand in this case. The negative key values are used to help associate the parameters together in the calibration. You must input all the correct key values in the correct places for the files to correspond and save correctly.

SCE Parameters

The calibration in GSSHA uses an algorithm called Shuffle Complex Evolution (SCE). This algorithm is commonly accepted and used for calibration of hydrologic models. In the parameters dialogue there is a button marked *SCE Parameters*. The SCE dialogue is shown in Figure A.7

Most of the parameters here are default parameters and can be left the way they are. The two which you might want to consider changing is the number of iterations and convergence limit. If your project is not converging in the number of iterations the default gives you may need to increase the number to get convergence. If the project you are working on requires a lower level of accuracy you can increase the convergence limit and the computational time will decrease significantly.

Calibration Files

You are now ready to do your initial save of the file. WMS will write out all the files that it normally does along with three additional files. These files will have the

name of the project to start followed by: _calib_file.in , _calib_params.in , and _calib_observed.dat. I would like to describe what each of these files contains briefly.

The _calib_file.in will look something like the Figure A.8

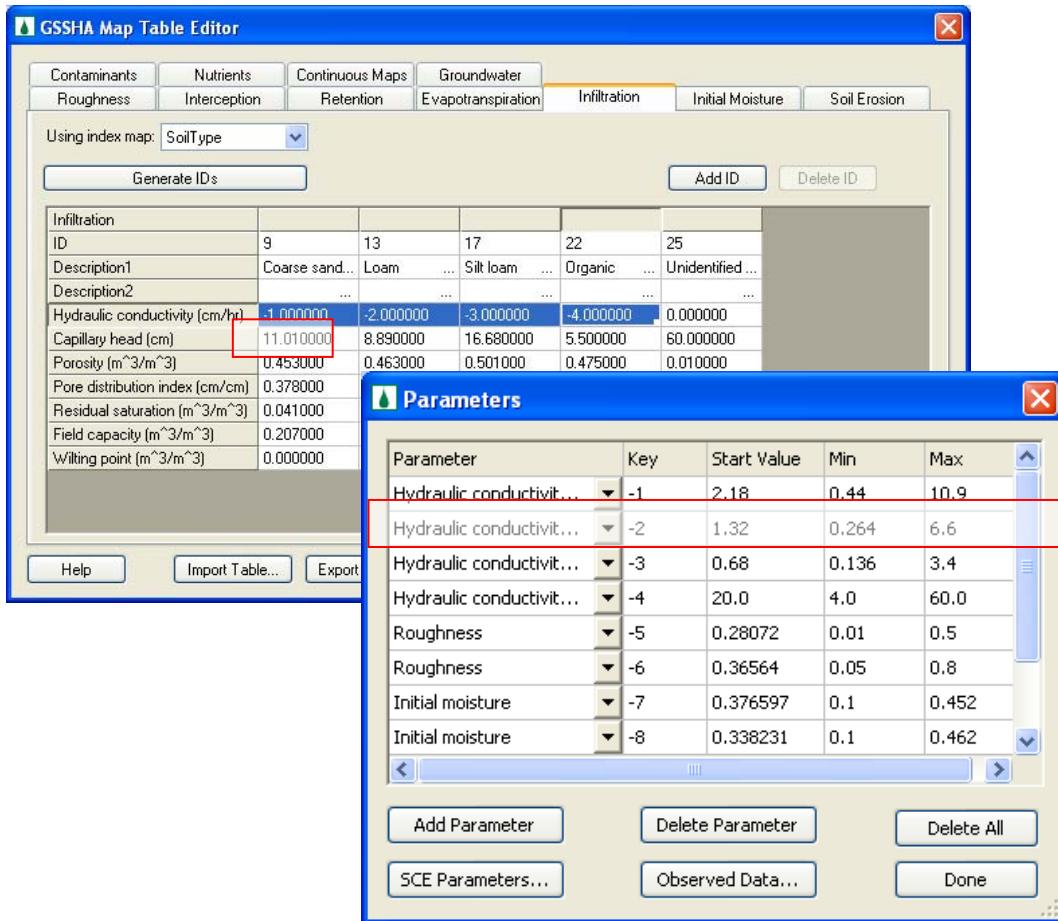


Figure A. 6: Example of key values input into mapping table.

The first three lines show the path of the project file and the other two calibration files. The next two lines are mostly SCE parameters where the default values are okay to use. I have circled three values in the fourth row that can be changed based on the project you are doing. The first value, which is 2000 in the figure, refers to the number of iterations which could be more or less depending on the project. The second value is 0.1000 and it refers to the convergence criterion. If the project doesn't require a high

level accuracy this value could be increased and the computational time would be decreased significantly. The third circle is the number of parameters that will vary in the optimization.

