2010-07-06

An Examination of Distributed Hydrologic Modeling Methods as Compared with Traditional Lumped Parameter Approaches

Murari Paudel
Brigham Young University - Provo

BYU ScholarsArchive Citation

Paudel, Murari, "An Examination of Distributed Hydrologic Modeling Methods as Compared with Traditional Lumped Parameter Approaches" (2010). *All Theses and Dissertations*. 2219.
https://scholarsarchive.byu.edu/etd/2219

An Examination of Distributed Hydrologic Modeling Methods as Compared with Traditional Lumped Parameter Approaches

Murari Paudel

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

E. James Nelson, Chair
Rollin H. Hotchkiss
Alan K. Zundel
Norman L. Jones
A. Woodruff Miller

Department of Civil and Environmental Engineering

Brigham Young University

August 2010

ABSTRACT

An Examination of Distributed Hydrologic Modeling Methods as Compared with Traditional Lumped Parameter Approaches

Murari Paudel

Department of Civil and Environmental Engineering

Doctor of Philosophy

Empirically based lumped hydrologic models have an extensive track record of use where as physically based, multi-dimensional distributed models are evolving for various engineering applications. Despite the availability of high resolution data, better computational resources and robust numerical methods, the usage of distributed models is still limited. The purpose of this research is to establish the credibility and usability of distributed hydrologic modeling tools of the United States Army Corps of Engineers (USACE) in order to promote the extended use of distributed models. Two of the USACE models were used as the modeling tools for the study, with Gridded Surface and Subsurface Hydrologic Analysis (GSSHA) representing a distributed and with Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) representing a lumped model. Watershed Modeling System (WMS) was used as the pre- and post-processing tool. The credibility of distributed models has been established by validating that the distributed models are efficient in solving complex hydrologic problems. The distributed and lumped models in HEC-HMS were compared. Similarly, the capabilities of GSSHA and lumped models in HEC-HMS in simulating land use change scenario were compared. The results of these studies were published in peer-reviewed journals. Similarly, the usability of the distributed models was studied taking GSSHA-WMS modeling as a test case. Some of the major issues in GSSHA-modeling using WMS interface were investigated and solutions were proposed to solve such issues. Personal experience with GSSHA and feedback from the students in a graduate class (CE531) and from participants in the USACE GSSHA training course were used to identify such roadblocks. The project being partly funded by the USACE Engineering Research and Development Center (ERDC) and partly by Aquaveo LLC, the research was motivated in improving GSSHA modeling using the WMS interface.

Keywords: hydrologic modeling, distributed models, lumped models, GSSHA, HEC-HMS, land use change modeling

ACKNOWLEDGMENTS

Though only my name appears on the cover of this dissertation, a great many people have contributed to its production. I owe my gratitude to all those people who have made this dissertation possible and because of whom my graduate experience has been one that I will cherish forever. This research was supported in parts by the US Army Corps of Engineers, Engineering Research and Development Center (USACE-ERDC) in Vicksburg, MS, and Aquaveo LLC in Provo, UT. I would like to express my thanks for all their support.

My deepest gratitude is to my advisor, Dr. E. James Nelson. I have been amazingly fortunate to have an advisor who gave me the freedom to explore on my own and at the same time provided the guidance for me to recover when my steps faltered. Dr. Nelson taught me how to question thoughts and express ideas. His patience and support helped me overcome many crisis situations and finish this dissertation. I hope that one day I will become as good a person as Dr. Nelson has been to me.

I thank my committee members, Dr. Rollin H. Hotchkiss, Dr. Alan K. Zundel, Dr. Norman L. Jones and Dr. A. Woodruff Miller for their helpful guidance, comments, and suggestions during the course of this research project and manuscript preparation. I would like to acknowledge Dr. Charles Downer (USACE-ERDC) for his help and support regarding the use of GSSHA and his help in my manuscript preparation. I would also like to thank Dr. Chris Smemoe and the entire WMS development team at Aquaveo LLC for their continued support.

I am grateful to my parents whose guidance and blessings have always put me on the right path and taught me to work hard.

I especially thank my wife Madhu for her continuing support and encouragement. Without her help this research would have been just impossible.

Dedicated to my daughter Kinju

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

1*D*	One Dimensional
2*D*	Two Dimensional
BYU	Brigham Young University
CN	Curve Number
DEM	Digital Elevation Model
DMIP	Distributed Model Intercomparison Project
EMRL	Environmental Modeling Research Laboratory
EPA	Environmental Protection Agency
ERDC	Engineering Research and Development Center
GIS	Geographic Information System
GSSHA	Gridded Surface Sub-surface Hydrologic Analysis
HEC − *HMS*	Hydrologic Engineering Center-Hydrologic Modeling System
NLCD	National Land Cover Database
NRCS	Natural Resources Conservation Service
SCS	Soil Conservation Service
SSURGO	Soil Survey Geographic Database
STATSGO	State Soil Geographic Database
SWWRP	System Wide Water Resources Program
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USGS	Unites States Geological Service
WMS	Watershed Modeling System

CHAPTER 1. INTRODUCTION

1.1 Objective Statement

The purpose of this research is to establish the credibility and usability of the US Army Corps of Engineers (USACE) hydrologic modeling tools for distributed hydrologic modeling. This research is intended to establish that a semi-distributed or distributed hydrologic model is a better choice in applications where the spatial distribution is of prime importance. This research results from years of collaboration between USACE and Environmental Modeling Research Lab (EMRL) on distributed hydrologic modeling. Specifically the objectives were to validate the improved performance in the USACE distributed models in HEC-HMS and GSSHA for specific applications. An important byproduct of this research was to establish guidelines for distributed model development and improve the process specifically in Watershed Modeling System (WMS).

1.2 General

The conceptual or computational procedure for numerically simulating the processes that occur in a watershed is generally called hydrologic modeling. Hydrologic modeling is commonly used to estimate runoff from a watershed which is one of the most important parameters in any water resources design project. One of the widely used applications of these estimates is to determine the design or flood discharge of a watershed. While useful, any simulation model is a simplification of real-world processes. Because of these simplifications, ther e is a range of suitable problems to which models can be applied.

Hydrologic modeling has been classified in various ways and one such classification distinguishes the hydrologic simulation modeling systems as (1) lumped parameter,

(2) semi-distributed parameter, or (3) distributed parameter systems. Similarly, another classification is based on the way a model is conceptualized. Depending on whether the model formulation is based on physical equations or on conceptual formulations, the models are categorized as (1) physically based and (2) empirical hydrologic models. A majority of the lumped parameter models are based on empirical methods whereas more recent distributed models are physically based. In terms of spatial discretization/resolution, these hydrologic model categories can be organized on an ascending scale of sophistication beginning with lumped models to the physically based distributed model.

Lumped models treat the complete basin as a single homogeneous element and develop a single outflow hydrograph (Jones, 1997). The majority of modeling systems used in practice today are simple lumped parameter models (Butts *et al.*, 2004). This can be attributed to the fact that these models require fewer parameters or data to be defined and calibrated for their operation (Butts *et al.*, 2004). Despite significant simplifications in these models, many of them have proven to be successful in simulating an observed flow hydrograph. The major benefits of using such simplified models are the ease in their calibration because fewer control parameters are used and the ease of establishing some pattern in their variation to produce a watershed response.

The three model categories discussed thus far are presented graphically in Figure 1.1.

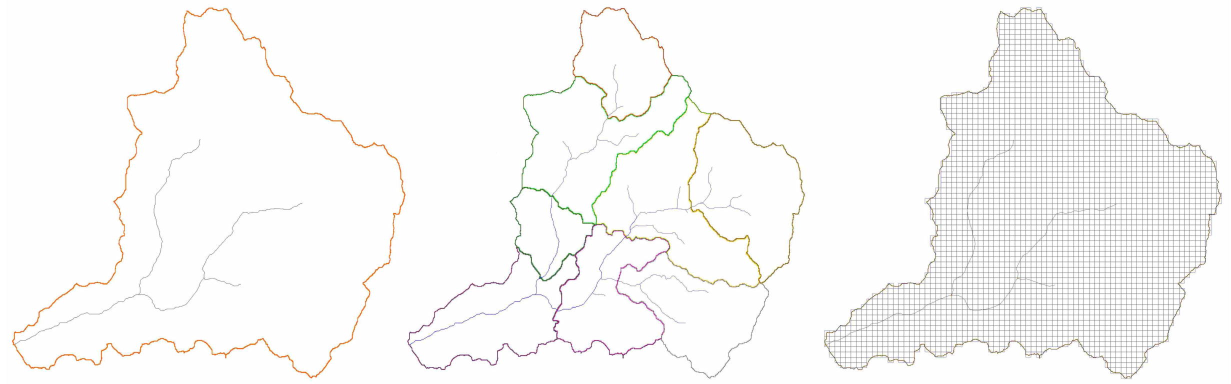


Figure 1.1: Graphic Representation of Lumped, Semi-distributed and Distributed Models

An important shortcoming of simple lumped parameter models is that their parameters are not directly related to the physical characteristics of the catchment (Reed *et al.*, 2004). In general, their applicability is limited to gauged watersheds where the expected conditions are within the historic data used for calibration and no significant change in catchment conditions has occurred (Reed *et al.*, 2004).

Blackie and Eeles (1985) defined a list of the cases where the lumped models are more suitable:

- Quality control and filling in of missing data
- Extensions of historic flow records
- Generation of synthetic data runs for civil engineering design work and other applications
- Water resources assessment
- Water resources management including real-time forecasting

This list represents the primary applications of lumped models. Because of greater changes in land usage and global changes in the climate as well as societal needs, the list of applications above is incomplete and other usage categories such as spatially distributed rainfall, scenario modeling, ground-water–surface-water interaction and sediment and nutrient transport could be added to the lumped hydrologic models.

The semi-distributed models discretize the watershed into homogeneous subareas or subbasins based on the topography or drainage area. The infiltration or rainfall parameters are treated as homogeneous within each subbasin and the runoff is determined (Biftu and Gan, 2001). Whether a model is defined as lumped or distributed depends upon whether the modeling domain is sub-divided. If the watershed being modeled is divided into smaller computational elements (or subbasins), then the lumped subbasin models that represent spatially variable parameters and conditions as a series of subbasins with average characteristics are formed. This model configuration is called a semi-distributed model (Hunter *et al.*, 2002).

Semi-distributed models use discretization schemes such as the hydrological response unit (HRU) or the group response (GRU) (Kouwen, 1988; Kite and A., 1996). Some semi-distributed hydrologic models divide the watershed into a number of subbasins drained by the predefined drainage network. The hydrologic processes are simulated for different land uses at a point scale and then aggregated according to the land cover percentage present in the subbasins.

More recently, models that attempt to simulate both the spatial heterogeneity and the physical processes occurring within a watershed have been developed (Bobba *et al.*, 2000). Such models are classified as distributed models. There are several approaches to how these models simulate the hydrologic cycle, and the distributed models can be further classified as

1. *Empirically distributed Models:* Even if the watershed is discretized into smaller grid cells, there are some models that perform the surface runoff transformation empirically. The ModClark Model implemented in HEC-HMS is an example of this category of models (HEC, 2000). In such models, the infiltration, evapotranspiration, and rainfall processes can be physically distributed to capture the spatial heterogeneity of the watershed, but the excess rainfall computed at each grid cells is transformed empirically to the outlet by lagging based upon the travel distance from each grid cell to the outlet. The resulting hydrograph is routed through a linear reservoir to achieve attenuation (Clark, 1945).

2. *Physically distributed Models:* The physically based fully distributed models use physics-based simulation methods which are closer to real-world processes. The rainfall excess produced at each grid cell is routed from one grid cell to another as water drains through the basin (Jones, 1997). This allows the heterogeneity of the watershed as well as the surface runoff transformation to be simulated at each of the grid cells, which is the physical reality. Grid resolution is generally chosen so that it is small enough to represent the spatial variation of important processes such as rainfall, infiltration, and runoff transformation parameters (Vazquez *et al.*, 2002).

The relationship between rainfall and runoff is a complicated process that is defined by numerous parameters, each with inherent uncertainties. If these uncertainties are modeled using a stochastic, or even a statistical deterministic approach, it results in significant computational requirements (Jones, 1997). To better incorporate the variations and uncertainties involved in defining a watershed response to the rainfall, a physically based distributed model is preferable (Kalin and Hantush, 2006). Distributed models can simulate both spatial and temporal variability of the watershed characteristics. In order to represent such variability in the watershed, a significant amount of input parameters need to be entered during the model formulation making them data-hungry. These models, because of the larger data requirements, add a significant computational burden both in pre-processing the data as well as in solving the numerical methods associated with the various processes. Historically, such computational resources were not available to general practitioners. With the advent of powerful computers and a wide variety of rich spatial data resources, numerous semi-distributed and distributed hydrologic models are emerging and many claim to be the best model, or at least capable of solving a wide variety of problems (Sui and Maggio, 1999).

Beven and O'Connell (1982) defined the role of distributed models in hydrology and identified four areas offering the greatest potential as

- Forecasting the effects of land-use changes
- Analyzing the effects of spatially variable inputs and outputs
- Forecasting the movements of pollutants and sediments
- Forecasting the hydrological response of ungauged catchments where no data are available for calibration of a lumped model.

Hydrologic model development has progressed significantly since this list was published, and the list of applications above is not inclusive of the present-day issues that are prominent in mainstream hydrologic analyses. Nevertheless, the list represents the primary applications of distributed models and reflects their capabilities of solving complex hydrologic issues. Many of the emerging engineering analyses involve estimating the impact or results of small spatial changes in a watershed; such as a land use change scenario and Best Management Practice (BMP) implementation, among others. Because the distributed models are more applicable to such situations, they are likely to be more heavily used in the future.

Basically, the primary limitations of typical lumped models are their inability to incorporate the spatial heterogeneity and an empirical model conceptualization. Because of this the lumped models are inefficient in solving complex hydrologic problems. Similarly, the distributed models are data-hungry, may be difficult to parameterize, require significant computational resources and demand a good understanding of the hydrologic processes.

A significant problem with selecting the most appropriate models for a specific problem or analysis is a lack of guidelines for application. On first inspection every hydrologic model can apparently simulate every watershed process in some fashion; however, the reality is that while theoretically a given model could solve a specific problem, it simply may not be practical or the model might not be able to model specific instances. For example, if an engineer is required to estimate the change in runoff from an addition of a small parking lot in a large watershed, this could be done with a quasi-distributed system by making a number of artificially small subbasins, but it is better accomplished using a distributed parameter model. To address the same problem with a lumped parameter model would require the modeler to estimate the effect of this small change on one of the lumped parameters. Along with this problem, there is a prominent issue of data aggregation in the current hydrologic modeling practice. Increasing availability of high quality digital spatial data adds the potential for better usage in distributed modeling. But, the modelers often simply use such data to get some averaged value or lose information by developing lumped parameter models from it.

New requirements of hydrologic analysis are emerging based on societal needs, and as a result new technologies are being developed in the land development industry (Guertin *et al.*, 2000). This requires effective hydrologic and hydraulic design parameters. Generally these parameters are the peak flow and runoff volume from a watershed as a response to short-term or long-term precipitation events (Guertin *et al.*, 2000). Lumped, semi-distributed, or distributed models all have relative strengths and weaknesses, and each can be the best choice for a certain category of problems. However, a different type of model may be more appropriate for another set of problems. All models estimate the runoff response, though each is best suited to answering specific types of questions. There are cases when it might be more appropriate to use a model that is only partially suited to answering a specific question if an engineer is most familiar with that model, or if a calibrated and validated model is already available even though it may not scientifically be the best model for that specific application. This means that in addition to the problem domain, a modeler's knowledge of the model and data availability must also be included in model selection for suitable application.

Early simulation models, adopted now as standard practice, did not have the ability to account for spatial variations because of both computational and data limitations. While many of these limitations have been overcome through the increased computational power of standard desktop computers and the widespread availability of geographic data easily downloaded from the internet, the ability to adapt geographic information system (GIS) tools to standard hydrologic modeling paradigms has lagged. This limitation has inhibited more widespread acceptance of simulation models that account for spatial variations.

There is a prevailing assumption that the use of distributed parameter models is complicated because of the rigorous data and computational requirements (Paniconi *et al.*, 1999). Because of this presumption, the use of distributed models has been limited by the previous generation of engineers, who believe that the additional information is not justified by the effort required or believe that it is not possible to acquire the data needed to develop a distributed parameter model. In addition, practicing engineers, mainly because of their familiarity with the uses and limitations of the lumped parameter models, believe that lumped models are capable of solving most (if not all) hydrologic design problems. They are reluctant to accept that a distributed parameter model can be more suitable in more situations. In reality, the 2D distributed models have been inconvenient, and the lack of proper guidelines and of efficient GIS-based pre-processing tools has added credence to the idea that the extra effort is, in fact, not worth it.

Based on a literature review, it is observed that even though the use of distributed parameter models has increased, they are not used to the extent they could be. In the literature of the early 1990s, researchers claimed that unavailability of high-resolution geo-spatial data, appropriate tools to process such data and the powerful computational resources, are the major setbacks for distributed modeling practices. Now the technology has advanced much and all such data, pre- and post-processing tools, and powerful desktop computers are available at hand for an engineer. Despite this, the distributed models are not practiced much and are still considered academic research models.

Most governmental agencies and consulting firms still use lumped parameter models in solving literally all categories of hydrologic problems. In many cases, the lumped models are forced to solve complex problems that are simply an extrapolation of their capabilities. Several researchers have established the necessity and validity of the use of the distributed models, but all such findings are somehow limited to the literature and the engineering community habitually resorts to lumped models.

The aim of this research is to establish the credibility of distributed models. In an attempt to leverage the appropriate use of distributed models, this research also strives to assess the usability of distributed models by identifying the problems that an engineer with a fundamental hydrologic modeling background would face while performing distributed modeling. The lumped, semi-distributed, and distributed models in the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) and Gridded Surface Subsurface Hydrologic Analysis (GSSHA) (Downer and Ogden, 2006; HEC, 2008) are used as the representative models. Intrinsically, it is not possible for an engineer to get mastery in all the available models, and it is not worth learning as most of the distributed models are physically based and use the fundamental equations of watershed flow dynamics. The selected tools are USACE's flagship models, and it is expected that they are good representatives of the current state of the art in mainstream hydrologic analysis.

The USACE has played a significant role in developing the models and establishing the modeling standards in the United States. The USACE models are extensively used in the United States and all over the world for hydrologic and hydraulic modeling works. These models offer the lumped (HEC-HMS), numerically distributed (HEC-HMS, ModClark), as well as the distributed (GSSHA) models for hydrologic modeling, and the comparison of different aspects of these three models fit the current research objectives. Other similar models can be substituted for such research, and the modeling data sets that are developed in the current research will be saved and documented in such a way that a similar study can be carried out using this data on similar models. It is expected that the new generation of engineers who are interested in physically based distributed modeling practices will benefit from this research.