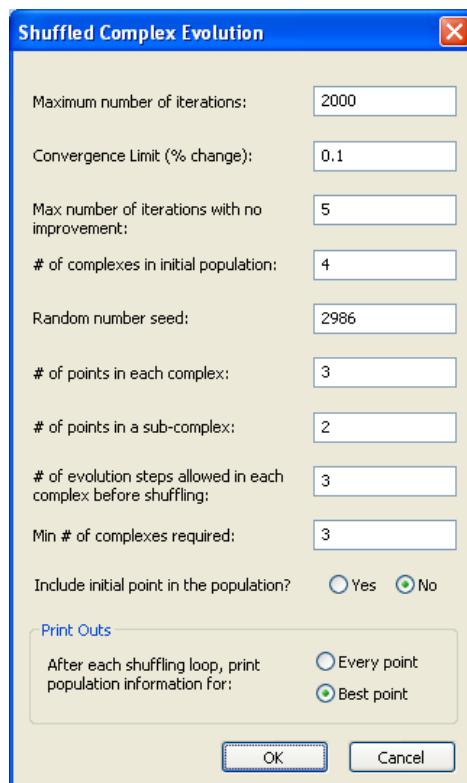


Figure A. 7: Shuffled Complex Evolution window.

If you wanted to input new data by hand this value would need to change to always reflect the number of parameters involved in the calibration. The rest of the rows are each of the parameters and their initial value, minimum value, and maximum value respectively. So if you are adding a parameter you would input those values at the end of the file and save the file when you are done. The _calib_params.in will look something like Figure A.9.

```

sixth_calib_file.in - WordPad
File Edit View Insert Format Help
C:\ReynoldsOptimize\example\sixth.prj
C:\ReynoldsOptimize\example\sixth_calib_params.in
C:\ReynoldsOptimize\example\sixth_calib_observed.dat
2000 5 0.1000 4 2986 1 11
3 2 3 3 0 0
2.1800 0.4400 10.9000
1.3200 0.2640 6.6000
0.6800 0.1360 3.4000
20.0000 4.0000 60.0000
0.28072 0.0100 0.5000
0.36564 0.0500 0.8000
0.376597 0.1000 0.4520
0.338231 0.1000 0.4620
0.338411 0.1000 0.5000
0.380696 0.0500 0.4740
0.035000 0.0250 0.1500

```

Figure A. 8: An example of a _calib_file.in file.

This file has a number in the top left hand corner that says how many parameters that will vary in the calibration. Each row then has a letter or two and a number separated by a _ the letter describes the parameter type. For example, the first row under the 11 has [HC_9] . The HC stands for hydraulic conductivity and the 9 is the key value that was assigned to that particular hydraulic conductivity. The key values in this particular example were done to correspond to the ID number of the parameters so it would be easier to remember which parameter was associated with what key value. The brackets are used to denote a calibration parameter. Each one of these values would be found in the .cmt file in the location where it is replacing that particular variable. The “%6.4lf” is the default and refers to the number of decimal places that are carried out in the calibration phase. The order of variables in this file corresponds to the _calib_file.in file. The two must be in the same order.

```

sixth_calib_params.in - WordPad
File Edit View Insert Format Help
[HC_9]      "%6.4lf"
[HC_13]     "%6.4lf"
[HC_17]     "%6.4lf"
[HC_22]     "%6.4lf"
[R_33]      "%6.4lf"
[R_42]      "%6.4lf"
[IM_9]      "%6.4lf"
[IM_13]     "%6.4lf"
[IM_17]     "%6.4lf"
[IM_22]     "%6.4lf"
[C_R]       "%6.4lf"

```

Figure A. 9: An example of a _calib_params.in file.

The rows of these two files need to be in sync with each other as shown in Figure A.10. I have highlighted the last row which happens to be channel roughness. The initial value is 0.035 the min is 0.025 and the max is 0.15. Also something to note is that the 11 (which represents how many variables are included in the calibration) at the top of the params.in file and the 11 in the file.in file are the same which should always be the case.

There is another file that is created to store the observed data that will be used for calibration purposes. It is called The _calib_observed.dat file and it should look something like Figure A.11.

The first row records how many rain events we are modeling. Since we are dealing with a single event calibration this number is one in our case. For a simulation with multiple storm events each one needs to be included. If a storm is not included in the calibration a weighting value of zero can be used. The second row is where the peak and volume values are found. The peak is given first and this case it is 2.7884 cms. There is a 0.5 that follows the value of the peak. This value is used as a weighting function for the