This research is partly funded by the US Army Corps of Engineers-Engineering Research and Development Center (USACE-ERDC) and partly by Aquaveo LLC. The research has a practical aspect in that it focuses on improving the usability of GSSHA and enhancing the capabilities of WMS as a pre- and post-processor, thus directly applying what is learned with respect to the limitations in developing distributed modeling.

1.3 Definitions of the Methods Used for the Study

Hydrologic models are classified in various ways, and there is an overlap in the model categories among such classifications. Often the hydrologic procedures used to solve a problem are referred as 'models', which represents the algorithm involved in such procedure. At the same time, the computer programs and software that provide numerical method to solve such hydrologic procedures are also termed as 'models'. As such, the term 'model' is used to represent the procedure as well as the software.

In order to eliminate any possible confusion, the terminology used in this dissertation is defined below:

1. *Lumped Model*: It represents all the hydrologic models that depict the watershed as a single basin with:
    - Mean Areal Precipitation (single value for the whole watershed)
    - Uniform infiltration method (either Curve Number method or Green and Ampt method)
    - Conceptual surface transformation method (Clark Unit Hydrograph method of transformation)

2. *Semi-distributed Model*: It represents all the hydrologic models in which the watershed is divided into a series of multiple subbasins:
   - Subbasin is not gridded
   - Mean Areal Precipitation (single value for each subbasin)
   - Uniform infiltration method (either Curve Number method or Green and Ampt method; uses single value for each subbasin)
   - Conceptual surface transformation method (Clark Unit Hydrograph method of transformation within a subbasin; the flow from each subbasin to the watershed outlet is transformed using conceptual channel routing methods such as Kinematic Wave or Muskingum methods)
3. *Distributed Model*: It represents all the hydrologic models in which the watershed is divided into smaller grid cells. There are two categories of distributed models used in this research:
   (a) Empirically distributed:
      - Watershed is gridded
      - Mean Areal Precipitation distributed over each grid cell
      - Varying infiltration parameters over each grid cell (Gridded Curve Number method; uses separate CN for each grid cell)
      - Conceptual surface transformation method (ModClark transformation is used)

   (b) Physically distributed:
      - Watershed is gridded
      - Mean Areal Precipitation distributed over each grid cell
      - Varying infiltration parameters over each grid cell (Gridded Green and Ampt method; uses separate Green and Ampt parameters each grid cell)
      - Cell-to-cell flow tracking that allows water to infiltrate even while performing surface runoff

The following numerical codes are used to simulate the above-mentioned models:

1. *Lumped Models*: HEC-HMS (CN or Green and Ampt methods with Clark Unit Hydrograph transformation)
2. *Semi-distributed Models*: HEC-HMS (CN or Green and Ampt methods with Clark Unit Hydrograph transformation and Muskingum Channel routing)
3. *empirically-distributed Models*: HEC-HMS (Gridded CN method with ModClark transformation)
4. *Physically Distributed Models*: GSSHA (Gridded Green and Ampt with soil moisture redistribution and cell to cell flow routing)

1.4 Objectives

There has been a prevailing trend in mainstream hydrologic analyses of using the traditional lumped modeling approaches to solve water resources problems, many of which stretch beyond the capability of lumped models to address properly. The purpose of this research is to validate the necessity of using distributed hydrologic models to solve such complex problems while still acknowledging appropriate use of lumped models.

This research is intended to establish that using distributed hydrologic models is important in specific applications where the spatial distribution is of prime importance. Owing to factors such as rigorous data requirement, complicated parameterization, heavier computational requirements, and lack of efficient pre- and post-processing tools, the distributed modeling has been cumbersome and problematic. Thus, another aspect of the research is to investigate the common hurdles in the development of a distributed hydrologic model and to explore suitable solutions. The goals of this research are

1. Establish the credibility of distributed models
    - Establish the importance of using distributed hydrologic modeling practices, particularly in solving complex hydrologic problems

    - Verify that GSSHA and ModClark are appropriate distributed hydrologic modeling tools in solving hydrologic problems and publish these works in peer-reviewed journals

2. Establish the usability of distributed models
    - Investigate the problems and/or common issues in model parameterization and model formulation while creating distributed models
    - Propose solution(s) to these problems so that a practicing civil engineer with fundamental background in hydrologic modeling can use such tools.

The credibility of distributed models was established by publishing the result of this research in peer-reviewed journals. The lumped and distributed models in HEC-HMS were compared to evaluate the capabilities of these models. Similarly, GSSHA was used to simulate the land use change scenario. The same scenarios were simulated using the lumped and numerically distributed models in HEC-HMS. With the observations from this study, the capabilities of lumped and distributed models in simulating the land use change scenario were compared. This research has demonstrated how the distributed model behaves differently in simulating the hydrologic problems in which the spatial representation of the processes is important.

The pertinent problems in developing GSSHA models using publicly available geospatial data were studied. The interface as well as implementation issues in the modeling interface were identified using personal observations, experiences with a graduate-level class and the USACE training course. Most of these issues were solved and suitable workflow was suggested for better model development.

1.5 Dissertation Outline

This dissertation is presented in six chapters. Chapter 1 is the introduction that establishes the research background and its goals and objectives. In Chapter 2, a complete literature survey conducted to support this research is summarized. This chapter discusses the current state of art and establishes the necessity and validity of this research.

A comparison of the lumped and empirically distributed hydrologic simulation is presented in Chapter 3. The comparison is carried out using the tools available in HEC-HMS. Chapter 4 discusses the area of application of GSSHA. A land use change scenario simulation helps illustrate in detail. Common issues and roadblocks that might be encountered while developing distributed hydrologic models using the publicly available geo-spatial and hydro-meteorological data sets are discussed in Chapter 5. This chapter uses GSSHA as the representative distributed model and outlines guidelines on application of GSSHA and WMS so as to mitigate the identified issues. This chapter also outlines some of the development and enhancement in WMS pre- and post-processing as well as documentation for better use that evolved as the result of this research. Lastly, Chapter 6 concludes and presents the specific findings of the research. The future scope of the research is also discussed.

CHAPTER 2. LITERATURE REVIEW

2.1 Abstract

The main focus of this chapter is to establish that the proposed research is an important contribution to the engineering community and that it has not been previously accomplished. Despite the inconclusiveness between the efficiency of distributed versus lumped models, the literature establishes that the physically based distributed models have distinct advantages over the traditional lumped modeling approach. A distributed model has the ability to analyze a wide variety of problems, including runoff process details at small scales within a watershed, the rainfall-runoff response for ungauged and uncalibrated watersheds, the impact land use changes have on the overall hydrologic response of a watershed. At the same time, the lumped models have been proven to be more efficient in many situations. With such observations, it can be seen that both lumped and distributed models need to be used and that research to identify the suitable area of their application will be an important contribution. This research attempts to identify the area of application of a distributed model (taking GSSHA as the representative model).

This chapter also aims at demonstrating that an investigation of common issues or setbacks in setting up a distributed model using the publicly available geo-spatial data sets will be valuable. The following four aspects of the hydrologic modeling will be discussed in this chapter: (1) background of the lumped, semi-distributed, and distributed hydrologic modeling philosophies, (2) review of existing models that use the above mentioned modeling philosophies, and (3) review of the application aspect of these models.

2.2 Background

Lumped models have been used for over fifty years as a hydrologic technique to estimate stream flow at a basin outlet. Distributed models, on the other hand, are evolving at a slower pace than they should be as the next generation of hydrologic models. Many researchers have performed hydrologic simulations for both lumped and distributed models to see if distributed models are more advantageous than traditional lumped models. This chapter deals with the study of the history and development, as well as of the current practice, of such models. Quite a few studies have been conducted that specifically address how distributed models show improvement over the traditional lumped model. The hypothesis that distributed models, which use higher-resolution data, are more accurate than lumped models is largely untested (Smith *et al.*, 2004).

2.3 Lumped Hydrologic Models

A numerical formulation that represents a watershed as a single homogeneous unit is referred to as a lumped model. In such models, all of the parameters which impact the hydrologic response of a watershed are spatially averaged together to create uniformity across the basin (USACE, 1994) (Johnson and Miller, 1997). Since the watershed is considered one complete unit, the lumped models often constitute a relatively small number of parameters and variables (Refsgaard, 1997).

Lumped models make the assumption that rainfall is uniformly distributed over a watershed both spatially and temporally over a given time period. Such rainfall distribution does not occur in the real world watershed, although there might be a limited number of cases where this might become a closer approximation (Smith *et al.*, 2004; Reed *et al.*, 2004).

Lumped models assume uniform soil types, vegetation types, and land use practices over a watershed. This is a significant assumption as the infiltration properties that are often governed by the soil and land use widely vary in a watershed. Mean aerial runoff for the drainage basin is computed by making abstractions from the mean aerial precipitation. Traditional lumped models use a unit hydrograph concept to transform this runoff to determine the total streamflow at the basin outlet (Chow *et al.*, 1988). In 1932, Sherman introduced the concept of the unit hydrograph. The unit hydrograph is the runoff that results at the downstream outlet of a drainage basin from a unit depth (i.e. 1 inch or 1 mm) of excess rainfall for a storm of uniform intensity for a specified duration over an entire watershed drainage (Sherman, 1932).

Historically, hydrologic modeling has been conducted using a lumped modeling approach. There are many instances when such models have been proven to work effectively. Since the formulation of these models does not rely on the watershed physics, the reliability of their results is valid only if the models are calibrated. The watershed characteristics are conceptualized using a number of parameters, and it is often easy to calibrate the models. But many researchers claim that because the watershed physics are not involved, the calibration is often not unique. An important shortcoming of simple lumped parameter models is that their parameters are not directly related to the physical characteristics of the catchment (Reed *et al.*, 2004). In general, their applicability is limited to gauged watersheds where the expected conditions are within the historic data used for calibration and where no significant change in catchment conditions has occurred (Reed *et al.*, 2004). For such models to have general applicability, extended calibration periods are required (Refsgaard, 1997).

2.4 Semi-distributed Hydrologic Models

In an attempt to consider the spatial variation of watershed characteristics, semi-distributed models were developed. This approach of hydrologic modeling is popular in practice. In such models, the watershed is divided into smaller computational elements (or subbasins), and hydrologic computation is carried out for each element. There is a wide variation on how these computational elements are formulated. Some of the models use natural watershed-divides as the criterion for dividing a watershed, e.g. HEC-HMS (HEC, 2008) whereas others such as HSPF use the hydrological response unit (HRU), which is based upon the land use and/or soil characteristics (Bicknell *et al.*, 1997).

The subbasin has one set of watershed characters that are essentially assumed to be uniform over each subbasin. Basically, the semi-distributed models represent the spatially variable parameters or conditions as a series of subbasins with uniform characteristics (Vieux *et al.*, 2004; Biftu and Gan, 2001). The infiltration/watershed loss and rainfall excess are calculated for each subbasin independent of the other subbasins. The rainfall excess is converted to subbasin outflow using the same methods as used in the lumped models. All such sub-responses are routed through the channel to the watershed outlet, thus yielding an overall watershed response. There are several methods used in performing channel routing, such as Kinematic wave, Muskingum Cunge, etc. (USACE, 1994).

2.5 Distributed Hydrologic Models

Distributed models are an extension of the lumped and semi-distributed models. Distributed models attempt to simulate both the spatial heterogeneity and the physical processes occurring within a watershed (Bobba *et al.*, 2000). The distributed models divide the basin into elementary unit areas such as grid cells and solve basic physical equations to simulate the watershed processes. While even at the finest grid resolution some information is still lumped into a grid cell, the distributed model can be used to account for the spatial variation of precipitation, land use, or soil type within a watershed (Paudel *et al.*, 2010). In such models, the flows are routed from one grid cell to another as water drains through the basin (Jones, 1997). This allows the heterogeneity of the watershed to be simulated at each of the grid cells. Grid resolution is generally chosen in such a way that it is small enough to represent the spatial variation of major runoff processes such as rainfall, infiltration, transformation, etc., but large enough to be practical computationally (Vazquez *et al.*, 2002).

Distributed modeling is an active area of research in part due to the emergence of high-resolution data sets, the increasing capabilities of GIS, and the increasing power of modern computers (Smith *et al.*, 2004). Until the development of powerful computers, the use of distributed models was hindered by the inability of computers to efficiently process and store large amounts of data required in solving numerous complex physics-based equations associated with these types of models. Also, from the perspective of operational forecasting, the implementation of distributed models has been set back due to uncertainties in rainfall input, parameter errors, model structure, and parameterization. (Carpenter and Konstantine, 2004).

The goal of distributed modeling is to better simulate the hydrologic response of a watershed by representing the spatial and temporal characteristics that govern the transformation of precipitation into runoff (Vieux and Moreda, 2003). Distributed hydrologic models explicitly consider the geo-spatial variations and different processes across a watershed (USACE, 1994). These models attempt to quantify the spatial variability of hydrologic parameters and use these parameters to analyze rainfall-runoff processes at desired locations within a watershed basin (Smith, 1993). Distributed models take into account the spatial variability of hydrologic variables for a given watershed as well as the hydrologic response at ungauged locations within the basin (Smith *et al.*, 2004).

2.6 Comparison of Lumped and Distributed Models

There is always a question of which model to use among so many to solve a particular hydrologic problem. Several studies have presented qualitative comparisons of watershed models that may help in the initial screening (Ward and Benaman, 1999; Fitzpatrick *et al.*, 2001; Borah and Bera, 2003; Kalin *et al.*, 2003). Although there are several efforts seen in the literature on model comparison e.g. (Loague and Freeze, 1985; Michaud and Sorooshian, 1994; Refsgaard and Knudsen, 1996), no study has resulted in an objective categorization of such models based on the application. A literature review reveals that research concerning the comparison of hydrologic simulations between distributed models and lumped models has been inconclusive. It has been demonstrated that the distributed models are superior in many situations over the lumped models, but the complexity involved in model parameterization and the amount of workload added to the study might reduce the overall effectiveness of the distributed models (Reed *et al.*, 2004). Smith *et al.* (2004) indicates that few studies have addressed the improvements distributed models can make over the traditional lumped models for flood forecasting at basin outlets. Although predicting the hydrologic response at an interior point is a given, the use of distributed models to improve the hydrologic simulations at basin outlets is largely untested (Smith *et al.*, 2004). Refsgaard (1997) also discusses that, in many cases, lumped models perform just as well as distributed models. However, distributed models may have advantages for predicting runoff in ungauged watersheds, for simulating water quality parameters, and for predicting impacts due to changes in land use scenarios.

While physically based distributed models are typically thought to be more accurate than the simpler conceptual lumped models, in some instances lumped models are a reasonable choice based on available data and operational applications (Bergstrm and Graham, 1998). Overall efficiency cannot be solely attributed to the model performance because numerous other factors, such as the knowledge and efficiency of the modeler, the quality of the data and tools available to pre-process such data, etc., are also responsible for better modeling results.

In another case study, three different models on three different basins in Zimbabwe were compared. The three systems included a lumped conceptual model, a distributed physically based model, and an intermediate model between the lumped and distributed system. In this study, all models performed equally well when they were calibrated. The distributed model, however, performed marginally better for cases when the models were uncalibrated (Refsgaard and Knudsen, 1996) .

Similarly, in another case study, the basin response was found to have a higher sensitivity to the temporal resolution of the rainfall data than to spatial resolution. Also, the lumped model tended to severely underestimate flood peaks compared to a distributed model (Krajewski *et al.*, 1991).

In one part of this research, comparison was done between the performance of lumped and distributed models available in HEC-HMS. The lumped model used SCS-CN as the loss method and the Clark transformation method, whereas the distributed model used the gridded SCS-CN loss method and the ModClark transformation. The results showed that the gridded (distributed) models always result in higher peak and runoff volume (Paudel *et al.*, 2009).

Obled *et al.* (1994) found that results from the use of distributed inputs were inconclusive. The semi-distributed representation when compared to a fully lumped model did not lead to improved hydrologic simulations. It is suspected that the saturated runoff mechanism used in this model may be responsible for the lack of improvement in the results. If the dominant runoff process are surface and subsurface runoff of the Dunne type, where most of the water infiltrates into the soil, the resulting local runoff will be smoothed as the movement of water is stored and delayed within the soil. Watershed basins that respond predominately to this type of subsurface physical runoff may be much less sensitive to different rainfall patterns at the small catchment scale. (Obled *et al.*, 1994).

Reed *et al.* (2004) indicates that depending on the characteristics of a drainage basin, a distributed or semi-distributed model may or may not improve the hydrologic simulations when compared to a lumped model.

2.7 Review of Existing Models and Tools

There is a host of hydrologic models, each having its own merits and demerits. Many such models are developed to meet some specific requirement of some particular project or in many situations the development is driven by the interest of the model developer. There is no such model that is capable of solving all the problems related to water resources. It is obviously not practical to evaluate all available models and pre- and post-processing tools. A literature review was done while performing this research to identify what other models and tools are available for an engineer to perform hydrologic analyses. The following sections present an overview of some of the available hydrologic models (both distributed and lumped) as well as modeling tools. This research, however, uses two of the USACE's hydrologic modeling tools, which are discussed in detail later.

2.7.1 Available Distributed Models

The literature discusses a number of distributed hydrologic models that have been developed. These models range in complexity from physically based, fully distributed models; semi-distributed models; and smaller-scale conceptually lumped rainfall-runoff models. These models are built on a grid-based network, small subbasins, and triangulated irregular networks (TINs) (Koren *et al.*, 2004). A number of organizations have developed distributed models. These models and organizations include:

1. Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) - USACE-ERDC (Downer and Ogden, 2006)
2. Modular Modeling System (MMS) - U.S. Geological Survey (Leavesley *et al.*, 2004)
3. HLRMS - National Weather Service Hydrology Laboratory (Koren *et al.*, 2004; Reed *et al.*, 2004)
4. VfloTM - University of Oklahomantal Science, Institute of Environmental and Natural Sciences, Lancaster University, UK. (Vieux and Moreda, 2003)
5. CASC2D (Predecessor of GSSHA) - Colorado State University (Downer *et al.*, 2002)
6. MIKE-SHE - Danish Hydraulic Institute (DHI, 1998)
7. Hydrologic Research Center Distributed Hydrologic Model (HRCDHM) - Hydrologic Research Center (Carpenter and Konstantine, 2004)
8. Soil and Water Assessment Tool (SWAT) - US Department of Agriculture, Agriculture Research Service (USDA-ARS)
9. TIN-based Real-Time Integrated Basin Simulator (tRIBS) - Massachusetts Institute of Technology.
10. Variable Infiltration Capacity (VIC) - University of Washington

Each of these models is a physically based, distributed hydrologic model. GSSHA, CASC2D, MIKE-SHE, HLRMS, Vflow, and tRIBS use a square-grid-based GIS raster system in describing the meteorological, hydrological, and geological inputs into the system. MMS, HRCDHM, SWAT, and TOPMODEL use a catchment-based system. Most of these models use a kinematic wave channel routing approach. SWAT, however, uses the Muskingum routing method. MIKE-SHE uses the full dynamic wave approach. These models are complex state-of-the-art distributed hydrologic models. A discussion of the technical intricacies of these models is outside the scope of this report. The reader is invited to refer to the user manual for further information on each distributed model . (Luzio and Arnold, 2004; Ivanov *et al.*, 2004; Bandaragoda *et al.*, 2004)

2.7.2 Available Lumped Models

Most of the lumped parameter models are conceptual, and most of the watershed responses are controlled by a set of empirical parameters that are not based on the watershed physics. These models have been used in practice for many years. These models include the following:

1. Stanford Watershed Model (Crawford and Linsley, 1966)
2. SSARR (Rockwood *et al.*, 1972)
3. Sacramento model (Burnash *et al.*, 1973)
4. tank model (Sugawara *et al.*, 1976)
5. HEC-1 (HEC, 1998)
6. HYMO (Williams and Hann, 1973)
7. TR-20, TR-55 (SCS, 1986)
8. NFF (Now called NSS) (III and Crouse, 2002)

Recent conceptual models incorporate the soil moisture interaction as well for the dynamic variation in areas contributing to direct runoff. Some of the popular hydrologic models include the following:

1. HEC-HMS (HEC, 2008)
2. ARNO model (Todini, 1996; Zhao, 1984; Moore and Clarke, 1981)
3. TOPMODEL (Beven and Kirkby, 1979; Beven *et al.*, 1984)

4. HSPF (Bicknell *et al.*, 1997)
5. KINEROS(Woolhiser, 1996)
6. TOPNET [NIWA, New Zealand]
7. SWMM[EPA]
8. WATFLOOD [University of Waterloo] and so on

Application of some of these tools is very limited, while some others, such as HEC-HMS have been extensively used in solving a greater variety of problems. The applicability of these lumped models is governed by a variety of factors, such as the nature of the problem to be solved, knowledge that the modeler holds, and available input data.

2.7.3 Available Pre- and Post-processing Tools

Integration of GIS-based pre- and post-processing tools and hydrologic models has become popular. Increasing ease of use and availability of hydrologic models, GIS interfaces, and decision-support tools have expanded the scientific user base to include application-oriented users such as planners, farmers, politicians, and environmental groups (Goodchild and Wright, 1997). There are both free and pay computer programs such as WMS, ArcGIS, GRASS, HEC-GeoHMS, and HEC PrePro that help generate the input parameters for several hydrologic models using the information from a spatial GIS data source. The main motivations behind using such tools include the following:

- The availability of GIS interface to create spatial data
- Scientific visualization of the available data
- Possibility of coupling the hydrologic model with GIS
- Visualization for a hydrologic model
- The modeling application (Customizable interface like ArcGIS)

- Data management
- Result visualization

The use of GIS-based modeling interfaces started with the application of ArcView and its extensions. The use of these tools became obsolete with the evolution of a new generation of GIS by ESRI, now called ArcGIS. The integrated tool 'Arc Hydro' has been developed as an application of ArcGIS for its specific application in water resources (Maidment, 2002). Arc Hydro has enhanced capabilities for hydrologic modeling with the ArcGIS platform. HEC-PrePro (USACE) is another ArcGIS-based tool developed to extract hydrologic, topographic, and topologic information from digital spatial data of a hydrologic system and to prepare an input file for the Hydrologic Modeling System (HMS) developed by the Hydrologic Engineering Center (HEC) of the United States Army Corps of Engineers. Geographic Resources Analysis Support System, commonly referred to as GRASS GIS, is another GIS application used for data management, image processing, graphics production, spatial modeling, and visualization of many types of data (Westervelt *et al.*, 1992). GRASS has been popularly used as a free GIS application in the hydrologic modeling by both the governmental and non-governmental agencies.

USACE released HEC GeoHMS, another GIS-based tool intended to serve as a geospatial hydrology toolkit for engineers and hydrologists (Doan, 2000). HEC GeoHMS was specifically developed to create gridded input data for the ModClark model in HEC-HMS so that the HRAP Radar rainfall data could be used. It is still in use in various Army Corps offices to create HEC-HMS model parameters. The U.S. Geological Survey (USGS) Modular Modeling System (MMS) is an integrated system of computer software that integrates the models and tools at a variety of levels of modular design. A GIS interface has been integrated with MMS to enable spatial delineation and characterization of the watershed parameters and to provide objective parameter-estimation methods for selected models using available digital data coverages.

Watershed Modeling System (WMS) is another promising tool developed by Aquaveo LLC that serves as a platform for automated parameter generation for several hydrologic and hydraulic models (e.g., HEC-1, HEC-HMS, HEC-RAS, GSSHA, HSPF, NFF/NSS, and CEQUALW2). WMS is popularly used as both a pre- and post-processing tool for hydrologic modeling (Nelson, 2006). WMS is selected as the tool for this study because it has a complete interface for both HEC-HMS and GSSHA and also because of its robust capabilities to process the spatial datasets.

2.8 Models and Tools Selection

The US Army Corps of Engineers (USACE) has played a vital role in the development and application of hydrologic models in the Unites States. It is a government agency that establishes hydrologic modeling standards and guidelines, and it has developed a series of hydrologic, hydraulic, and environmental models since the early 1960s. USACE models are extensively used throughout the world, and they include such pioneering models as HEC-1, HEC-2, HEC-HMS, HEC-RAS, and GSSHA. Two of the USACE's models, HEC-HMS and GSSHA, will be used as the tools for this research.

As a straightforward and well-established standard model, HEC-HMS is widely used in the United States and worldwide. GSSHA is a more sophisticated physically based research model that the USACE is promoting as a next generation model capable of simulating more complicated hydrologic and hydraulic situations, such as the levee failures in New Orleans and sediment and nutrient transport within a watershed. Both models are commonly used with many applications in peer-reviewed literature. GSSHA is supported by the US Army Engineer Research and Development Center and is embedded into the Watershed Modeling System (WMS) (Nelson, 2006).

2.8.1 HEC-HMS

The USACE model, Hydrologic Modeling System (HEC-HMS), is designed to simulate the precipitation-runoff processes of dendritic watershed systems (HEC, 2008). HMS is widely used in a broad range of hydrologic problems varying from the analysis of large river basin water supply and flood hydrology to the study of small urban or natural watershed runoff. HEC-HMS has been used for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, flood plain regulation, and systems operation (HEC, 2008).

HEC-HMS is popular for its simple and relatively easy approach, and it has been shown to perform an excellent job for certain problems, but the general perception (largely because of familiarity) is that it can be applied for almost all problems, even for complex scenarios. The capability of HEC-HMS to analyze the watershed hydrology in both lumped and quasi-distributed (HEC-HMS ModClark Method) fashions is its strength.

The HEC-HMS technical reference manual lists the following as the major components that HEC-HMS provides:

- Precipitation-specification options that can describe an observed (historical) precipitation event, a frequency-based hypothetical precipitation event or an event that represents the upper limit of precipitation possible at a given location.
- Loss models that can estimate the volume of runoff given the precipitation and properties of the watershed.
- Direct runoff models that can account for overland flow, storage, and energy losses as water runs off a watershed and into the stream channels.
- Hydrologic routing models that account for storage and energy flux as water moves through stream channels.
- Models of naturally occurring confluences and bifurcations.

HEC-HMS also has few water-control measures modeling tools such as the following (HEC, 2008):

- A distributed runoff model for use with distributed precipitation data, such as the data available from weather radar.
- A continuous soil-moisture-accounting model used to simulate the long-term response of a watershed to wetting and drying.

Besides the above mentioned basic features, HEC-HMS also includes:

- An automatic calibration package that can estimate certain model parameters and initial conditions, given observations of hydrometeorological conditions.
- Links to a database management system that permit data storage, retrieval, and connectivity with other analysis tools available from HEC and other sources.

HEC-HMS provides a wide variety of options to create models that can be used to perform a rough estimate of watershed response as well as distributed-parameter-gridded models that are capable of analyzing more complex phenomena. The objectives of a study govern the level of model complexity and data requirement. The majority of the models available in HEC-HMS are conceptual and of the lumped-parameter type besides distributed modeling options, such as gridded Curve Number (CN) or gridded SMA methods. Various combinations of infiltration and surface transformation equations can be used, which provides flexibility to the modeler to develop a model that best fits the problem and site-specific needs (HEC, 2008).

Different evapo-transpiration, base flow, and sub-surface modeling options add further strength to HEC-HMS. Simplicity, stability, and familiarity make HEC-HMS a standard practice in the United States and quite popular all over the world.

2.8.2 GSSHA

The Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model is a reformulation and enhancement of the distributed runoff model CASC2D (Ogden *et al.*, 2000). GSSHA is a physically based, two-dimensional model in which the watershed is discretized into finite difference grids of any size. Processes that occur before, during, and after a rainfall event are calculated for each grid cell, and then the responses from individual grid cells are integrated to produce the watershed response. It is capable of simulating a long-term or an event simulation, sediment and nutrient transport, groundwater surface-water interaction, wetland simulation, and lumped and distributed rainfall by solving the finite difference equations. The model solves transport equations using finite difference and finite volume techniques, and it uses 2D diffusive-wave overland flow routing and 1D diffusive-wave channel routing (Downer *et al.*, 2002).

GSSHA is a process-based model with an option to select the specific processes to be modeled for a particular application. Among the processes that can be simulated are precipitation distribution, snowfall accumulation and melting, precipitation interception by vegetation, surface water retention, infiltration, overland flow runoff, overland erosion and deposition, channel routing of water, channel routing of sediments, channel routing of conservative contaminants, unsaturated groundwater flow (vadose zone modeling), saturated groundwater flow, stream recharge/discharge to groundwater, exfiltration of groundwater to land surface, and evapotranspiration (ET) (Hunter *et al.*, 2002; Wiki, 2009; Downer *et al.*, 2008).

During an event, rainfall is spatially and temporally distributed over the watershed. Rainfall may be intercepted by vegetation before reaching the land surface. Once an initial interception demand is reached, a fraction of the precipitation will reach the land surface. Upon reaching the land surface, precipitation may infiltrate due to gravity and capillary forces. Water remaining on the land surface may runoff as 2D overland flow, after a specified retention depth representing micro-topography has been reached. This water may eventually enter a stream and be routed to the watershed outlet as 1D channelized flow. Between precipitation events, soil moisture accounting, evapo-transpiration (ET), and 2D lateral groundwater flow can be simulated. When precipitation falls in the form of snowfall, the water equivalent volume remains on the land surface and is released as melt water according to an energy budget calculation (Downer *et al.*, 2002; Downer and Ogden, 2003, 2006; Downer *et al.*, 2008; Wiki, 2009).

On the overland flow plane, sediment is detached due to rainfall impact and shear stresses due to overland flow. Sediments are routed overland along with the 2D overland flow. Erosion and deposition continuously occur on the overland plane as sediments are transported. Sediments may eventually be routed to the stream network where fines (silt and clay) are routed according to an advection dispersion equation. Coarse materials are treated as bed load, which is computed according to Yang's method (Wiki, 2009).

Constituents may be assumed to be within the soil column or on the land surface. In either case, constituent uptake occurs when water is ponded on the soil surface. Constituents move along in the 2D overland flow, with reactions occurring as water moves across the watershed. Constituents may ultimately be deposited into the stream network where they are transported according to a reactive advection dispersion equation (Downer *et al.*, 2008; Wiki, 2009).

Hydrologic processes that can be simulated and the methods used to approximate the processes with the GSSHA model are listed in Table 2.8.2. With the exception of channel routing, all processes and approximations in the original CASC2D model are also contained in the GSSHA model.

Table 2.1: Processes and Approximation Techniques GSSHA

Process	**Approximation**
Precipitation distribution	Thiessen polygons (nearest neighbor) Inverse distance-squared weighting
Snowfall accumulation and melting	Energy balance
Precipitation interception	Empirical 2 parameter with seasonal variance
Overland water retention	Specified depth
Infiltration	Green and Ampt (GA)) Multi-layered GA Green and Ampt with Redistribution (GAR) Richards equation (RE)
Overland flow routing	2D diffusive wave – Explicit – Alternating Direction Explicit (ADE) – ADE Predictor-Corrector (ADEPC)
Channel routing	1D diffusive wave up-gradient explicit
Reservoir simulation	Inflow from overland Inflow from streams Rainfall input ET - Dingman (1995) Outlet structure control Variable area/volume

Table 2.1 – continued from previous page

Process	**Approximation**
Evapo-transpiration	Deardorff Penman-Monteith with seasonal canopy resistance
Soil moisture in the Vadose zone	Two layer model RE
Lateral groundwater flow	2D vertically averaged
Stream/groundwater interaction	Darcy‘s law
Exfiltration	Darcy‘s law
Overland Erosion	Rainfall Impact Rill and Gully – Kilinc Richardson – Engelund Hansen – Shear Stress
Overland Sediment Deposition	Shield‘s law
Overland Sediment Routing	Transport Capacity 2D Advection
Channel Routing of Fine Sediments	1D Advection-Dispersion
Channel Routing of Sand	Bedload according to Yang's method
Reservoir Sources of Sediment	Overland lateral flow Stream flow
Reservoir Routing for Fines	Completely mixed reactor
Reservoir Routing for Sands	Overland sources deposit in reservoir boundary cells Stream sources deposit in reservoir bottom
Reservoir Fines Deposition	Uniform deposition over submerged overland cells Deposition according to Shield's equation

Table 2.1 – continued from previous page

Process	**Approximation**
Overland Constituent Loading	Specified rainfall concentration Specified groundwater concentration Specified loading on soil surface Specified loading in top soil layer Point source loadings
Overland Constituent Uptake	First order reaction with materials on surface First order reaction with materials in top soil layer NSM reactions with top soil layer
Overland Constituent Transport	2D Advection-Dispersion
Overland Reactions	First Order Decay NSM reactions
Channel Constituent Loading	Lateral inflow from overland Interaction with groundwater-specified groundwater concentration Point source loadings
Channel Constituent Transport	1D Advection-Dispersion
Channel Reactions	First Order Decay NSM reactions
Reservoir Constituent Loading	Precipitation Lateral inflow from overland Interaction with groundwater - specified groundwater concentration Point source loadings
Reservoir Constituent Transport	Completely Mixed Reactor
Reservoir Reactions	First Order Decay NSM reactions

The Preissmann channel routing routine (Cunge et al., 1980) was excluded because of known stability problems with the scheme when simulating trans-critical flows (Mesehle and Holly, 1997). Also, the upwind explicit channel routing method was replaced with a similar up-gradient explicit method (Downer *et al.*, 2008; Wiki, 2009).

2.8.3 WMS

WMS offers state-of-the-art tools to perform automated basin delineation and to compute important basin geometric parameters such as area, slope, and runoff distances. It also serves as a graphical user interface for several hydrologic and hydraulic models. With its management of coordinate systems, WMS is capable of displaying and overlaying data in real-world coordinates. The program also provides many display tools for viewing terrain surfaces and exporting images for reports and presentations (Nelson, 2006; XMSWiki, 2010).

Many of the principal models such as HEC-1, TR-55, TR-20, Rational, NFF, HEC-HMS, OC Hydrology, and MODRAT are supported by WMS, with the additions of a complete SWMM interface and a much-improved and fully functional interface to a spatially distributed model, GSSHA. WMS also provides a hydraulic interface making it compatible with HEC-RAS. The RAS model can be run as steady or unsteady state, and results are used to delineate floodplain extents and animations of flood waves for complete flood plain analysis. WMS also has an integrated hydraulic toolbox and incorporates the latest release of the widely used Federal Highways culvert design model, HY-8 (Nelson, 2006; XMSWiki, 2010).

WMS is used primarily to set up and run hydrologic models. The distinguishing difference between WMS and other similar applications is its ability to manipulate digital terrain data for hydrologic model development within a GIS-based environment. WMS uses three primary data sources for model development:

- Geographic Information Systems (GIS) Vector Data

- Digital Elevation Models (DEMs) or Gridded Elevation Sets
- Triangulated Irregular Networks (TINs)

2.9 Summary

The fundamental concepts associated with different classes of the hydrologic models were discussed in this chapter. Various research and investigations that have been conducted over a large number of sub disciplines associated with the lumped and distributed modeling and their intercomparison were reviewed. The literature has established a clear distinction between the lumped and distributed modeling philosophies, but the application guidelines on when and where to use these models for best results is lacking.

It was observed that the distributed modeling is capable of simulating the majority of the hydrologic problems that involve the spatial characteristics, more than lumped models could simulate. In practice, though, distributed models are seldom used, whereas the lumped models are extensively used, even to solve complex problems. The distributed models, by the way they are formulated to capture the spatial variation in the watershed characteristics, require a lot of data and are often complicated to develop. The current research intends to verify that the semi-distributed or distributed hydrologic models should be used for a variety of complex hydrologic applications when the spatial variation of watershed properties are of prime importance.

CHAPTER 3. LUMPED AND EMPIRICALLY-DISTRIBUTED MODELS

3.1 Abstract

This chapter focuses on the comparison of distributed and lumped curve number (CN) methods in simulating a watershed response. In the lumped model representation, a single CN value is used for the entire watershed and the rainfall excess is transformed using the Clark unit hydrograph method. Similarly, the gridded CN method is used with the ModClark transformation in the distributed model. HEC-HMS is used to simulate these scenarios, as both of these models are available in it. Furthermore, the study was carried out on the CN equation (USACE, 1994) and on precipitation ranges that make a significant effect on the lumped and distributed conceptualization.

Methodologies like the Clark synthetic unit hydrograph generally rely on the use of lumped or average rainfall and runoff parameters defined for the watershed, even though such parameters are spatially variable. In an attempt to leverage spatial parameters derived from geographic information, a modified Clark (ModClark) method, or a semi-distributed model, was developed for HEC-HMS. The ModClark method was initially developed to use the national network of WSR-88D radar (NEXRAD) rainfall data, but there has been little published on its application because of the difficulties in obtaining usable and reliable radar rainfall data and because of a lack of geo-spatial preprocessing tools required to parameterize a ModClark simulation. While the original implementation and testing of the ModClark method required the use of NEXRAD data in specific formats, this study shows that it is possible to use any real or synthetic rainfall data, whether it is spatially distributed or not. By not restricting the use of the distributed ModClark method to the use of spatially varying rainfall, distributed loss methods such as the commonly used SCS curve number can vary spatially over a grid, and the effects of distributed watershed loss parameters can be analyzed with or without distributed rainfall.

Further tests and examination of the SCS equation demonstrate that runoff computed from distributed CN is always greater than the runoff computed from the traditional composite or area-averaged CN for ordinary ranges of rainfall depths. Moreover, by allowing a relatively fine grid resolution, the ModClark method determines the overall runoff from the watershed using a discharge-weighted approach as opposed to weighted-CN, which is more accurate and preferable according to the original research done by USDA on the CN method (USDA, 2004).

3.2 Introduction

Hydrologic processes such as rainfall, infiltration, and runoff are by their very nature variable across both space and time. Traditional hydrologic simulation models used by engineers for evaluation and design have limitations in accounting for these variations. Temporal variations in hydrologic models are primarily derived from rainfall, which is the driving function of a runoff event. As long as the temporal variations of rainfall are understood, they can be accounted for in a simulation model. However, spatial variations of watershed properties affecting infiltration and surface runoff can be much more difficult to incorporate.