peak. The volume is given next and is 27,228.0462 m³ for this example. The 0.5 is the weighting function for the volume. These weighting values can be changed if extra emphasis is desired for peak or volume, but the two numbers must add up to one for each event.

```

sixth_calib_file.in - WordPad
File Edit View Insert Format Help
C:\ReynoldsOptimize\example\sixth.prj
C:\ReynoldsOptimize\example\sixth_calib_params.in
C:\ReynoldsOptimize\example\sixth_calib_observed.dat
2000 5 0.1000 4 2986 1 11
3 2 3 3 0 0
2.1800 0.4400 10.9000
1.3200 0.2640 6.6000
0.6800 0.1360 3.4000
20.0000 4.0000 60.0000
0.28072 0.0100 0.5000
0.36564 0.0500 0.8000
0.376597 0.1000 0.4520
0.338231 0.1000 0.4620
0.338411 0.1000 0.5000
0.380696 0.0500 0.4740
0.035000 0.0250 0.1500

sixth_calib_params.in - WordPad
File Edit View Insert Format Help
|1
[HC_9] "%6.4lf"
[HC_13] "%6.4lf"
[HC_17] "%6.4lf"
[HC_22] "%6.4lf"
[R_33] "%6.4lf"
[R_42] "%6.4lf"
[IM_9] "%6.4lf"
[IM_13] "%6.4lf"
[IM_17] "%6.4lf"
[IM_22] "%6.4lf"
[C_R] "%6.4lf"

```

Figure A. 10: Interaction of calibration files.

```

sixth_calib_observed.dat - WordPad
File Edit View Insert Format Help
|1
2.7884 0.5 27228.0462 0.5

For Help, press F1

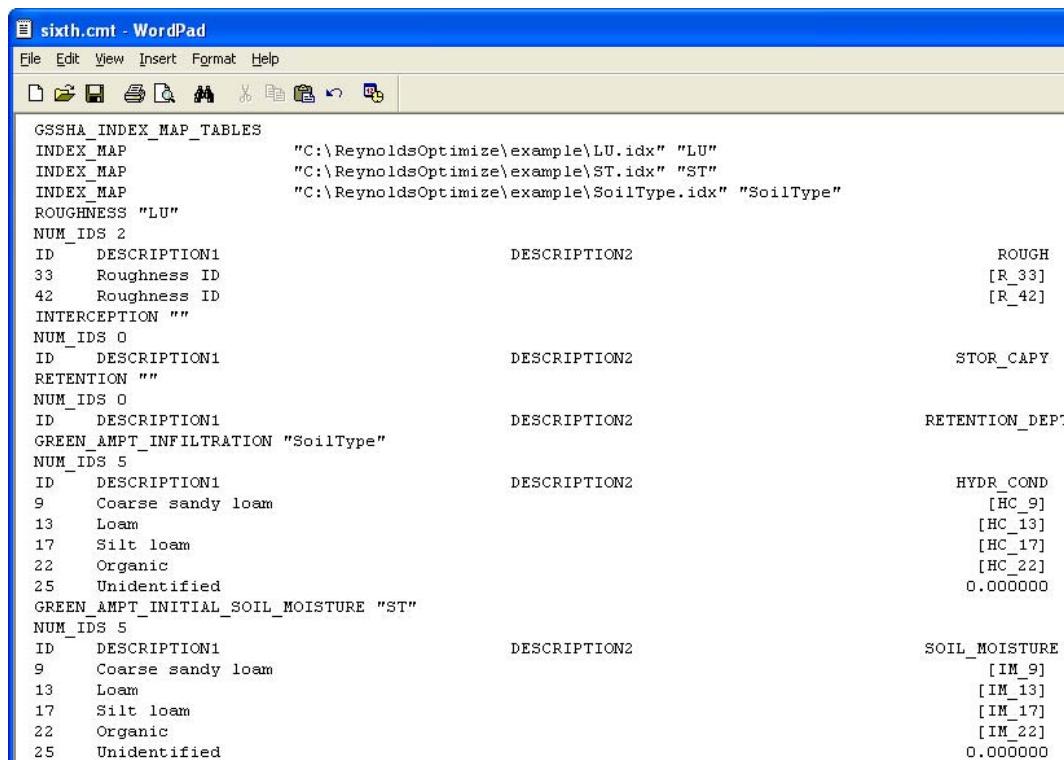
```

Figure A. 11: An example of a _calib_observed.dat file.

Changes to WMS Files When Performing Calibration

We also need to take a look at how some of the standard GSSHA project files are altered in a calibration run so we can alter them by hand when necessary.

First we will look at the .cmt file. This file shows how the index numbers are mapped to the parameters of the model. Figure A.12 shows how a standard .cmt file might look in a calibration model.



```
GSSHA_INDEX_MAP_TABLES
INDEX_MAP "C:\ReynoldsOptimize\example\LU.idx" "LU"
INDEX_MAP "C:\ReynoldsOptimize\example\ST.idx" "ST"
INDEX_MAP "C:\ReynoldsOptimize\example\SoilType.idx" "SoilType"
ROUGHNESS "LU"
NUM_IDS 2
ID DESCRIPTION1 DESCRIPTION2 ROUGH
33 Roughness ID [R_33]
42 Roughness ID [R_42]
INTERCEPTION ""
NUM_IDS 0
ID DESCRIPTION1 DESCRIPTION2 STOR_CAPY
RETENTION ""
NUM_IDS 0
ID DESCRIPTION1 DESCRIPTION2 RETENTION_DEPT
GREEN_AMPT_INFILTRATION "SoilType"
NUM_IDS 5
ID DESCRIPTION1 DESCRIPTION2 HYDR_COND
9 Coarse sandy loam [HC_9]
13 Loam [HC_13]
17 Silt loam [HC_17]
22 Organic [HC_22]
25 Unidentified 0.000000
GREEN_AMPT_INITIAL_SOIL_MOISTURE "ST"
NUM_IDS 5
ID DESCRIPTION1 DESCRIPTION2 SOIL_MOISTURE
9 Coarse sandy loam [IM_9]
13 Loam [IM_13]
17 Silt loam [IM_17]
22 Organic [IM_22]
25 Unidentified 0.000000
```

Figure A. 12: Standard .cmt file showing calibration variables in brackets.