Early simulation models, adopted now as standard practice, had minimal capability to account for spatial variations because of both computational and data limitations. While many of these limitations have been overcome through the increased computational power of standard desktop computers and the widespread availability of geographic data easily downloaded from the internet, the ability to adapt geographic information system (GIS) tools to standard hydrologic modeling paradigms has lagged. This limitation has inhibited more widespread acceptance of simulation models that account for spatial variations (Sui and Maggio, 1999).

This case study focuses on the performance comparison of a traditional lumped hydrologic modeling processes and a semi-distributed hydrologic model in computing the hydrologic response from a watershed. The lumped model uses the Clark unit hydrograph runoff transformation method where as the semi-distributed model uses the more recent

ModClark method. In both simulations the SCS curve number (CN) equation is used to determine direct runoff from the rainfall input. The SCS method is chosen because it is commonly used and understood and because of its common implementation for both Clark and ModClark models. The Clark method was first implemented in the HEC-1 (HEC, 1998) computer program, which became a standard for performing routine hydrologic studies. Later, HEC-1 evolved into the HEC-HMS (HEC, 2008) computer program, which was part of a next generation of computer programs developed by the US Army Corps of Engineers (Davis, 1993). As part of the update from HEC-1 to HEC-HMS, new technologies and methods were implanted that included the ModClark method, which accounts for spatial variations in rainfall and runoff on the watershed (Calder, 1993). The Watershed Modeling System (WMS), capable of processing digital spatial datasets for watershed analysis, was used in this study to process geospatial data and generate input files for the two models (Nelson, 2006). Further, unlike the ArcGIS-based interface WMS allows for the use of any size grid for the ModClark method and is not restricted to the use of NEXRAD rainfall data.

The study consists of three parts:

- Results from watershed runoff using the Clark and ModClark methods were compared using identical CN values to demonstrate the performance and accuracy of using the HEC-HMS ModClark model and the WMS pre-processing of the required spatial input parameters.
- After verifying that the ModClark method produced identical results to Clark for non-spatially varying CN, the CN values were allowed to vary over the ModClark grid in order to demonstrate the importance of analyzing watershed runoff using distributed rather than lumped watershed loss parameter values.
- Sensitivity studies of the precipitation depth and various CN and area combinations on basin runoff were also carried out to further examine the differences in runoff depth calculations between lumped and distributed CN.

3.2.1 Curve Number Method

The Soil Conservation Service (SCS), currently known as Natural Resources Conservation Service(NRSC) Curve Number (CN) method is a simple, widely used, and efficient method for determining the amount of runoff from a rainfall event in a particular area. Although the method was designed for a single storm event, it can be scaled to find average annual runoff values. The data requirements for this method are minimal: rainfall amount and curve number. The CN number is based on the area's hydrologic soil type, land use, treatment, and hydrologic condition.

The SCS equation defines the runoff from a watershed as:

$$R = \frac{P^2}{P + S'} \tag{3.1}$$

where R = Watershed Runoff

P = Rainfall

S′ = Storage in the watershed = $\frac{1000}{CN} - 10$

This equation was derived based on trends observed in data from collected sites and is an empirical formulation instead of a physically based equation. This equation does not consider the initial abstraction term (Ia), which is the total amount of loss that occurs in the watershed before the surface runoff begins. It includes water retained in surface depressions and water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally is correlated with soil and cover parameters. Through studies of many small agricultural watersheds, I_a was found to be approximated by $I_a = 0.2 * S$ (SCS, 1986).

Modifying Equation 3.1 to include the initial abstraction term (I_a) transforms the equation to the more recognized form of (HEC, 1998):

$$R = \frac{(P - Ia)^2}{P - Ia + S'} \tag{3.2}$$

where Ia = Initial abstraction

The CN is a transformation of the watershed storage S, and it is used to make the interpolation, averaging, or weighting operations more linear. Soils are classified into hydrologic soil groups (HSG's) such that they indicate the minimum rate of infiltration for the bare soil condition exposed to prolonged wetting (SCS, 1986). If the soil profile has been altered because of urbanization or a similar cause, TR55 recommends using Table 3.1.

Table 3.1: Hydrologic Soil Groups for Disturbed Soil Profiles, (SCS, 1986; Rawls *et al.*, 1983)

HSG	Soil textures
A	Sand, Loamy sand or Sandy loam
B	Silt loam or Loam
C	Sandy clay loam
D	Clay loam, Silty clay loam, Sandy clay, Silty clay or Clay

Another parameter necessary to determine the curve number is land cover type and hydrologic condition. The land cover is obtained from aerial photos, land use maps, or field reconnaissance. USGS has grouped land cover into several groups, each group represented by land use code (LU code), e.g. the LU Code of 11 means residential area. (See Appendix A, Table A.1 for a list of land use codes). The hydrologic condition indicates the effects of cover type and treatment on infiltration and runoff, and it is generally estimated from density of plant and residue cover on sample areas. Treatment is a cover type modifier to describe the management of cultivated agricultural lands (SCS, 1986). (See Appendix A, Table A.2 for a portion of CN table as presented in TR55).

3.2.2 Weighted CN versus Weighted Discharge Methods

In most of the hydrologic modeling that uses the lumped approach of the CN method, an aerial-averaged CN is calculated for a watershed, and this CN is substituted into the CN equation (Equation 3.2) to determine the overall watershed runoff. Composite watershed CN values are determined using area-weighted averaging equation as follows:

$$CN_{comp} = \frac{\Sigma CN_i * A_i}{\Sigma A_i} \tag{3.3}$$

where CN_i = Curve Number in each individual area

A_i = Area with different CNs

The individual area in Equation 3.3 is a unique combination of land cover type and hydrologic soil group, each characterized by a different CN value. Because of the limitation of the lumped modeling approach, such a variation in CN cannot be processed and a composite CN is determined as discussed above.

On the other hand, if a gridded CN approach is used, then the weighted discharge method can be used, which is defined to be more accurate than the traditional composite CN method in NEH4 (USDA, 2004). In the weighted discharge method, the CN value is determined for each subarea with a unique combination of land cover type and hydrologic soil group. Then the CN equation (Equation 3.2) is applied to determine the runoff from each subarea and the runoff is area-averaged to determine the overall watershed response. Figure 3.1 schematically shows how these two methods work. The following equation (3.4) is used to determine weighted discharge:

$$Q_{comp} = \frac{\Sigma Q_i * A_i}{\Sigma A_i} \tag{3.4}$$

where Q_i = Runoff from each individual area

A_i = Area with different CNs

Figure 3.1 schematically shows how these two methods work.

3.2.3 Clark Unit Hydrograph Method

The Clark method is a well-established unit hydrograph approach to rainfall runoff simulation in which the basin shape, watershed storage, and timing can be accounted for. However, rainfall and loss parameters are lumped by determining average values over the domain. The Clark model is one of a handful of unit hydrograph methods that are

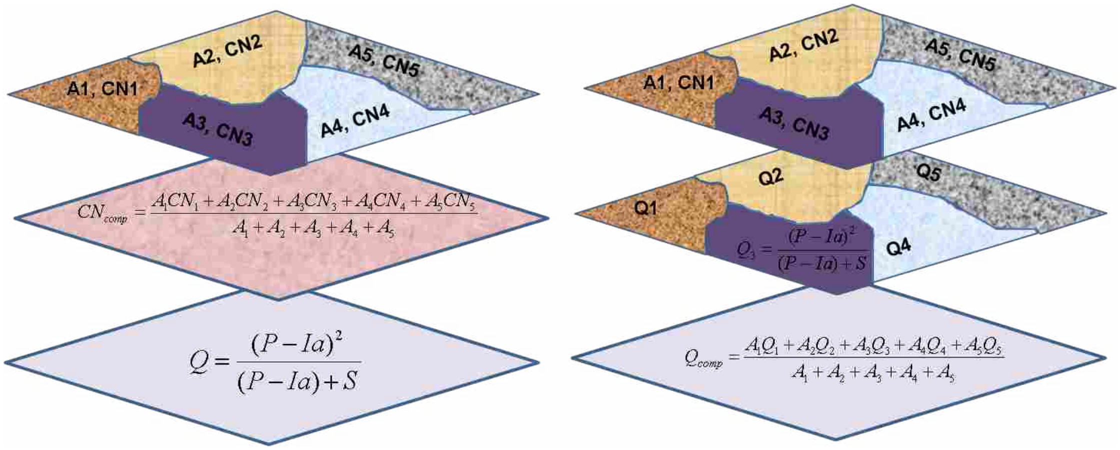


Figure 3.1: Schematic Representation of Composite CN and Composite Q Calculation

widely accepted and have been applied in established models like HEC-1 and HEC-HMS (HEC, 1998; USACE, 1994).

The Clark method uses a time-area curve, a watershed storage coefficient (R), and the time of concentration to develop a translation hydrograph. The model is illustrated conceptually in Figure 3.2. The watershed is divided into several areas of equal travel time to the outlet. From these areas a mass curve (time area curve) is developed and used to determine a time discharge histogram. The time discharge histogram is then routed through a linear reservoir to account for watershed storage (Clark, 1945) using the following equation:

$$O(t) = C_a I + C_b(t-1) \tag{3.5}$$

where $C_a = \frac{\Delta t}{R+0.5\Delta t}$

$C_b = 1 - C_a$

$O(t)$ = Ordinate of an Instantaneous Unit Hydrograph (IUH) at time t

I = Ordinate of translation hydrograph for interval t-1 to t

R = Storage Coefficient for linear reservoir

Δt = Time interval for which IUH is defined

Besides the time interval and storage coefficient (R), the overall time of concentration or length of time for water to travel from the hydraulically most remote point in the watershed to the outlet is required to compute runoff with the Clark method. Time of concentration can generally be estimated knowing the length, slope, and surface properties of the longest flow path, whereas the storage coefficient R can be estimated with empirical equations as some multiple of the time of concentration and then adjusted through calibration (Dodson and Associates, 1988). The time interval is user-defined and short enough to capture temporal variations of the storm being modeled.

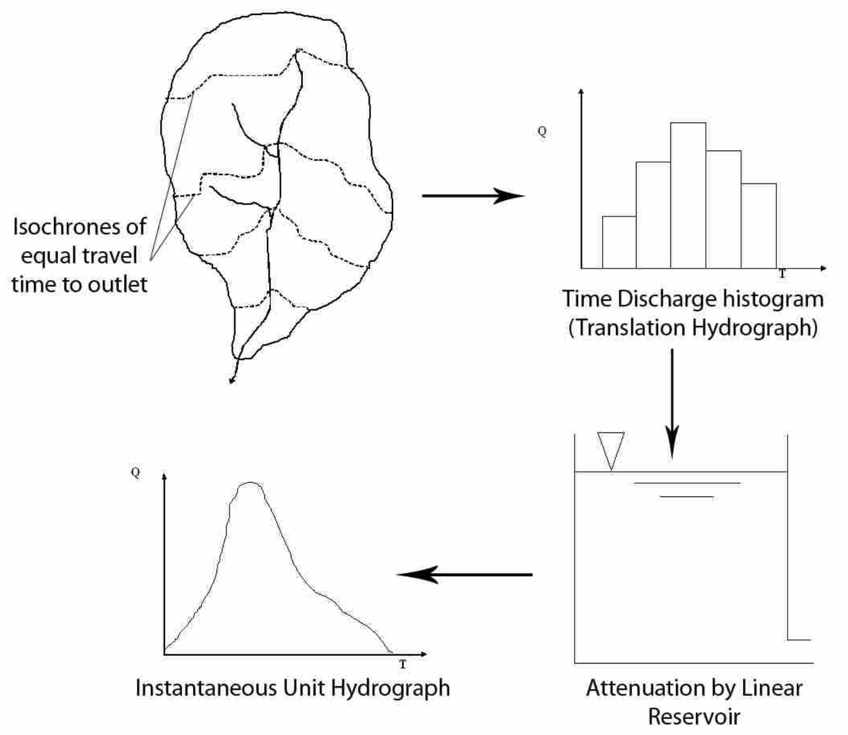


Figure 3.2: Clark Conceptual Model (Kull and Feldman 1998, ASCE)

3.2.4 Modified Clark Method

The Modified Clark method, referred to as ModClark in HEC-HMS, discretizes the watershed domain into a uniform grid. It is a linear, semi-distributed transform method that is based on the Clark conceptual unit hydrograph. This method is different than the Clark model because spatial differences in rainfall and losses can be accounted for by using relatively small grid cells. Rainfall excess determined for each grid cell is then lagged based on the travel time to the outlet for that grid cell and then routed through a linear reservoir using Equation 3.1 to account for the effects of watershed storage. Instead of a single time of concentration and a generalized time-area curve that are used to develop the Clark instantaneous unit hydrograph (See Figure 3.3). The travel time for each cell is based on the travel time to the watershed outlet (Peters and Easton, 1996).

The results from each cell are combined to produce the final hydrograph as shown conceptually in Figure 3.3. If the same CN value were used for each grid cell, then ModClark implemented correctly should produce the same result as Clark where the time area curve is essentially derived from the times of travel and areas of the individual grid cells.

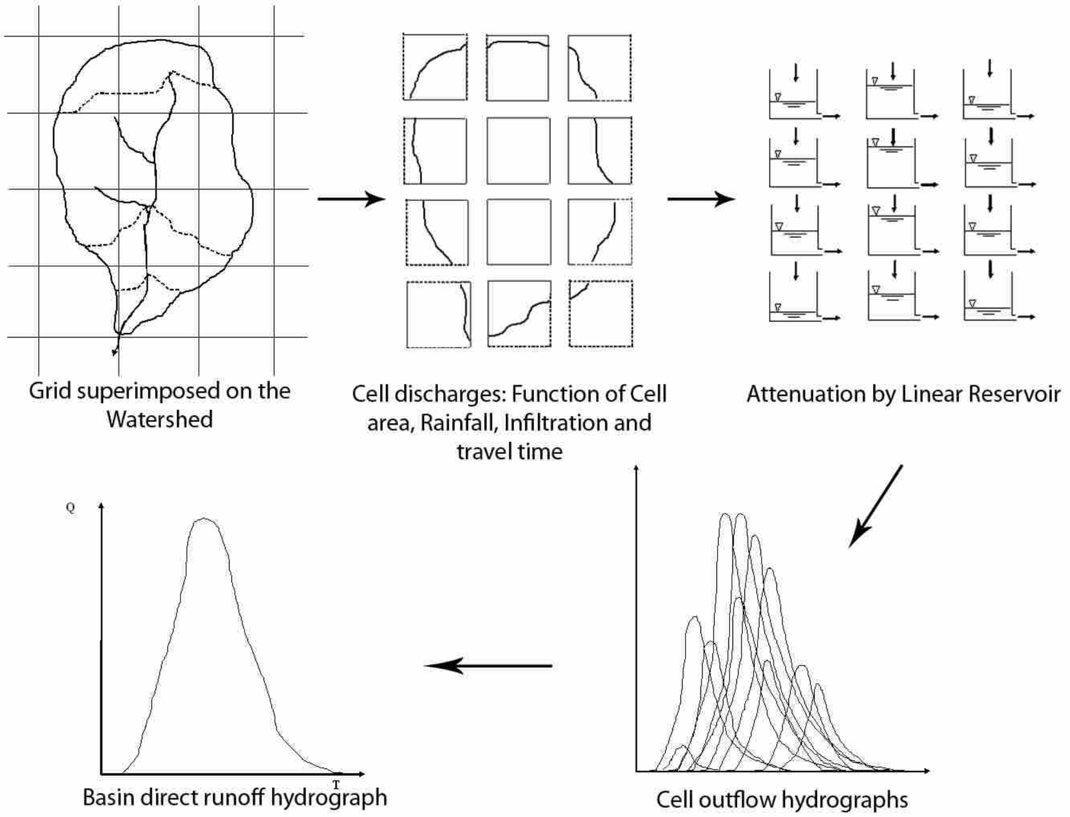


Figure 3.3: ModClark Conceptual Model (Kull and Feldman 1998, ASCE)

3.2.5 Implementation and Use of ModClark

ModClark was implemented in HEC-HMS for hydrologic analysis to facilitate using spatially varying rainfall and watershed properties (Charley *et al.*, 1995). Because the ModClark method divides the watershed into relatively small grid areas, each of which can be thought of as a quasi-sub-watershed, there is a possibility of capturing the variability introduced by distributed rainfall and watershed loss parameters. The method was originally developed with the primary motivation of incorporating the NEXRAD radar rainfall data (Davis, 1993). The ModClark pre-processing utilities were thus constrained to developing meteorological models based on the HRAP grid of radars that are provided at a resolution of approximately four kilometers. This limitation restricted applications to relatively large watersheds for which the NEXRAD radar data could be obtained.

The evolution of radar rainfall data that can be applied to hydrologic modeling applications with quantifiable uncertainty has been slow (Ajami *et al.*, 2004). For this reason, and because the GIS pre-processing tools to support ModClark have not been widely available, very few applications involving ModClark have been developed or published. However, in addition to accounting for spatial variations in rainfall, the method can be used to account for variations in soil and land use used to derive CN and other watershed loss methods. By implementing a set of GIS pre-processing tools for the ModClark model that allows a meteorological model to be defined from gauge or standard synthetic design storms, the distributed runoff can be calculated without being restricted to the use of radar rainfall data. Such tools are available in WMS and were used as the basis of deriving the test watersheds of this study.

For the comparison studies developed hereafter, the Clark model represents a hydrologic model in which the CN values are lumped or spatially averaged, and the rainfall response is determined using the Clark transform method. Similarly, the ModClark model represents a semi-distributed gridded model in which the CN values can be varied over each grid cell and the ModClark method of runoff transformation is used to determine the rainfall response of the watershed.

In this study, comparisons are made between these two model formulations for the purposes of demonstrating the following:

1. The HEC-HMS ModClark model behaves similarly to the Clark model, as it should. This comparison will serve to verify that the concept of ModClark as programmed in HEC-HMS is functioning as expected, and that WMS or a similar GIS interface can be used to properly parameterize a ModClark simulation without the requirement of using spatially varying NEXRAD rainfall data (though it could be used where available) as the basis of the grid cell size and overall meteorological model.

2. There is a distinct and predictable response in the watershed when the CN is allowed to vary spatially, as it does with the ModClark model, and that such a response is not produced when the watershed parameters are lumped or averaged as it must be with the Clark model. This supports the research statement that distributed models are better than the traditional lumped models.

3. The ModClark method, when implemented with a relatively high grid resolution computes runoff from the SCS equation using the preferable weighted discharge rather than the weighted CN approach (USDA, 2004).

3.3 Methodology

Geospatial watershed information is valuable for developing parameters for any hydrologic response model, including both the Clark and ModClark models. These data, including digital elevation models (DEMs), land use, and soils, are readily available in common GIS data formats (Hartman and Nelson, 2001). DEMs are used to delineate the watershed area as well as to calculate slope, flow path distances, aspect and other related watershed parameters. To identify the variation of infiltration, storage, and runoff behavior, which in this case is simulated using CN, land use and soil information of the watershed are required.