This file would normally contain all of the tables that are created from the map tables feature in WMS. As can be seen some of the values have been replaced with a bracket with a sort of code on the inside. The brackets are used so the program knows this is a calibration run. It can then find the corresponding code in the other files that are

created when the project is saved with the calibration mode toggled on. All of the other values are held at the constant rate that is found in the .cmt file. WMS will generate this file based on the calibration set up.

If there is a parameter that is currently not available in the drop down list and you want to include it in the calibration you can edit this file by hand. The key to doing this is creating a key value that you know represents that particular parameter. You would then need to replace the value that is in the .cmt file with the key value and brackets. Then you would need to go to the files created for calibration and input the needed data there.

Including Channel Roughness in Calibration

A good volume calibration variable is channel roughness. In order to include this variable we need input the key value in place of the Manning's roughness value on the reaches that we want to include in the calibration. First, we must click on the map module. Then we need to click on the *Select Feature Line Branch Tool* and double click on the stream near the outlet. The Properties dialogue for the stream will come up and should look like Figure A.13.

I have input the key value of -1 in this case for every reach of the stream. You can do this simply by typing in the -1 in the yellow box in the Manning's n column and pressing enter and it will fill in the key value for every reach of the stream. If you only want to include certain reaches in the calibration you can select the individual segments of the stream and fill in the key value for the Manning's n value the same way.

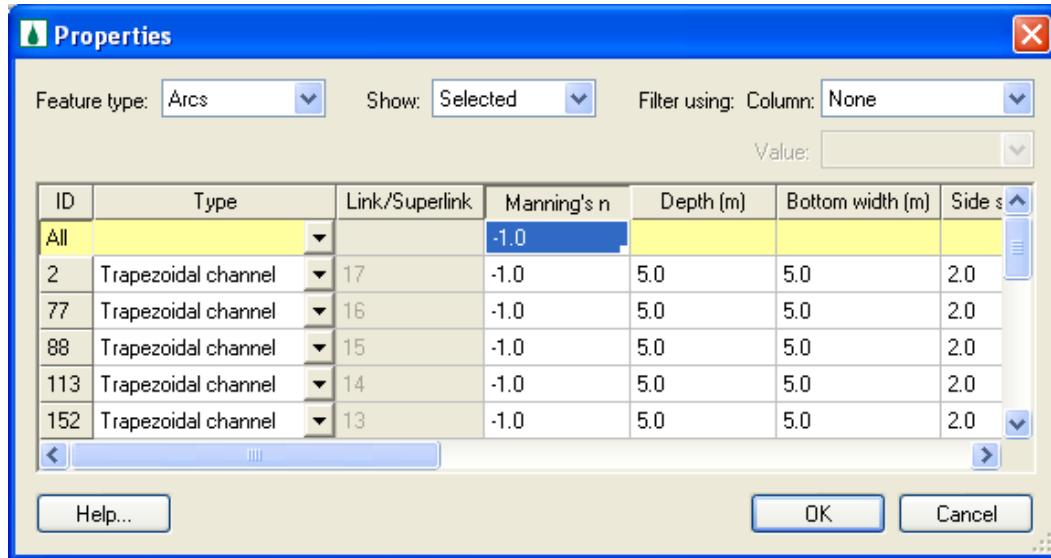
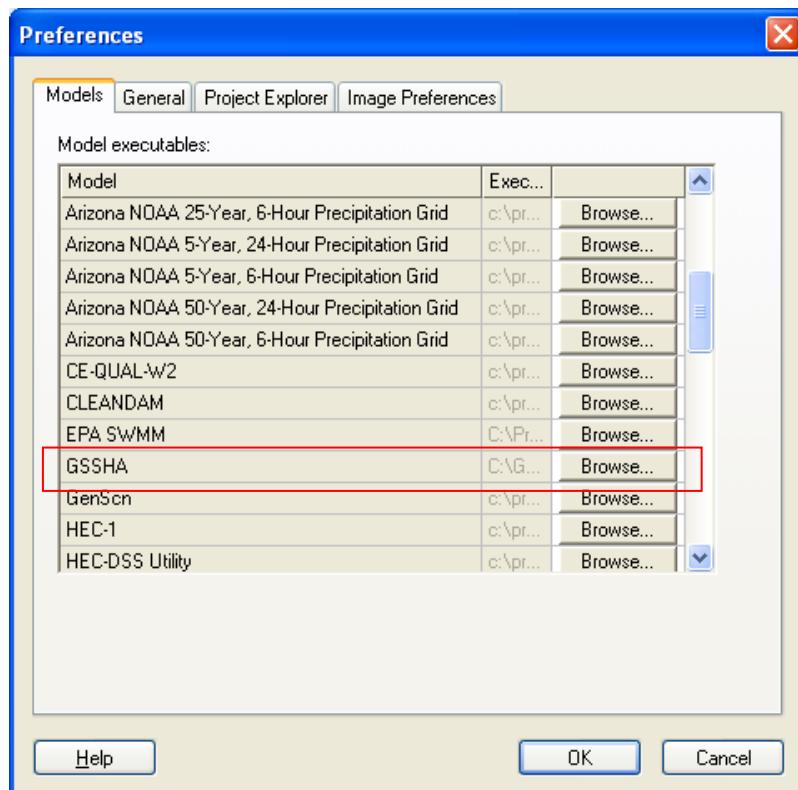