Different GIS software programs are available that can be used to process the digital spatial files and to create the necessary input for either the Clark or ModClark models. To date, the primary tool used to create the quasi-distributed ModClark parameters is HEC Geo-HMS, which requires the model to be defined using the $4*4\ km^2$ gridded radar rainfall data. While the use of spatially varying rainfall data such as the NEXRAD product is ideal for rainfall runoff simulations, technical problems associated with developing accurate ground estimates continue; therefore, the availability of such data remains limited and its application underdeveloped.

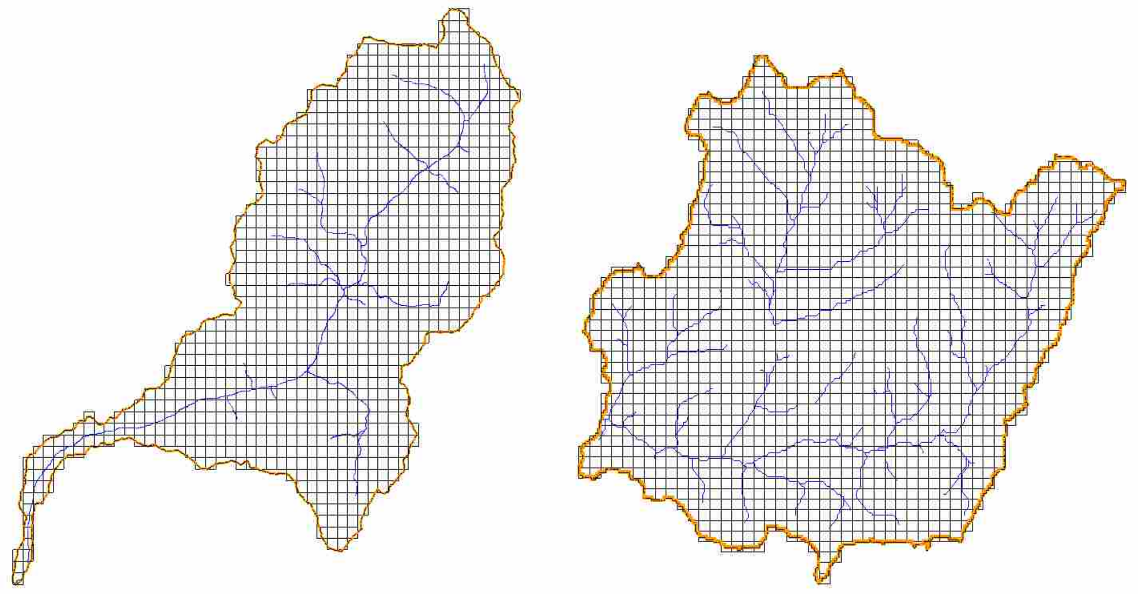


Figure 3.4: American Fork River and Virgin River Watersheds Descritized into 50 by 50 Grid Cells for ModClark Model

In this study, the pre-processing tools have been designed to separate the overlying watershed grid from the rainfall data so that grids of any resolution can be used together with any of the possible HEC-HMS rainfall (meteorological) models. Making the computational grid independent of the rainfall model thus increases the potential uses of the ModClark method and its ability to better capture spatial variations associated with hydrologic calculations. WMS has been used in this research because it has an interface for the necessary GIS-based processing of the digital watershed data, the Clark simulation in HEC-1, and the ModClark simulation in HEC-HMS.

3.3.1 Case Studies

Two different watersheds of varying sizes, shapes, and land uses are studied to make a comparison between the runoff responses from the HEC-1 Clark and the HEC-

HMS ModClark models. In this study HEC-1 was used for the Clark simulations rather than HEC-HMS because of the ability of HEC-1 to define a time area curve from the actual watershed DEM data, a capability that was not carried over to HEC-HMS. HEC-HMS always uses a synthetic time-area curve based on "typical" geometry, whereas in HEC-1 a basin specific time-area curve of actual runoff patterns derived from a DEM can be used. The only difference in the two models is the way rainfall excesses are transformed into a unit hydrograph. If the implementation of ModClark is correct, it should produce nearly identical results to the Clark model. The following section of the study compares these results. The watersheds are

1. The American Fork watershed with an area of 64.5 sq. miles and
2. The Virgin River watershed with an area of 955.4 sq miles.

Figure 3.4 illustrates how WMS develops a ModClark grid from a delineated watershed for the American Fork and Virgin River case studies.

Rainfall for the study was obtained from NOAA Atlas for the "100 year 24 hour" events for each of the watersheds, though for the purpose of this study any rainfall depth significant enough to generate runoff could be used. The basin average rainfall depth meteorological model is used with a standard "SCS Type II 24 hour" temporal distribution of the storm (Wanielista *et al.*, 1997) for both the Clark and ModClark models so that the rainfall input is identical for both methods.

Watersheds were delineated using 30m-resolution seamless DEM data obtained from the USGS NED web server (USGS, 2009a). CN values were derived from spatial land use and soil data downloaded from the EPA web server (EPA, 2009). These data can be used to classify a separate CN for each grid cell in the ModClark model as well as to determine a composite value for the Clark model using standard SCS tables relating hydrologic soil classification and land use.

In order to validate the implementation of the ModClark model, a lumped CN simulation is performed for both watersheds using the composite CN for the Clark model and the identical CN for all grid cells in the ModClark model. The average composite CN of 59.3 was used for the American Fork watershed and 64.9 for the Virgin River watershed.

A histogram of CN for the American Fork and Virgin River watershed grids is shown in Figures 3.5 and 3.6 respectively.

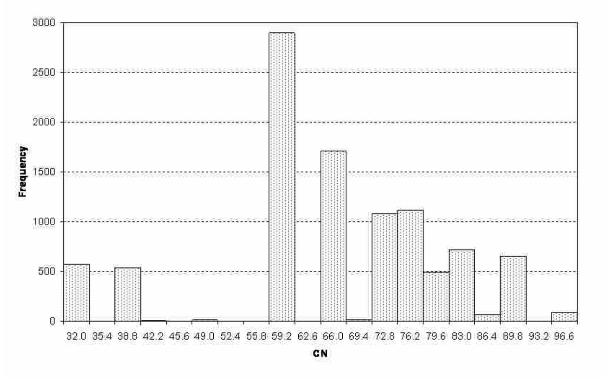


Figure 3.5: **CN Histogram for American Fork Watershed Using ModClark Grid**

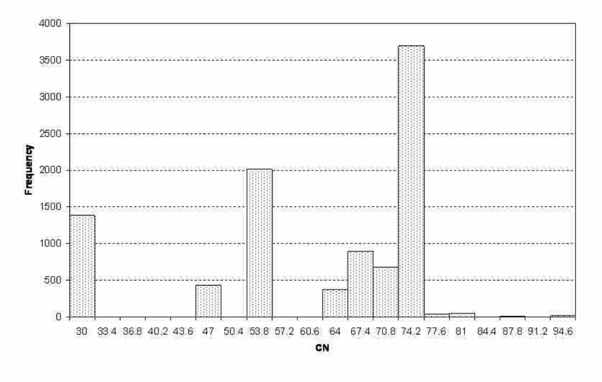


Figure 3.6: **CN Histogram for Virgin River Watershed Using ModClark Grid**

Figures 3.5 and 3.6 show the variation of CN over the watershed. In a lumped model represented by Clark method in this study, there is no way to represent this variation so a single area averaged CN is used as a representative CN value for the entire watershed. This is a significant approximation as the spatial heterogeneity is blended. This approach underutilizes the data and computational resources that are readily available for the modelers.

3.4 Results

3.4.1 Validating ModClark Method

The ModClark model with uniform CN in each grid cell and the Clark model were compared to see if both these models produce identical results. If true, it validates that the implementation of the ModClark model in HEC-HMS works as expected.

Results from ModClark (with the same CN) and Clark Methods

Figure 3.7 illustrates the results for the American Fork watershed. Here, the resulting hydrographs obtained from simulating the runoff from the 100-year 24-hour storm with the Clark and ModClark models using the same CN (lumped) are shown. It can clearly be seen that the two hydrographs are nearly identical as they completely overlap throughout. Any discrepancy between them could be attributed to numerical round-off associated with the ModClark discretization of the watershed into smaller grid cells and numerical differences resulting from algorithm implementation.

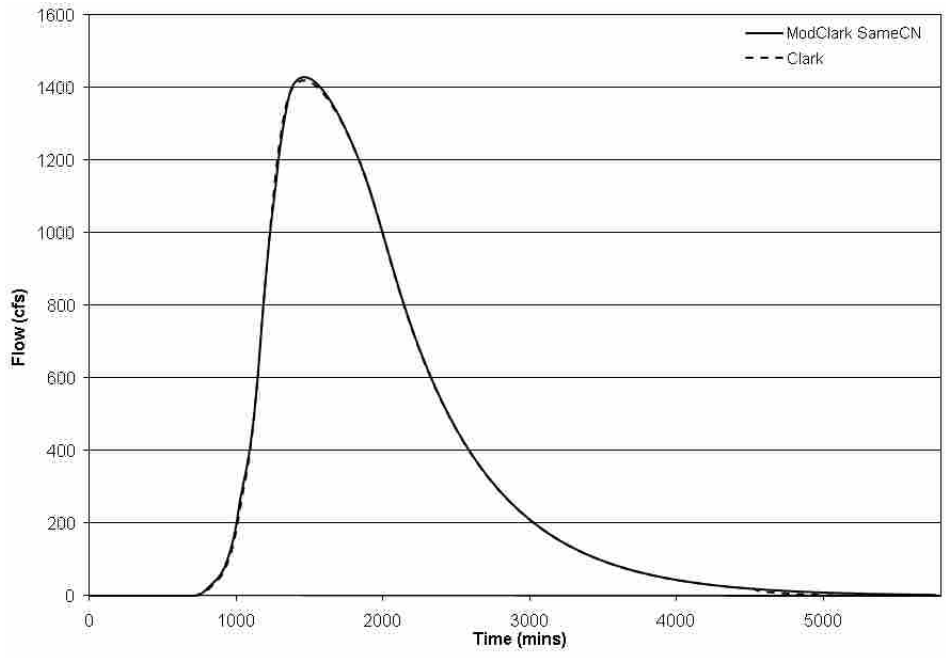


Figure 3.7: Comparison Between Clark and ModClark Hydrographs for American Fork River Watershed With Averaged CN Used for All Grid Cells

Similarly, for the Virgin River watershed, the hydrographs are as shown in Figure 3.8. As with the American Fork model, when the lumped CN (64.9) is used for each ModClark grid cell the hydrographs of the Clark and ModClark models are nearly identical (Figure 3.8).

The two hydrographs from Clark and ModClark (with same CN) are identical because of the following reasons:

- Both Clark and ModClark models use the same loss method, i.e. CN equations, and since the same CN value and the same precipitation input are used, both models produce the same surface runoff.

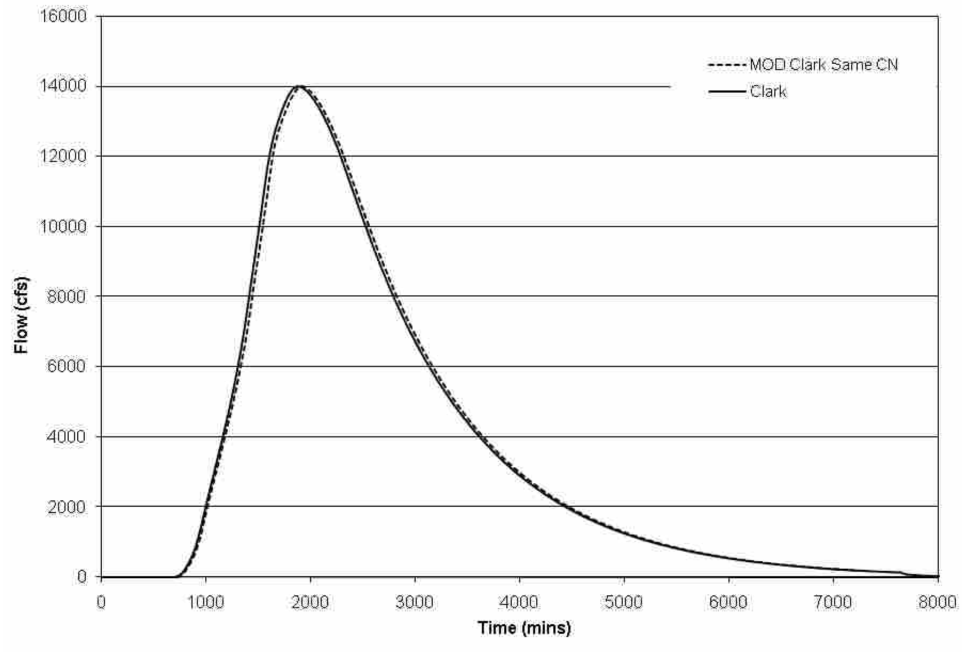


Figure 3.8: Comparison between Clark and ModClark Hydrographs for Virgin River Watershed with Averaged CN Used for All Grid Cells

- Both Clark and ModClark models use the Clark Unit hydrograph approach to transform the runoff to the watershed outlet.

Because of these similarities, both Clark and ModClark models, while using lumped CN, should produce the same result if properly implemented, and the results of this research corroborate this.

3.4.2 Distinction Between Lumped and Semi-distributed Approaches

Based upon theory, the distributed models should intuitively produce results that are closer to reality. The ModClark method is now used with variable CN over the grid, i.e. allowing the CN values to be distributed over the watershed domain.

The hydrograph in Figure 3.9 with increased volume and higher peak represents the runoff that results from using spatially varying CN values in the ModClark grid. The peak flow and runoff volumes are considerably higher using the ModClark model with variable CN rather than with using the lumped Clark model. This case study demonstrates the importance of considering the spatial variability of rainfall and infiltration/loss parameters.

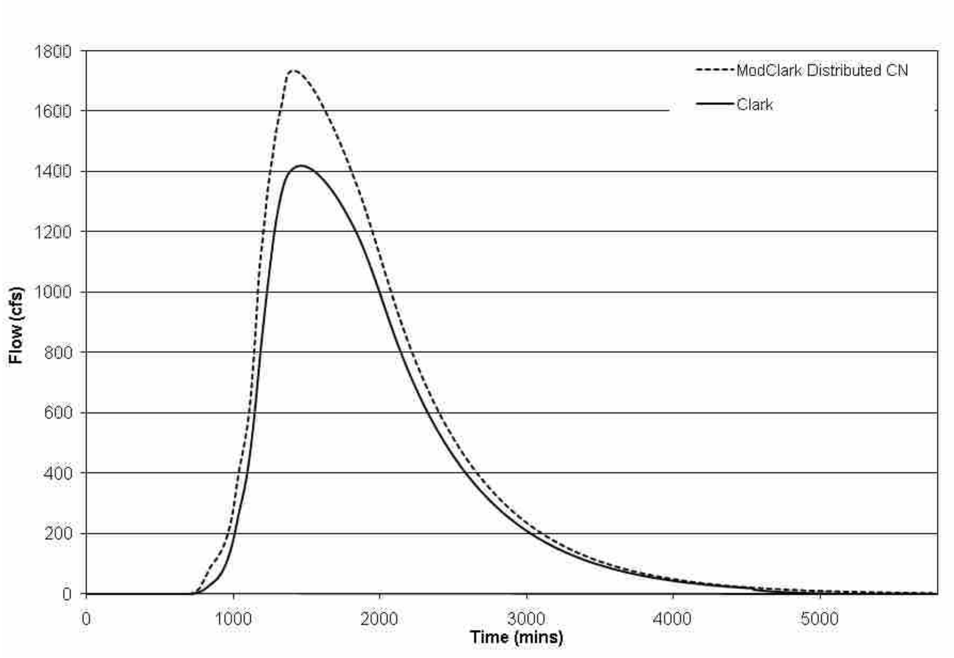


Figure 3.9: Comparison Between Clark and ModClark Hydrographs for American Fork River Watershed with Distributed CN Used for all Grid Cells

From the summary table in the HEC-HMS simulation and output files in the HEC-1 simulation, the rainfall, loss, and runoff volumes can be extracted. Table 3.2 summarizes the results from the Clark and both ModClark simulations.

In the ModClark model with spatially distributed CN, the amount of loss is less and runoff/peak flow is higher than for the single-valued CN used with Clark. The peak flow increased from 1429 to 1735 cfs, a 21.41% increase, for the same rainfall depth. The change in infiltration loss volume is also significant with a variation of 3.98% in the loss volume between lumped and distributed models.

The tabular results further corroborate the hydrograph analysis, showing the comparison of the computed flow data from the Clark and ModClark simulations with constant CN values to be virtually the same. The 4.0 inches of total rainfall over the watershed resulted in 3.27 inches of loss and 0.73 inches of runoff. The peak flows and times to

Table 3.2: Comparison of Flow Between Lumped (Clark) and Semi-distributed (ModClark) Methods in the American Fork River Watershed for Both Uniform and Variable CN

Flow Statistics	Lumped CN (59.3)		Distributed CN	% Variation in Clark and ModClark
	ModClark	Clark	ModClark	
Peak Discharge (cfs)	1429	1425	1735	21.41
Total Rainfall (in.)	4.0	4.0	4.0	0
Total Loss (in.)	3.27	3.27	3.14	3.98
Total Excess (in.)	0.73	0.73	0.86	17.81
Time to Peak (hr)	24 hr 24 mins	24 hr 15 mins	23 hr 30 mins	3.69

peak are slightly different, but within variations that might be expected from the separate algorithm implementations.

The higher peak and increased volume of runoff (Figure: 3.10) resulting from spatially varying CN are consistent for the Virgin River watershed. In the Virgin River Watershed, the peak flow is found to increase from 13991 to 17226 cfs, an increase of 23.12%. There is also considerable variation of 6.54% in the loss volume between the lumped and distributed models.

Table 3.3 also shows the variation of computed flow data between the results obtained from the Clark model with lumped CN and the ModClark model with variable CN.

Examination of the summary data for the Virgin River Watershed indicates that a total of 3.5 inches of rainfall results in 2.75 inches of loss and 0.75 inches of runoff. These depths are the same for both the Clark and ModClark (with constant CN) methods. The resulting peak flows and time to peak are again identical. Table 3.3 shows the comparison of these values.

The results from above tables and graphs establish the validity of ModClark model implementation. The results further illustrate a significant variation in results using an averaged or lumped CN value in the Clark model and using spatially distributed CN values in the ModClark model.

With distributed CN models, the time to peak for the American Fork and Virgin River Watersheds are found to decrease (i.e. the peak occurs earlier), but the variation be-

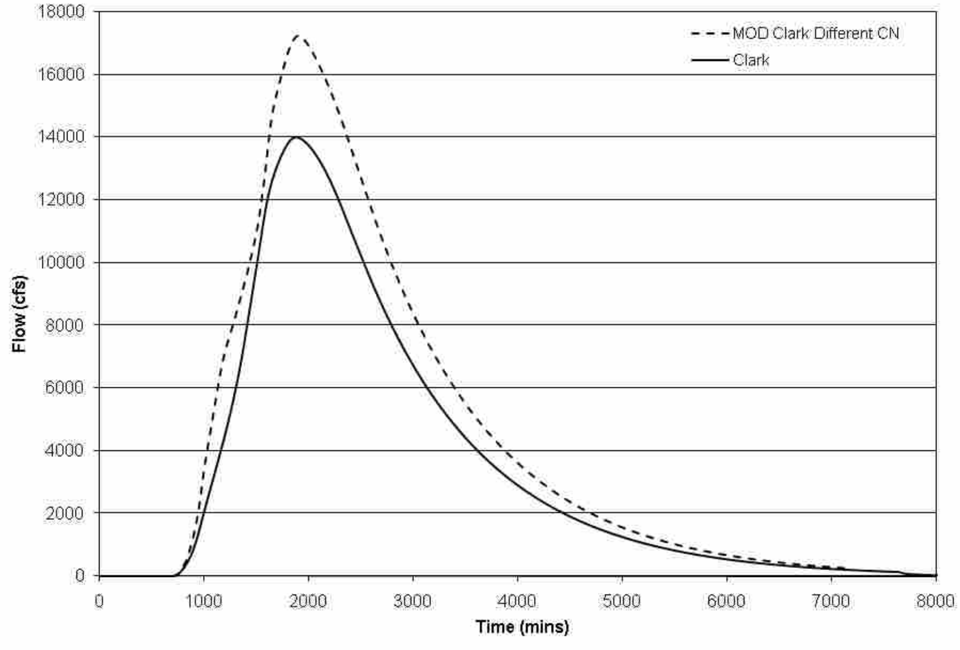


Figure 3.10: Comparison Between Clark and ModClark Hydrographs for Virgin River Watershed with Distributed CN Used for All Grid Cells

Table 3.3: Comparison of Flow Between Lumped (Clark) and Semi-distributed (ModClark) Methods in The Virgin River Watershed for Both Same and Variable CN

Flow Statistics	Lumped CN (64.9)		Distributed CN	% Variation in Clark and ModClark
	ModClark	Clark	ModClark	
Peak Discharge (cfs)	13991	14005	17226	23.12
Total Rainfall (in.)	3.5	3.5	3.5	0
Total Loss (in.)	2.75	2.75	2.57	6.54
Total Excess (in.)	0.75	0.75	0.93	24.0
Time to Peak (hr)	32 hr 6 mins	32 hr 0 mins	31 hr 48 mins	0.93

tween the lumped and distributed models is not significant. The variation is significantly higher for the peak flow, losses, and runoff volumes.

3.4.3 Results From Composite CN and Weighted Discharge Methods

The case study results show that the runoff response of the watershed is less for the same storm when the CN is averaged as with the Clark model than when a spatially varying CN is used with the ModClark model. Qualitatively, a composite curve number takes high-runoff areas and blends them into lower-runoff areas, resulting in less total runoff. This variation indicates that the use of ModClark is more conservative over the traditional Clark model.

Area-weighted averaging of CN (Equation 3.3) is linear. Conversely, the CN equation itself does not vary linearly. As can be seen in Figure 3.11, the runoff tends to linearity with increasing rainfall for a range of CN values, but the runoff is highly nonlinear for smaller rainfall values.

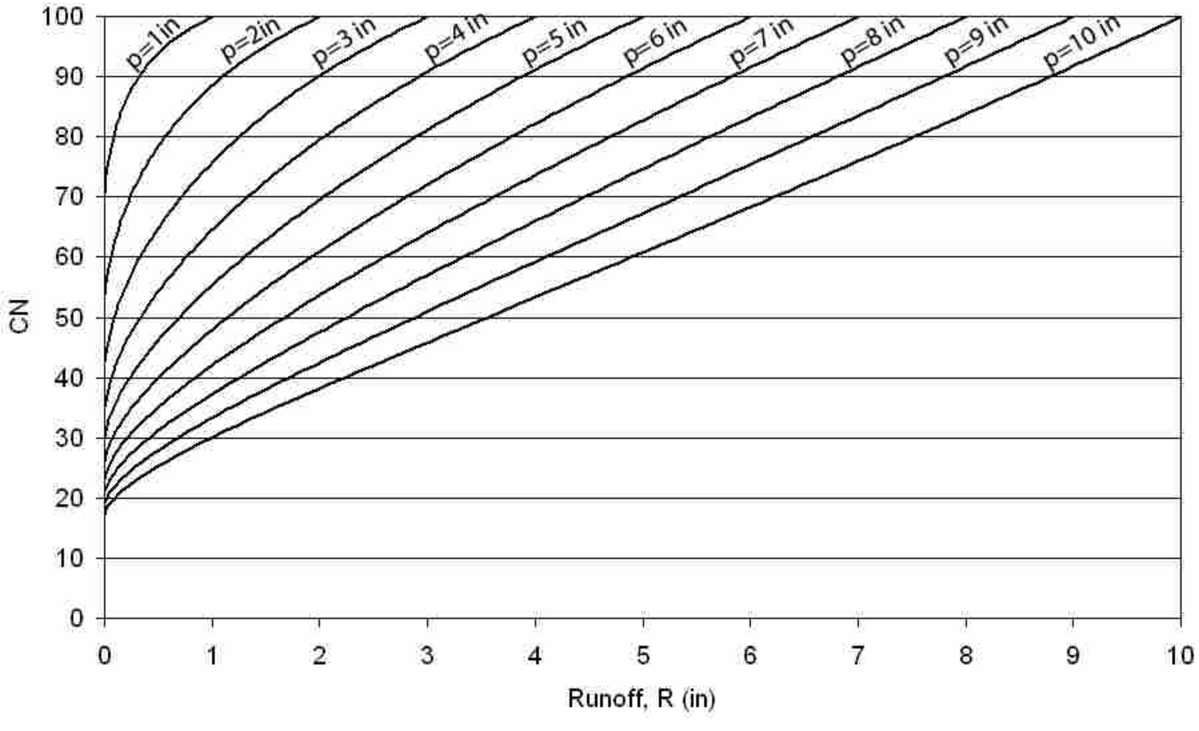


Figure 3.11: Variation of CN Value to Obtain a Runoff for Different Values of Rainfall

This implies that for cases when a composite CN value is used to determine watershed runoff, the result will be less than if runoff is determined for the watershed by summing the runoff computed using unique CN values for individual areas. In the development of the CN equations as discussed in the National Engineering Handbook (NEH), Part 630 Hydrology, a weighted CN and a weighted-discharge method are discussed (USDA, 2004). The weighted CN method computes an area-weighted average CN and then uses that CN to compute runoff from the SCS equation as illustrated in Figure 3.12. On the other hand, as illustrated in Figure 3.13, the weighted discharge method computes the runoff depth from the SCS equation for each unique land use–soil combination, and then area-weights these individual runoff depths to get total runoff. Because watershed and subbasins are not naturally divided along boundaries of similar CN values, the weighted CN method has been used almost exclusively in implementation of the SCS loss method. However, the NEH manual establishes that the method of weighted discharge is more accurate than the method of weighted CN (USDA, 2004).

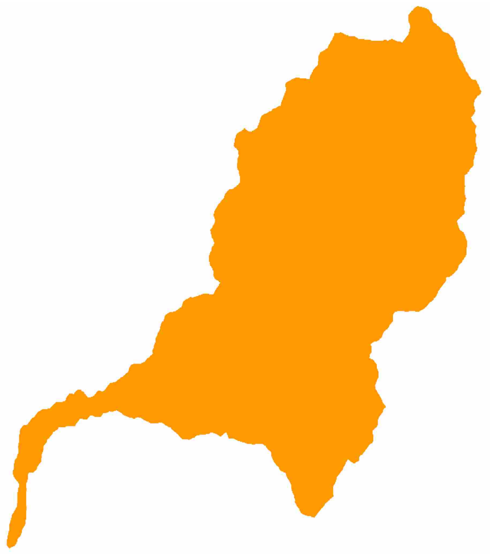


Figure 3.12: Lumped CN (Aerially Averaged) Over Watershed

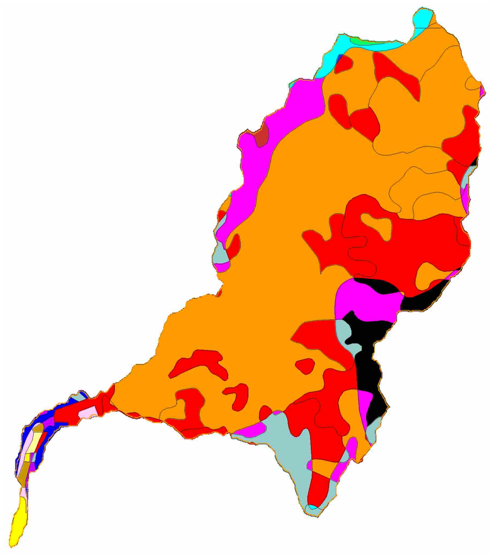


Figure 3.13: Variable CN According to Soils and Land Use

In the original implementation of the ModClark, the grid cells were derived from 4 km NEXRAD grid cells. At this resolution, the CN computed for each grid cell will be essentially averaged as shown in Figure 3.14. However, as shown in Figure 3.15, if the grid cells become small enough by using a higher resolution, the individual cells are no longer averaged in most cases but are instead defined by the single land use and soil combination they contain.

Therefore, as finer and finer grid resolutions are used, the computation of runoff using CN and the ModClark method approaches the weighted discharge method. Further,

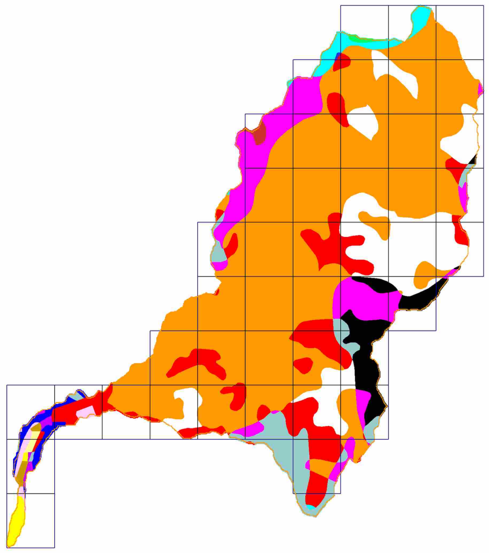


Figure 3.14: Conventional HRAP Grid Used in ModClark

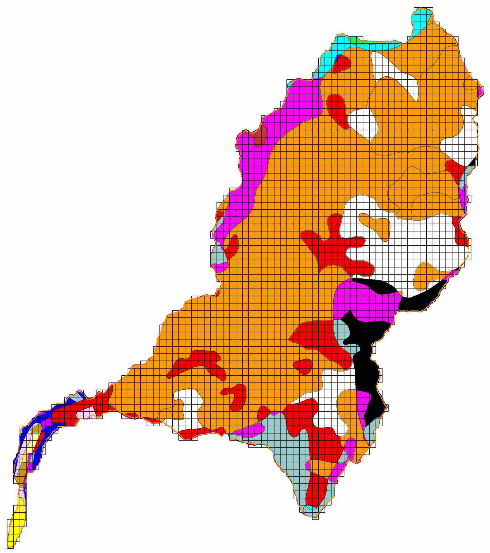


Figure 3.15: New Fine Resolution Grid Implemented in WMS

the case studies indicate that the weighted discharge method always produces more runoff for normal ranges of precipitation depths than the weighted CN method.

Because computing a complete runoff hydrograph using weighted discharge is not possible in HEC-1 or HEC-HMS, the runoff excess as given by the SCS equation was computed using the distributed CNs for both watersheds (See Figure 3.13 for an illustration of this using the American Fork watershed) With this method, runoff (R) is determined by applying the Equation 3.2. The weighted runoff R is calculated using Equation 3.4.

For the American Fork watershed the same rainfall depth was used and corresponding rainfall excess was 0.86 inches which is identical to the rainfall excess computed using the ModClark method and variable CN (see Table 3.2). Similarly, the rainfall excess for the Virgin River watershed was identical to the ModClark simulation with variable CN at 0.93 inches (Table 3.3). This indicates that the ModClark implementation computes the weighted discharge method of runoff excess, provided that the grid resolution is small enough to capture the spatial variations. This result was further tested by varying the grid resolution in the ModClark model and by comparing the results with the values from the weighted-discharge method. The runoff depths in ModClark became identical as the grid size became smaller.

3.4.4 Discussion on CN Equation

In order to determine the effects of using a distributed versus a composite CN over a range of precipitation values, the percent difference in runoff between the two as defined by Equation 3.6 was repeatedly solved for values of rainfall (P) beginning at 0.1 inch for all increments of 0.1 inches up to 20.0 inches using the American Fork Model.

$$\%\ \text{Difference} = \frac{R_{Distr} - R_{Comp}}{R_{Distr}} \tag{3.6}$$

where R_{Dist} is the runoff from the model shown in Figure 3.13 using the distributed CN (discharge weighted method) and R_{Comp} is the runoff from the model shown in Figure 3.12 using the composite CN (CN weighted method). These values are derived from the SCS Equation 3.1 as follows:

$$R_{Distr} = \frac{P^2 * A_1}{P + \left(\frac{1000}{CN_1} - 10\right)} + \frac{P^2 * A_2}{P + \left(\frac{1000}{CN_2} - 10\right)} + \ldots\ldots. + \frac{P^2 * A_n}{P + \left(\frac{1000}{CN_n} - 10\right)} \tag{3.7}$$

$$R_{Comp} = \frac{P^2}{P + \left[\frac{1000}{\left(\frac{A_1*CN_1+A_2*CN_2+\ldots..+A_n*CN_n}{A_1+A_2+\ldots\ldots+A_n}\right)} - 10\right]} * (A_1 + A_2 + \ldots\ldots + A_n) \tag{3.8}$$

If the terms R_{Distr} and R_{Comp} in equations 3.7 and 3.8 are equated and a value of 10.0 inches is substituted for P, then:

$$\frac{1000 * A_1}{\frac{1000}{CN_1}} + \frac{1000 * A_2}{\frac{1000}{CN_2}} + \ldots\ldots + \frac{1000 * A_n}{\frac{1000}{CN_n}} = \frac{1000 * A}{\frac{1000*A}{A_1*CN_1+A_2*CN_2+\ldots\ldots+A_n*CN_n}}$$

$$(A_1 * CN_1 + A_2 * CN_2 + \ldots\ldots + A_n * CN_n) = (A_1 * CN_1 + A_2 * CN_2 + \ldots\ldots + A_n * CN_n)$$

$$R_{Distr} = R_{Comp}$$

This shows that at P = 10.0 inches the values of R_{Distr} and R_{Comp} become equal. It can also be shown that for values of P < 10.0 inches, $R_{Distr} > R_{Comp}$ and for P > 10.0 inches $R_{Comp} > R_{Distr}$.

Similarly, if the initial abstraction term is considered nonzero as in Equation 3.2, then it can be shown that $R_{Distr} > R_{Comp}$ for all P < 8.0 inches and that $R_{Comp} > R_{Distr}$ for all P > 8.0 inches. Using the American Fork watershed as an example, several experimental calculations using high, medium, and low variations in CN were performed and the percent difference using Equation 3.6 determined. Figure 3.16 shows that with the higher variation in CN, R_{Distr} becomes equal to R_{Comp} when P approaches 10.0 inches. With lower variation in CN, the theoretical value of P approaches 8.0 inches (it can only reach 8.0 inches as the variation approaches 0, or in other words, all CN values are the same). Figure 3.17 shows that for $I_a = 0$, the transition point at which $R_{Distr} = R_{Comp}$ always occurs for a precipitation depth of 10.0 and is independent of the variation in CN.

Both cases show that the percent difference is comparatively higher at smaller precipitation depths and that when the variation in CN is low, the percentage variation between R_{Distr} and R_{Comp} becomes small because for small variations in CN, distributed CN essentially becomes composite or the average CN.

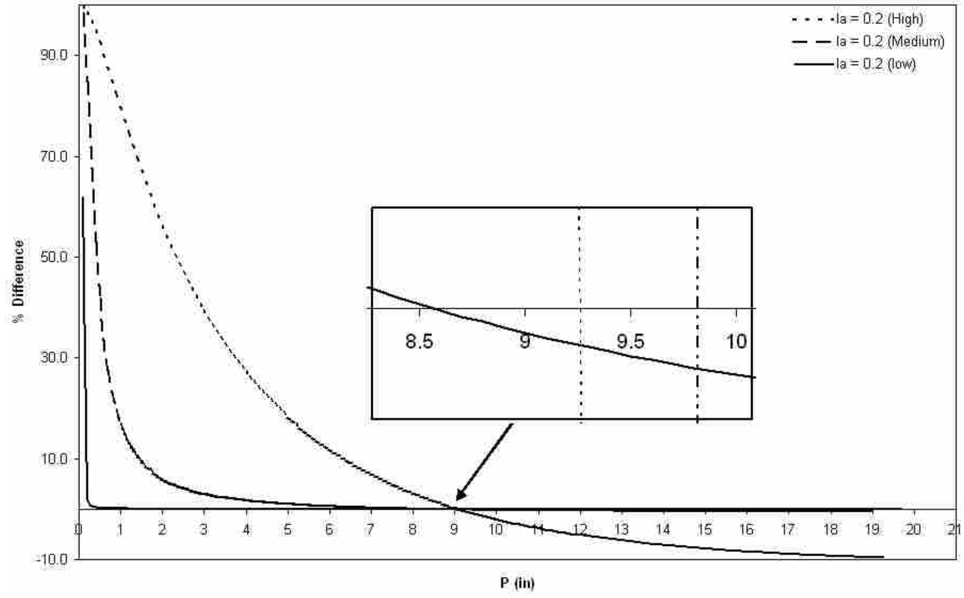


Figure 3.16: % Difference Between R_{Distr} and R_{Comp} with High Variation of CN

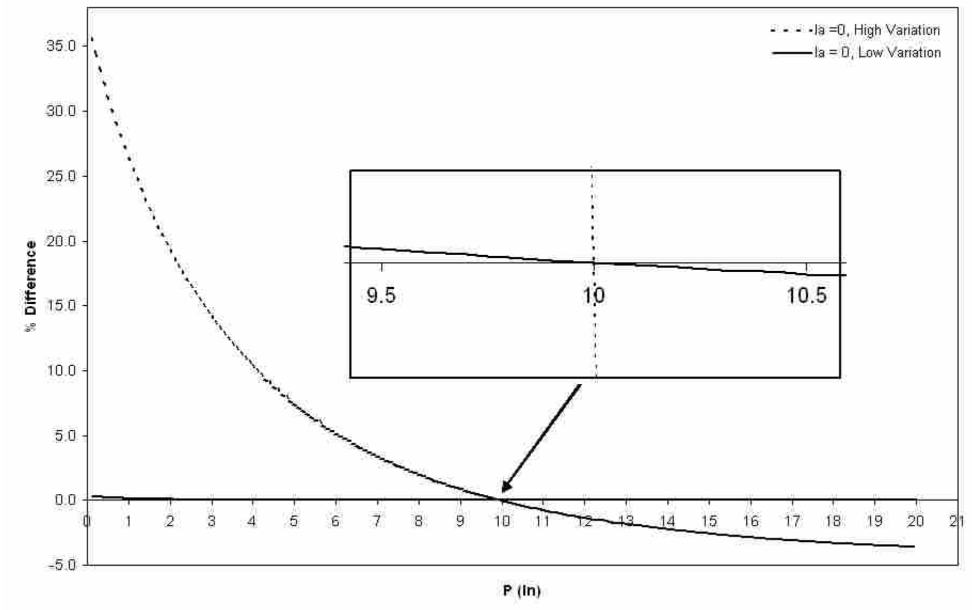


Figure 3.17: % Difference Between R_{Distr} and R_{Comp} with Low Variation of CN

Further experiments using different percentages of S for I_a (0.2S, 0.1S, 0.05S, etc.) showed that the lower limit of the transition (when there are relatively small differences in CN) occurred at $(1\text{-}M_{I_a})*10$ where M_{I_a} is the multiplier of S used in determining Ia. The upper limit for the transition remained at 10.0 for all cases stemming from the constant 10 used in the CN equation (Equation 3.1).