Figure A. 13: Inputting “key” value to include channel roughness in calibration.

Location of GSSHA Executable

All of the calibration files are written in the same folder as the GSSHA executable that is being used. It is important to find where the current executable is located and make a copy of it in the same folder as your project. Once you have copied the executable into the correct folder you need to go to the edit menu in WMS and select preferences. This window should look like Figure A.14.

You will then find GSSHA and click on the *Browse* button and map to the executable that is in the same folder as the project you are working on. This is not necessary for the calibration to work; however, the executable will write all of the calibration files in the same folder as the GSSHA executable being used. This is a good practice so you can keep all of the data for a particular project together. Also if you don't do this and run another calibration without changing the location of the GSSHA executable it will overwrite the calibration files that were there from the previous project.



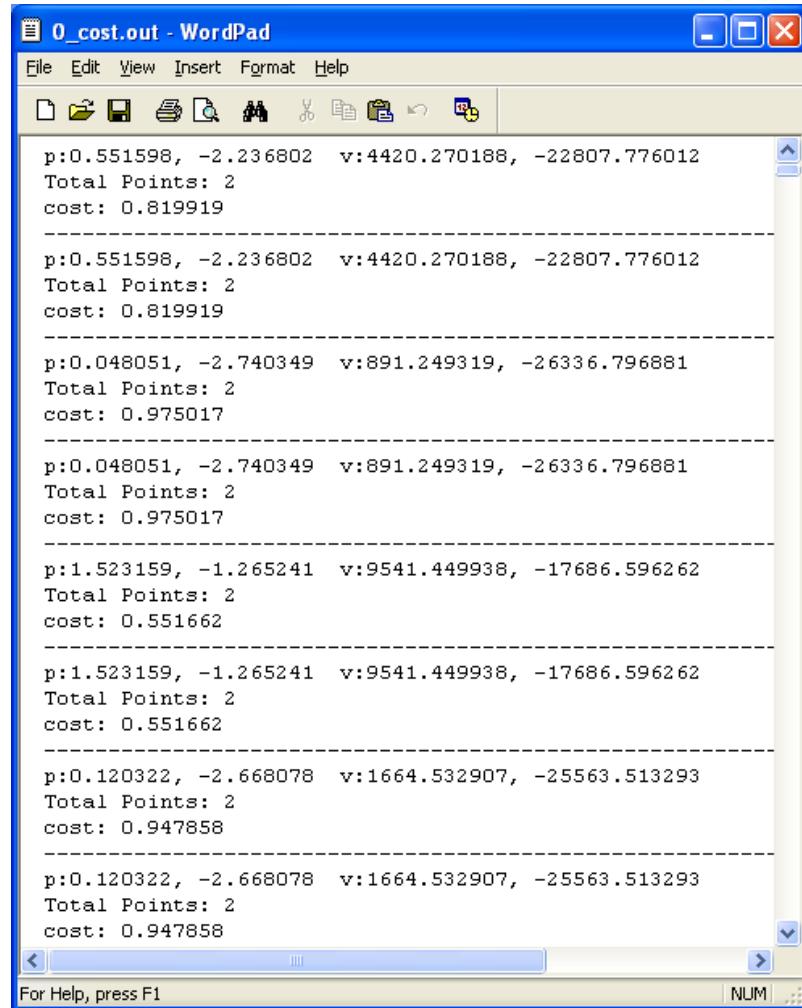
Model	Exec...	
Arizona NOAA 25-Year, 6-Hour Precipitation Grid	c:\pr...	Browse...
Arizona NOAA 5-Year, 24-Hour Precipitation Grid	c:\pr...	Browse...
Arizona NOAA 5-Year, 6-Hour Precipitation Grid	c:\pr...	Browse...
Arizona NOAA 50-Year, 24-Hour Precipitation Grid	c:\pr...	Browse...
Arizona NOAA 50-Year, 6-Hour Precipitation Grid	c:\pr...	Browse...
CE-QUAL-W2	c:\pr...	Browse...
CLEANDAM	c:\pr...	Browse...
EPA SWMM	C:\Pr...	Browse...
GSSHA	C:\G...	Browse...
GenScn	c:\pr...	Browse...
HEC-1	c:\pr...	Browse...
HEC-DSS Utility	c:\pr...	Browse...