These results further validated what was initially observed from the comparison of the Clark and ModClark modeling case studies. Specifically, because of the non-linearity of the CN equation for low values of rainfall, computing runoff with a composite or average CN value will be less than runoff computed with distributed or weighted discharge CN. As the rainfall approaches 10.0 inches and the SCS equation approaches linearity, the magnitude of the difference decreases but the runoff from average CN is still less than that from weighted discharge.

The ModClark results with distributed CN call the previous lumped models into question. It should be noted that all models are subject to uncertainty, and it is therefore good practice to use measured rainfall and stream flow data when available to calibrate a runoff simulation. Using calibrated CN values, composite or distributed, would accurately reflect anticipated runoff for the particular watershed and storm conditions.

However, in practice many hydrologic models are applied to regions where observed data are not available or feasible to collect. In such cases the ModClark quasi-distributed model would be a more conservative choice for values of rainfall<= 8.0 inches when the standard assumption of I_a = 0.2S is made.

3.5 Conclusion

The ModClark method of transforming rainfall excess to a hydrograph was implemented in HEC-HMS as a means of accounting for spatial variability in watershed parameters. While specifically developed as a means of using NEXRAD radar rainfall data, it also allows loss calculations, such as the SCS curve number to be determined spatially. The WMS interface allows for the definition of an HEC-HMS ModClark model with non-spatial rainfall data such as can be defined from design storms where a basin average or rainfall gauge data are used.

Two case studies were examined to test the definition of ModClark models that allowed for runoff volume to be computed spatially without the requirement of spatially varying rainfall data. When compared to the Clark model, the ModClark simulations produced identical results when the same average CN value that was determined for the watershed was used for the single Clark basin and all ModClark grid cells.

Having validated the implementation of the ModClark with the Clark model from which it was derived, the CN values were allowed to vary spatially for the grid cells according to available land use and soil definitions derived from spatial dataset of the USGS and NRCS. In both case studies, the volume and peak of the resulting hydrographs were greater when CN varied spatially. Further analysis of the SCS CN equation reveals that runoff volumes will be higher for rainfall less than 8.0 to 10.0 inches (when assuming initial abstraction is equal to 0.2*S) when distributed CN values are used in a model such as ModClark than when the more traditional lumped approach id used as required for a Clark simulation.

This analysis leads to the following specific conclusions:

1. The ModClark method, implemented in HEC-HMS, functions well and provides an important capability for defining spatially different loss parameters, even in the absence of radar rainfall data.

2. Lumped CN as used by unit hydrograph transformation methods such as the Clark model underestimates the runoff volume and peak flow, as opposed to the results from the spatially varying ModClark method. This result led to a further examination of the SCS equation for which the following conclusions were made:

    - When the traditional value of initial abstractions is defined by 20% of the potential storage ($I_a = 0.2S$), runoff from a distributed modeling method is greater for all values of rainfall less than 8.0 inches with some variations of this value depending on the relative differences of CN. It was found that the value of precipitation at which the runoff from the lumped model will be higher varies between 8.0 to 10 inches depending upon the relative differences of CN.
    - When the initial abstraction is neglected, runoff from a distributed modeling method is greater for all values of rainfall less than 10.0 inches. It was found that the value of precipitation at which the runoff from the lumped model will be higher is 10.0 inches irrespective of the relative differences of CN.

3. The ModClark model was found to use the weighted discharge method as discussed in NEH Part 63, which is more accurate than the CN weighted method of runoff computation. By using the ModClark model with proper grid resolution, the practice of dividing the watershed into subbasins that are hydrologically similar is not necessary.

4. The overall comparison validates the fact that distributed models give different results than the lumped ones, and that these results are intuitively accurate.

Distributed or semi-distributed models take a lot of effort in their development owing to rigorous input data requirement, relatively cumbersome parameterization, and complex formulation. However, the capacity of distributed and semi-distributed models to solve complex problems and to produce results that are intuitively accurate, out-weigh the difficulties.

CHAPTER 4. LAND USE CHANGE SCENARIO MODELING

4.1 Abstract

This chapter discusses a comparison of the capabilities of lumped and distributed hydrologic models in simulating the watershed response to changed land usage. The main intent of this study is to validate the capability of distributed models, represented by GSSHA, to simulate such complex problems.

For this study, the HEC-HMS model is used in a fully lumped mode and the GSSHA model represents the fully distributed approach. A synthetic watershed is used to establish that a distributed model like GSSHA more intuitively simulates land use change scenarios by distinguishing the spatial location of the change and its effects on the watershed response. An actual watershed at Tifton, Georgia, is used to validate the observations made from the synthetic watershed. Both GSSHA and HEC-HMS models use Green and Ampt methods for infiltration with the same rainfall input. A significant difference in both peak flow and runoff volume was observed between GSSHA and HEC-HMS models while simulating different scenarios.

The proper modeling of overland flow in conjunction with the channel flow routing is important in simulating such scenarios. It is evident from the conceptualization of lumped models that they are not capable of representing overland flow. As GSSHA performs cell-to-cell transformation of the excess precipitation, this can be effectively implemented. To show the importance of overland flow simulation for land use change scenario modeling, the ModClark model with the gridded CN method was applied to the synthetic watershed. Despite both being grid-based models, GSSHA and HEC-HMS ModClark results were not directly comparable because they used two different infiltration/loss methods. But the relative difference between the various scenarios as simulated

by the individual models further illustrated differences in the way the models handle this class of problems.

4.2 Introduction

Surface runoff occurs when the soil is no longer capable of absorbing rainwater, an not capable of removing it via the processes of transpiration, infiltration and sub-surface runoff. It is intuitive that the changes in land cover result in corresponding changes in watershed condition and overall hydrologic response of the watershed. Rainfall-runoff relationships within a watershed are the result of the interplay of many factors, but are driven primarily by the interaction of climate, land cover, and soils (Hernandez *et al.*, 2000). In general, change in the watershed response such as peak discharge and runoff volume can be used as predictors for changes in land use practices over the watershed.

Land use change has a direct effect on hydrologic response of a watershed because the hydrologic processes such as evapo-transpiration and infiltration are interconnected with the land cover characteristics. For example, afforestation can cause an increased interception during the wet periods of the year and increased transpiration during the dry periods because of increased water availability to deep root systems of trees (Fohrer *et al.*, 2001). For the seasonal flow, this can lead to a rise of soil moisture deficits and a reduction of dry season flow. The higher interception in the forest reduces floods by removing a proportion of the storm rainfall and by allowing a build-up of soil moisture storage. This effect is generally small but significant for small storm events. High infiltration rates under forests and an effective soil cover reduce surface runoff and erosion (Calder, 1993). Similarly, development of an agricultural land to an urban area causes a decreased infiltration rate and eventually an increased peak flow as well as the runoff volume.

As already discussed in the literature review (Chapter 2), most of the hydrologic practices to analyze such problems use the lumped hydrologic modeling approach (Butts *et al.*, 2004). In some situations, semi-distributed models with subbasins or hydrologic response units (HRUs) are used so as to isolate the different land uses. But recently a significant number of physically based distributed models have been developed that are capable of simulating complex hydrologic problems by effectively using the geospatial data; they have been used in some cases (Bobba *et al.*, 2000). Mostly, such models are still considered as academic or research models (Paudel *et al.*, 2010).

This study focuses on differentiating the ability of the simple lumped-parameter modeling approach and the fully-distributed modeling approach to analyze the common watershed development issue of land use change.

The processes that control surface runoff are directly or indirectly related to the land surface features such as vegetative cover and soil texture (Loch, 2000). Therefore, changes to the landscape that affect the vegetative cover or soil matrix are expected to change the hydrologic response of the affected areas and the watershed as a whole.

When modeling land use change, the spatial location of the modified land use is of primary importance. An efficient model that simulates such scenarios should be capable of incorporating the spatial variation of the hydrologic parameters such as precipitation, infiltration, and surface transformation among others. Based upon model conceptualization, there are different approaches that can be used to define such variations.

For a lumped model the location cannot be distinguished within a sub watershed. In such a case two common approaches are generally used. In the first one, the watershed is subdivided in such a way as to isolate or treat the area affected by land use change as a single entity or subbasin. Then flows from the subbasin are routed to the watershed outlet requiring estimation of routing parameters, which adds further approximation to the models. In most situations, defining a subbasin for the areas where the change in land use occurs would be tedious since such boundaries do not coincide with natural watershed divides. In addition, if scenarios include changes to such features, then the discretization of watersheds must change. Changing the discretization would call into question the accuracy of the newly discretized model, which would be different from the calibrated model. Another more common approach is to assign modified parameters for a certain percentage of the watershed. For example, lumped models can treat impervious land either as "directly connected" or "not directly connected" to the stream based upon how the parameter modification is done. Such variations can make significant differences in the outflow (J. K. Lrup, 1998). Still, this approach fails to adequately address the issue of the flow path. If the flow path is important, then a gridded model that allows the water to flow from one cell to the next permitting water to infiltrate while performing surface runoff better represents actual conditions. Such models will be able to represent the distributed nature of the watershed more explicitly.

A physically based distributed hydrologic model like GSSHA takes the spatial variation of the infiltration and routing parameters into consideration (Downer *et al.*, 2002). The value of a distributed model lies in its capacity to model the processes considering the topology of land use changes (J. K. Lrup, 1998). Even if the watershed is discretized into smaller grid cells, there are some models that perform the surface runoff transformation empirically. The ModClark Model implemented in HEC-HMS is an example of this category of models.

As seen in figure 4.1, for both GSSHA and HEC-HMS ModClark models, the watershed is discretized into small grid cells with each cell representing a smaller sub watershed. The watershed characteristics such as infiltration parameters, surface roughness, etc. can be defined for each cell separately. Then precipitation is input to each grid cell independent of one another, thus allowing for the spatial variation of rainfall. After that, the loss methods such as infiltration or evapo-transpiration are applied, thus computing excess rainfall at individual cells. This rainfall excess is transformed to the watershed outlet at each time step, resulting in the outlet hydrograph. But there is a significant difference between how GSSHA and HEC-HMS ModClark methods perform surface runoff transformation, as described below.

As shown schematically in 4.1, GSSHA routes (point scale diffusive wave routing) the rainfall excess from one cell to one of the four neighboring cells. Q_1, Q_2, Q_3, and Q_4 represent the surface runoff from the cells marked 1, 2, 3 and 4 respectively. So, the surface runoff from Cells 1 and 3 flow to Cell 2 and before leaving Cell 2, the water is allowed to infiltrate. Thus the runoff from Cell 2 will be $Q_2 = Q_1 + Q_3 - \text{Infil}_2$. Such process will continue until the flow reaches the stream from where it will be routed to the watershed outlet using 1D channel routing schemes. This implementation is closer to what actually happens in a real watershed. Such implementation in GSSHA makes it capable of tracking the changes in each grid cell thus simulating in a truer sense the overall watershed response to land use change (Downer and Ogden, 2004).

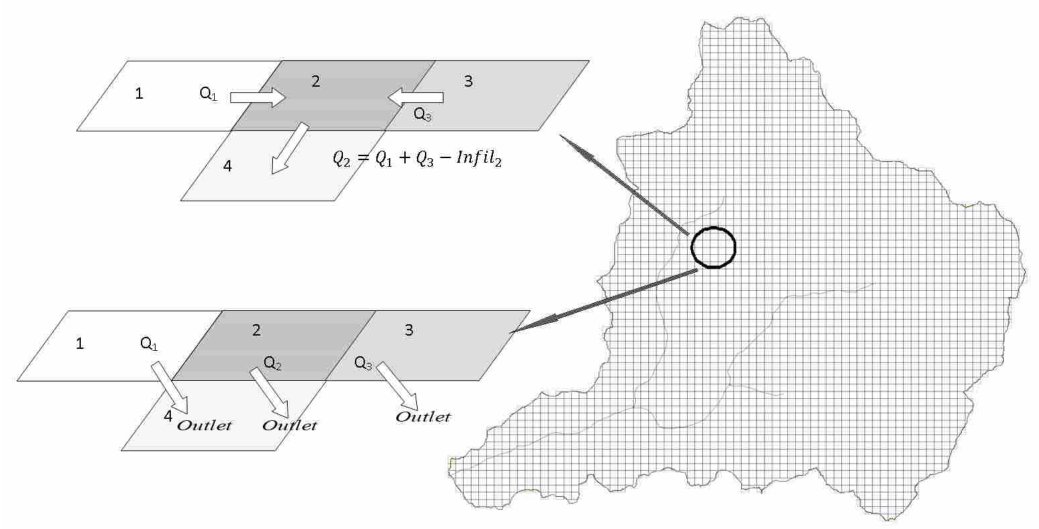


Figure 4.1: Illustrating Surface Runoff Transformation in GSSHA (top left) and HEC-HMS ModClark (lower left) Method

The ModClark model is the only semi-distributed hydrologic model available in HEC-HMS. It uses a gridded basin approach similar to GSSHA to calculate surface runoff. As seen in 4.1, the ModClark model does not flow from one cell to the next. Rather, the excess rainfall computed at each grid cell is transformed empirically to the outlet using the Clark Unit Hydrograph approach (Clark, 1945). Clark's method transfers the surface runoff by lagging the flow based upon the travel distance from each grid cell to the outlet, and it routes the resulting hydrograph through a linear hydrograph to achieve an attenuation effect (for further detail on ModClark method see Chapter 3) (Paudel *et al.*, 2009). Although the ModClark model is capable of capturing the spatial heterogeneity in the infiltration, evapo-transpiration, and rainfall processes, it loses the distributive nature in surface runoff transformation. Another issue that makes ModClark different from GSSHA is that there is no stream network representation.

So, we may define GSSHA to be a physically based distributed model while ModClark is an empirically based semi-distributed model as far as the surface runoff transformation is concerned.

4.3 Problem Definition

Analysis of the effects of changed land use in watershed response to a rainfall event has been one of the major concerns in the construction industry (Calder, 1993). Existing waterways, culverts, or bridge crossings may not be sufficient to pass increased flow safely to the stream because of urbanization. In order to assess and determine such hydrologic and hydraulic concerns, suitable hydrologic modeling tools are necessary. The current study is carried out with two primary objectives. The first is to compare watershed simulations that use two different modeling philosophies (lumped and distributed) by employing the tools developed by the USACE: GSSHA and HEC-HMS. The second purpose is to examine the differences in results when different surface runoff transformations are used. The same scenarios are simulated with GSSHA and ModClark method in HEC-HMS and the variation in watershed response are evaluated.

The first part compares how a distributed model like GSSHA gives different results and if it can efficiently model the land use change scenario over a lumped model in HEC-HMS. The number of experimental variables has been minimized by using similar precipitation (SCS Type II 24-hour distribution) and infiltration methods (Green and Ampt) in both HEC-HMS and GSSHA. The Green and Ampt infiltration equation in HEC-HMS is used in a lumped fashion such that the entire watershed is represented by a single set of infiltration parameters. Similarly, in GSSHA, the Green and Ampt equation is scaled down to grid-cell level, allowing for varying infiltration parameters for each cell. The surface runoff method is another distinction between the two model categories being examined. The lumped model with HEC-HMS uses the conceptual Clark Unit Hydrograph method, and the distributed model with GSSHA uses a cell-to-cell 2D diffusive wave technique. Both of these differences enable the GSSHA model to be sensitive to the spatial location of the changed land use.

On the other hand, the second part addresses the fact that the distributed modeling approach has to be implemented consistently across all simulated hydrologic processes to effectively model such scenarios and to validate that GSSHA actually does model all these scenarios. It is done by analyzing the results from the HEC-HMS ModClark model, which uses a distributed approach in defining precipitation and infiltration/loss methods but transforms the surface runoff conceptually, and by comparing the excess to the GSSHA results. The current publicly available version of HEC-HMS does not include the gridded Green and Ampt model, which makes a direct comparison with GSSHA impossible, but comparing the observations made from these two classes of models holds merit in accomplishing the objectives of this research.

4.4 Methodology

Geospatial information for a watershed is valuable for parameterization of any hydrologic model, including both GSSHA and HEC-HMS. These data, including digital elevation models (DEMs), land use, and soils are available in common GIS data format (Hartman and Nelson, 2001). DEMs were used to delineate the watershed area as well as to calculate slope, flow path distances, aspect, and other related watershed parameters. Similarly, land use and soil information were used to identify the spatial variation of infiltration, storage and runoff behavior. In this study, the Green and Ampt method is used to simulate the infiltration processes because it is available in both models. Rainfall depth and duration is the driving input and essential for any surface runoff model. For lumped models in HEC-HMS, an averaged value of all such parameters was used. However, for distributed models like GSSHA, the variations of these parameters over the watershed were evaluated. As previously stated, the purpose of this research is not to compare GSSHA and HEC HMS but to compare the lumped and distributed approaches with respect to modeling land use change scenarios. In that light HMS is used in a fully-lumped fashion, which is not necessarily the most accurate way to apply the model to these test cases. In this research a synthetic and an actual watershed are used as test cases.

4.4.1 Test Cases

Synthetic Watershed

A rectangular watershed in the form of an open book (Figure 4.2) was created for the synthetic watershed. The drainage area is 13.73 km^2 (5.3 sq miles) and the two planes with an average slope of 4% drain to a stream located at the middle of the watershed. The outlet is on the left side of the basin with the stream flowing from right to left. This being a completely synthetic watershed, there is neither precipitation nor observed flow records for any of the pre- or post- development scenarios. The purpose of using a synthetic watershed is to isolate the effect of land use change from natural heterogeneities that may affect model results.