Figure A. 14: Selection of correct GSSHA executable.

Running the Model

You can now run the model in calibration mode. From WMS, you can click on GSSHA run GSSHA, but you cannot allow the project to resave if you have made some changes to the files by hand. The model will now begin running. There are a bunch of new files that will be generated. Many of them have the suffix of .out. These files are related to the output of the calibration.

The cost.out is a file that lists the simulated peak and volume of each run and then gives a respective cost function which is a measure of how well the simulated matches the observed. For calibration of GSSHA models we are trying to minimize the cost function. Figure A.15 shows what a cost.out file might look like.



The screenshot shows a Windows WordPad application window titled "0_cost.out - WordPad". The menu bar includes File, Edit, View, Insert, Format, and Help. The toolbar contains standard icons for opening, saving, and printing. The main text area displays a series of simulation runs, each consisting of parameter values (p), vertex coordinates (v), total points, and cost. The runs are separated by dashed lines.

```
p:0.551598, -2.236802 v:4420.270188, -22807.776012
Total Points: 2
cost: 0.819919
-----
p:0.551598, -2.236802 v:4420.270188, -22807.776012
Total Points: 2
cost: 0.819919
-----
p:0.048051, -2.740349 v:891.249319, -26336.796881
Total Points: 2
cost: 0.975017
-----
p:0.048051, -2.740349 v:891.249319, -26336.796881
Total Points: 2
cost: 0.975017
-----
p:1.523159, -1.265241 v:9541.449938, -17686.596262
Total Points: 2
cost: 0.551662
-----
p:1.523159, -1.265241 v:9541.449938, -17686.596262
Total Points: 2
cost: 0.551662
-----
p:0.120322, -2.668078 v:1664.532907, -25563.513293
Total Points: 2
cost: 0.947858
-----
p:0.120322, -2.668078 v:1664.532907, -25563.513293
Total Points: 2
cost: 0.947858
```

Figure A. 15: An example of a Cost.out file.

After roughly 100 simulation runs another file is created that has more useful information. It is called the 0000_log_file.txt. This file gives the cost function of each run and lists the parameter values that were used for each specific run. This file is useful because you can look at it while the model is calibrating and see how well the calibration is converging. Figure A.16 shows what a file of this type might look like.

Sim No.	Cost	Minimum Cost:	Parameter Values
1	0.820	0.214	10.662422 2.665774 2.100998 38.334705 0.265056 0.262530 0.176736 0.363912 0.120824 0.150756 0.110580
2	0.975	0.214	9.635733 4.433800 1.791012 6.242603 0.070984 0.094073 0.167056 0.366246 0.224784 0.075978 0.075209
3	0.552	0.214	9.476987 1.927349 3.149803 11.683390 0.062626 0.605679 0.397469 0.328915 0.336368 0.348207 0.148348
4	0.948	0.214	9.803317 6.564892 2.286590 52.822208 0.115222 0.721544 0.390653 0.184101 0.401363 0.340346 0.120768
5	0.401	0.214	4.424800 4.368483 0.499561 55.991750 0.017047 0.725953 0.392433 0.412210 0.320310 0.340124 0.115941
6	5.550	0.214	9.691567 2.016276 0.505063 4.937323 0.324428 0.324800 0.161298 0.440464 0.497195 0.404129 0.116963
7	0.502	0.214	1.121547 2.597689 0.792920 53.368866 0.166754 0.616336 0.306249 0.117540 0.402145 0.374457 0.148421
8	0.318	0.214	0.522127 3.562074 2.271750 25.821579 0.410156 0.770949 0.271256 0.265000 0.663732 0.307437 0.079308
9	0.914	0.214	6.311574 4.289102 5.411482 24.510317 0.434941 0.148648 0.349039 0.117100 0.419994 0.319852 0.094265
10	1.000	0.214	2.250167 4.167871 3.355636 54.473231 0.256542 0.610892 0.135530 0.165658 0.125724 0.346168 0.043627
11	0.571	0.214	0.886697 1.700517 2.249062 26.503915 0.460903 0.335920 0.198393 0.371779 0.126329 0.410167 0.087474
12	0.763	0.214	3.082241 4.342307 1.243334 30.599848 0.316428 0.729125 0.233959 0.231227 0.360948 0.271021 0.066285
13	0.806	0.214	8.057930 3.922072 5.558278 22.193072 0.122925 0.295990 0.322150 0.363882 0.460936 0.081716 0.146996
14	0.543	0.214	3.327200 3.382014 1.432030 14.949420 0.236201 0.440978 0.292205 0.421789 0.327322 0.133022 0.030094
15	0.543	0.214	9.122745 6.326338 0.396089 32.478067 0.268460 0.680253 0.192755 0.395074 0.218803 0.174713 0.135362
16	0.695	0.214	8.643188 3.644559 0.753918 17.360929 0.223921 0.166388 0.309496 0.407974 0.122196 0.452286 0.122901
17	0.635	0.214	8.319138 1.526139 2.922507 5.488118 0.070742 0.405378 0.357550 0.345833 0.493400 0.465418 0.148034
18	0.961	0.214	7.654144 4.727359 2.977230 4.555398 0.347569 0.101609 0.225931 0.170490 0.405468 0.353129 0.053706
19	0.859	0.214	3.463471 5.910832 3.067668 13.592738 0.395856 0.763172 0.419620 0.461168 0.339469 0.455105 0.070246
20	0.520	0.214	8.153674 2.502179 1.046817 48.186978 0.331760 0.581520 0.333368 0.354507 0.282161 0.037739
21	0.414	0.214	6.845626 2.310629 1.752861 30.974324 0.043566 0.168563 0.117565 0.324991 0.305778 0.281672 0.093720
22	3.459	0.214	1.996129 2.958301 0.383694 54.484301 0.020060 0.496833 0.116735 0.335569 0.464790 0.302537 0.102687
23	0.944	0.214	8.706049 5.473968 2.148133 48.014801 0.471625 0.528480 0.282151 0.109480 0.388537 0.379362 0.097312
24	0.546	0.214	8.553852 6.473543 3.318642 27.642738 0.438858 0.146465 0.136188 0.402974 0.398392 0.467768 0.086151
25	0.214	0.214	3.771430 2.308797 1.033196 16.830728 0.390722 0.445393 0.158003 0.303662 0.462243 0.167792 0.133844
26	6.907	0.214	5.938297 0.493209 1.653811 53.001341 0.370099 0.191478 0.183221 0.355441 0.430381 0.168751 0.072979
27	0.531	0.214	3.188988 1.817131 2.237606 38.506172 0.354037 0.498434 0.418375 0.329482 0.304603 0.106454 0.047833
28	3.012	0.214	0.482930 3.224087 0.726709 42.860640 0.252873 0.448864 0.230083 0.157988 0.478991 0.413394 0.040798
29	0.513	0.214	10.576182 2.935899 1.005120 10.927106 0.490708 0.692330 0.215131 0.405911 0.378790 0.153222 0.149699
30	0.491	0.214	5.044029 1.606804 2.458814 39.796907 0.022801 0.087226 0.381424 0.264509 0.142712 0.420175 0.139228

Figure A. 16: An example of a _log_file.txt file.

When the calibration finishes a file will be generated called best.out. This file will have the best parameters from the calibration effort listed in the same order as the _calib_params.in file. These parameters from the best.out file are taken and used for a final forward run which then produces the optimized outlet hydrograph. You can then plot this hydrograph with the observed data to compare how well the optimization worked.

Long Term Calibration

A long term calibration is set up in a similar way to a single event calibration. The main difference between the two is long term events with multiple storms requires evapotranspiration (ET) data and a rain gage file with multiple storm events. There are three different file types that can be used for ET data. Each one is discussed in detail on the GSSHAWiki. The easiest of these file types is the WES format. Figure A.17 shows what this might look like.

CombinedClimateData.txt - Notepad									
File	Edit	Format	View	Help					
2009	2	28	0	29.63	81	90	3	60	9999.99 0
2009	2	28	1	29.63	85	90	3	59	9999.99 0
2009	2	28	2	29.61	86	90	4	58	9999.99 0
2009	2	28	3	29.6	88	90	3	59	9999.99 0
2009	2	28	4	29.59	92	90	3	59	9999.99 0.02
2009	2	28	5	29.59	94	90	4	59	9999.99 0
2009	2	28	6	29.59	95	90	4	59	9999.99 0
2009	2	28	7	29.58	95	90	5	60	9999.99 0.17
2009	2	28	8	29.59	94	90	4	60	9999.99 33.63
2009	2	28	9	29.55	90	90	6	63	9999.99 126.2
2009	2	28	10	29.56	87	90	7	66	9999.99 186
2009	2	28	11	29.53	79	90	7	68	9999.99 248.2
2009	2	28	12	29.51	70	90	8	72	9999.99 407.3
2009	2	28	13	29.48	63	90	8	75	9999.99 349.2
2009	2	28	14	29.45	80	90	6	73	9999.99 180.3
2009	2	28	15	29.47	83	90	5	71	9999.99 87.7
2009	2	28	16	29.51	96	90	4	63	9999.99 13
2009	2	28	17	29.51	97	90	4	64	9999.99 37.4
2009	2	28	18	29.49	95	90	4	65	9999.99 66.82
2009	2	28	19	29.51	95	90	5	64	9999.99 5.32
2009	2	28	20	29.49	95	90	6	64	9999.99 0
2009	2	28	21	29.48	96	90	6	64	9999.99 0
2009	2	28	22	29.47	96	90	3	64	9999.99 0
2009	2	28	23	29.44	96	90	2	64	9999.99 0

Figure A. 17: An example of climate data in the WES format.

This file is referenced by clicking on the edit parameter button next to long term simulation. The parameters for the watershed should be input in the open boxes and the climate data file should be referenced here. These are the two windows you should see are shown in Figure A.18

This is the location where you specify what type of climate data file you have and the pathway to where the file is stored. It is also important to turn on Evapotranspiration in the job control. The figure above shown for this simulation the Penman method was selected. Once this option is turned on the mapping table needs to be updated with values for the Evapotranspiration variables. The GSSHAwiki has tables to help estimate these parameters.

A long term event will have multiple storm events over the duration of the modeling time. It is good to allow the first storm or two to “wet” the watershed before calibration is taken into account. Each storm event must correspond to an event included in the _calib_observed.dat file discussed previously. The number of events in the top corner should correspond exactly to the number of rainfall events in the precipitation file.

The events that are included should have the peak and volume along with the weighting factors. If an event is not to be used in the calibration a zero weighting factor should be applied for both the peak and volume.

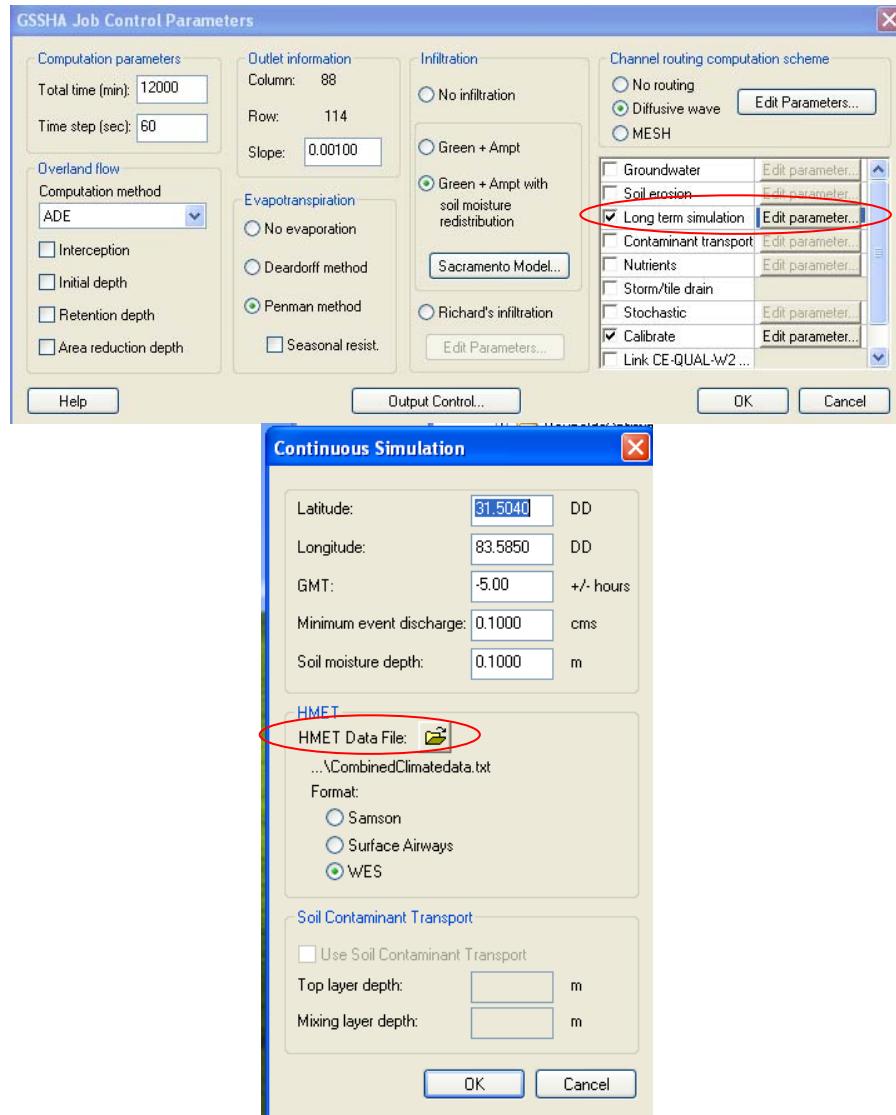


Figure A. 18: Continuous Simulation setup windows.

The model can now be run the same way as a single event calibration. It is good to make sure no output files are selected because this will slow the simulation down

significantly. For example, the surface water depth output file is always turned on by default. Another way to increase the speed of the simulation is to run your model in quiet mode which is done by selecting the suppress screen printing toggle after selecting the command to run GSSHA.