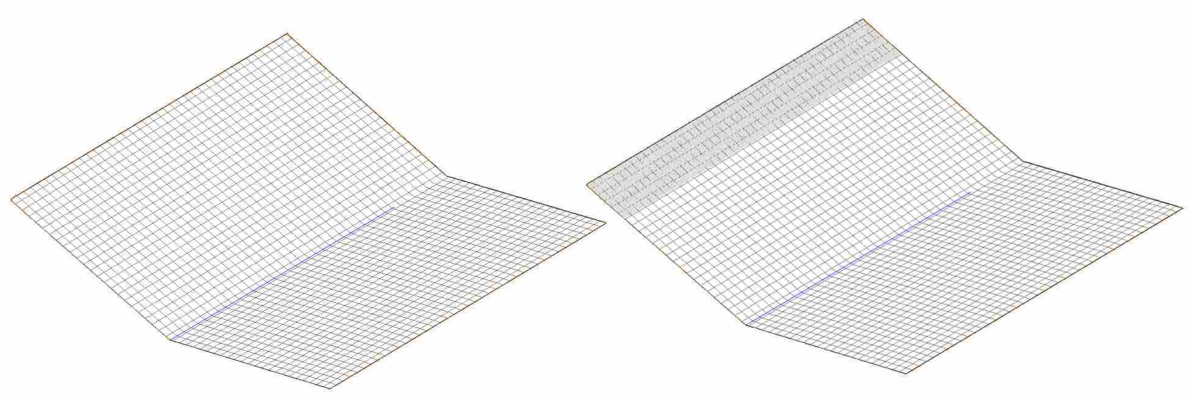


Figure 4.2: Synthetic Watershed with GSSHA Grids Showing Base Land Use (Left) and Changed Land Use (Right)

The soil was assumed as a homogeneous clay loam. The land use in the pre-development scenario was assumed cropland. In both HEC-HMS and GSSHA, the Green and Ampt model was used for estimating infiltration. Similarly, the Clark unit hydrograph was used in HEC-HMS to transform the rainfall excess to a runoff hydrograph. For GSSHA, the watershed was discretized into 50m-grid cells. Using these underlying assumptions, a model was parameterized for both HEC-HMS and GSSHA and was run as the base model or pre-development scenario, termed hereafter as LU_{Base}.

Since there was no observed flow, the HEC-HMS LU_{Base} model was calibrated to the GSSHA LU_{Base} peak flow and the runoff volume so that the post-development scenarios could be better compared against the same LU_{Base}.

The post-development scenarios were created by changing a portion (11%) of the watershed land use to residential (assumed impervious). Different spatial locations of the simulated impervious land use were selected based on the following conditions:

- Distance from the stream
- Distance from the watershed outlet
- Direct connection to the stream

While several scenarios were examined, three of the most representative are discussed here. As shown in Figure 4.3, LU$_{Top}$ represents land use changes at a location where the impervious area is as far from the stream and outlet as possible and completely disconnected.

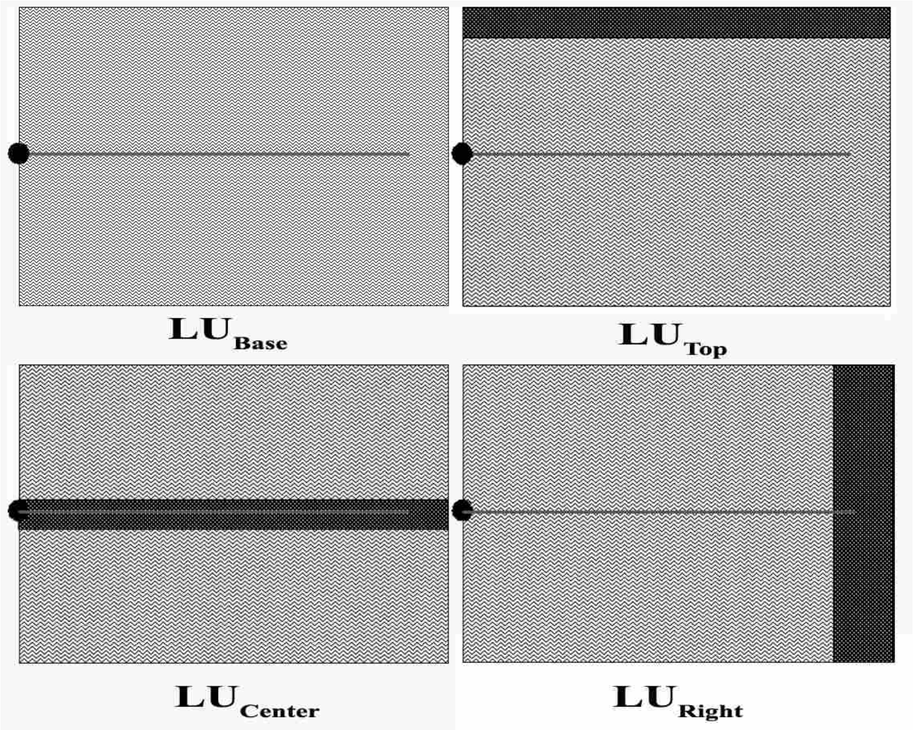


Figure 4.3: Different Post-development Scenarios

For the LU$_{Center}$ scenario, the impervious area is in close proximity to the stream and outlet, and it is directly connected. In the LU$_{Right}$ scenario, the impervious area is the furthest from the watershed outlet, but there is direct connectivity to the stream. For a lumped model like HEC-HMS, each of these three scenarios is represented by adjusting the percentage (11%) of the area of watershed that is impervious.

After all these scenarios are simulated, another set of tests using the ModClark method was carried out. As already explained, this test is intended to highlight the importance of distributed surface runoff transformation. Since a gridded Green and Ampt infiltration model is not available in the current version of HEC-HMS, a gridded curve number method was used. In the ModClark model, the same precipitation was input, the gridded CN was used for the loss method, and ModClark transformation was used for the surface runoff transformation. After simulating the base case, the land use was changed as described in a previous section, and an updated CN grid was generated. The process was repeated for each scenario. Updating the CN grid this way permits the representation of the location of change in land use, even if the actual methods for computing runoff are different than what was used for the lumped HEC-HMS and GSSHA models.

While the results from ModClark models are not compared number-to-number with the GSSHA results, the relative differences in peak and runoff volume between the base case and post-development scenarios can be analyzed. The ModClark simulation was carried out only with the synthetic watershed.

Tifton Watershed

Tifton is a 113.96 km^2 (44 sq miles) watershed (Figure 4.4) located near Interstate 70 east of Albany, Georgia. The Tifton watershed is used to verify the observations made in the synthetic watershed. Different hypothetical land development scenarios were analyzed by varying the location and extent of the changed land use in a way analogous to the synthetic watershed.

While developing the base model (pre-development), three rain gauges with precipitation data (non-synthetic) are used. Similarly, the stream gauge records are obtained from the station located at the watershed outlet. Tifton has four different soil textures (fine sandy loam, loamy sand, sand, and sandy loam), but the majority of the area is loamy sand. The dominant watershed coverage is cropland and pasture with a significant amount of evergreen forest and forested wetland. The spatial data sets used for the research were obtained from the EPA WebGIS data server (EPA, 2009) and NRCS SSURGO soil data mart (USGS, 2009b). The rainfall and observed flow data were obtained from the Agricultural Research Service website (ARS, 2008).

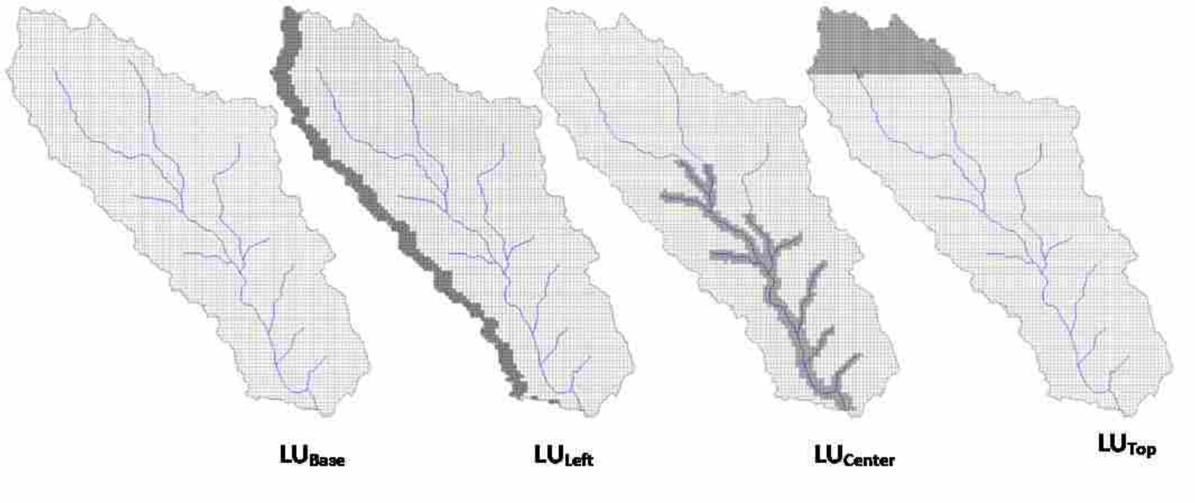


Figure 4.4: Tifton Watershed with GSSHA Grid Showing Base Case and Changed Land Uses

The Tifton base model was parameterized based upon available geo-spatial information from the soil, land use, and terrain data. The land cover was then changed to create three post-development scenarios that resembled what was done with the synthetic watershed. Developed land use covered approximately 11% of the total watershed area. The watersheds shown in 4.4 are intended to represent the LU_{Left}, LU_{Center}, and LU_{Top} cases from the synthetic watershed example where the impervious areas are shaded. These post-development scenarios are purely artificial and do not have observed flow records.

Before simulating the various post-development scenarios, both HEC-HMS and GSSHA models were calibrated to the observed flows in the base case. The calibration was done in order to have similar (if not the same) base case to compare the hypothetical post-development scenarios in both HEC-HMS and GSSHA. The calibrated models were then used to simulate scenarios analogous to the synthetic watershed.

4.5 Results and Discussion

4.5.1 GSSHA and HEC-HMS Lumped Model Comparisons

Runoff Volume Comparison in Synthetic Watershed

One of the significant watershed response indicators is the runoff volume from different scenarios. For LU_{Base}, both HEC-HMS and GSSHA have almost the same runoff volume. Because HEC-HMS is being used in the lumped-parameter mode, all three post-development scenarios LU_{Top}, LU_{Center}, and LU_{Right} produce the same results, and can be represented by LU_{Post}. For HEC-HMS models, the post-development scenario results in 218% greater discharge volume.

Volumes of runoff from the GSSHA models are sensitive to the relative position of the new land use (Table 4.1 and Figure 4.5). When the impervious area is closer to the stream, the runoff volume is high as compared to the other cases (Figure 4.5).

Peak Flow Comparison in Synthetic Watershed

For the HEC-HMS model, the peak flow for the developed case, 13.8 cms, was twice the peak flow from the pre-developed case, 6.9 cms (Table 4.2, Figure 4.6).

As shown in Figure 4.7, GSSHA produces a different response for each different development scenario. The spatial location of the changed land use affects the peak flow as is intuitively expected. The peak flow increased by up to 79.9% (Table 4.2) with the highest increase in peak flow occurring in the LU_{Center} simulation, which is best compared to the LUpost simulation with HEC-HMS (directly connected to the stream). The models

Table 4.1: Runoff Volume Comparison at Different Scenario for Synthetic Watershed

Model	Scenario	Volume (m^3)	% difference
GSSHA	LU_{Base}	41938	—
	LU_{Top}	57974	38
	LU_{Center}	109780	162
	LU_{Right}	91278	118
HMS	LU_{Base}	41938	—
	LU_{Post}	133216	218

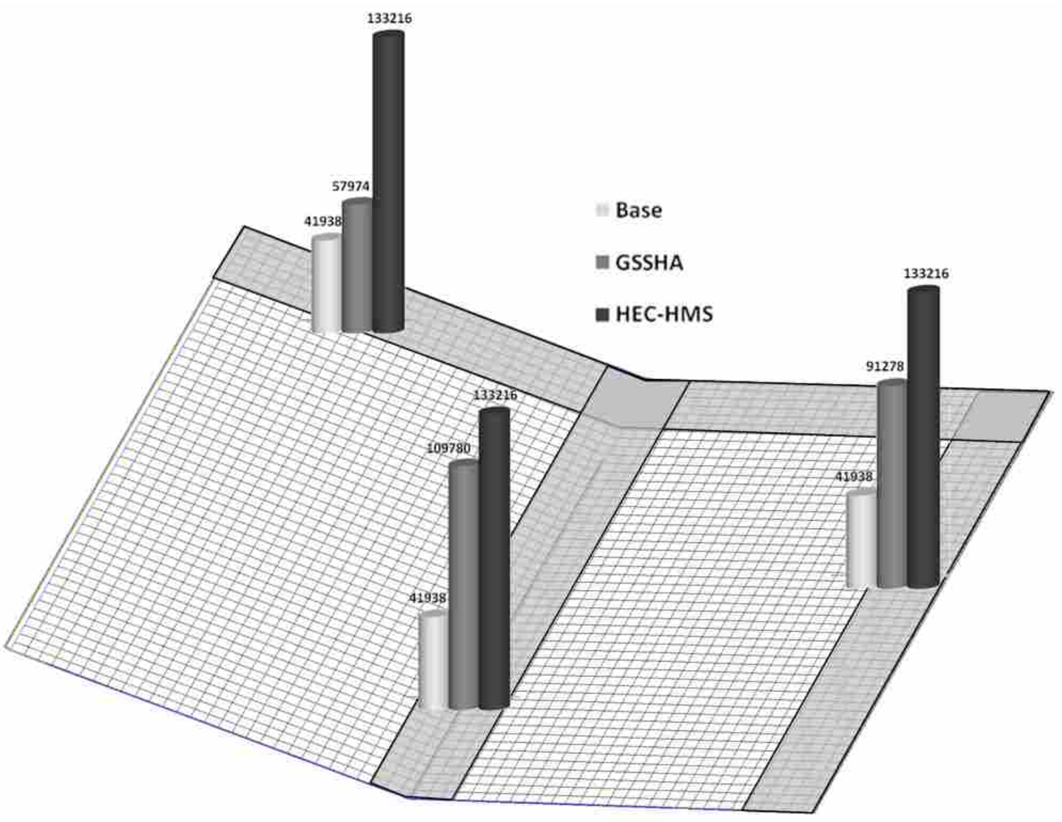


Figure 4.5: Runoff Volume (m^3) Comparison in HEC-HMS and GSSHA Models at Different Scenario

do not produce the same peak runoff because of the way these two models perform the hydrologic computations and transform the rainfall excess to the watershed outlet. In addition, whereas GSSHA calculates the runoff from the impervious area differently from the rest of the watershed area, HEC-HMS reduces the total runoff by the percent-impervious area.

Table 4.2: Peak Flow Comparison at Different Scenario for Synthetic Watershed

Model	Scenario	Peak Flow (cms)	% difference
GSSHA	LU_{Base}	6.8	—
	LU_{Top}	10.9	60.0
	LU_{Center}	12.2	79.9
	LU_{Right}	10.4	53.9
HMS	LU_{Base}	6.9	—
	LU_{Post}	13.8	100.0

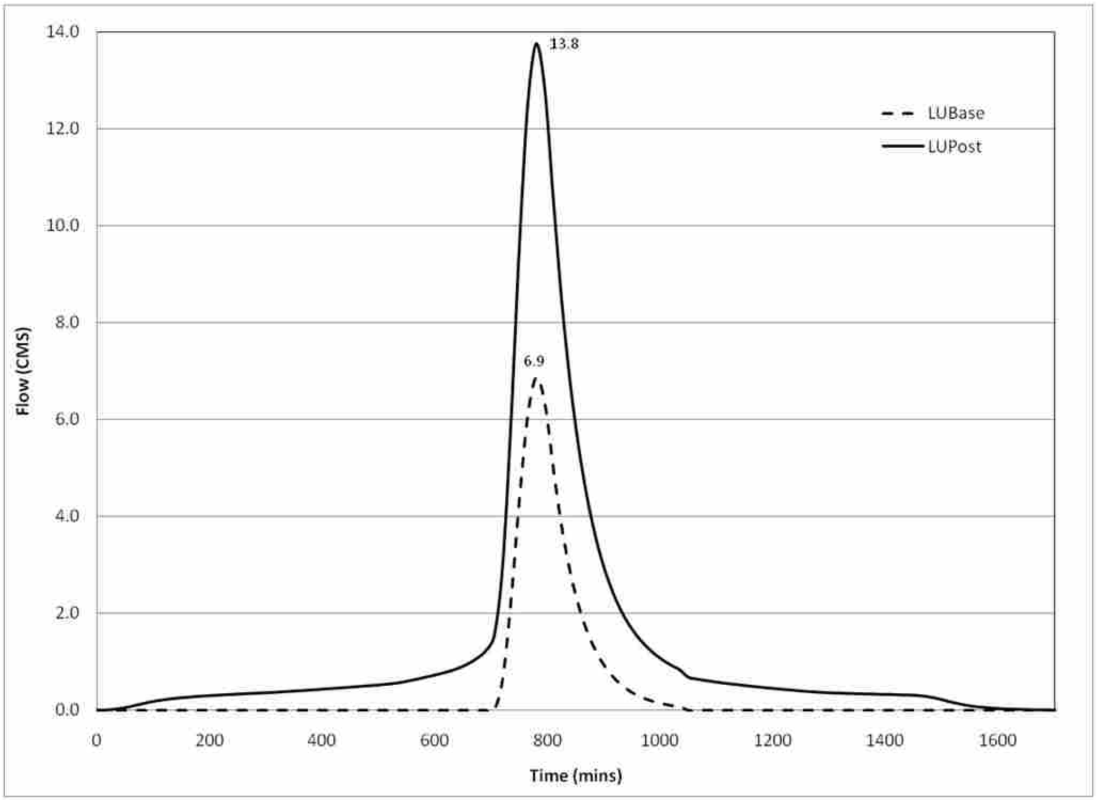


Figure 4.6: Outflow Hydrograph from the Pre and Post-development Scenario (HMS Models) in the Synthetic Watershed

The comparison in the peak flow between GSSHA and HEC-HMS results is shown in Figure 4.8.

The differences in the peak flow arise as a result of the way GSSHA represents the watershed as a collection of numerous grid cells for which all hydrologic computations are carried out. Similarly, the rainfall excess from one cell is routed to one or more of the four adjacent cells. As a result, any change in the watershed characteristics in any of the grid cells results in an overall change in the response of the watershed. Thus, the flow path is important. The location of the cell(s) at which the change in land use occurs also results in the change in watershed response. Because of this, the scenarios LU_{Top}, LU_{Center}, and LU_{Right} have different peaks as well as different runoff volumes. In general, the results from GSSHA seem intuitively realistic. The watershed response changes the way as one might expect it to.

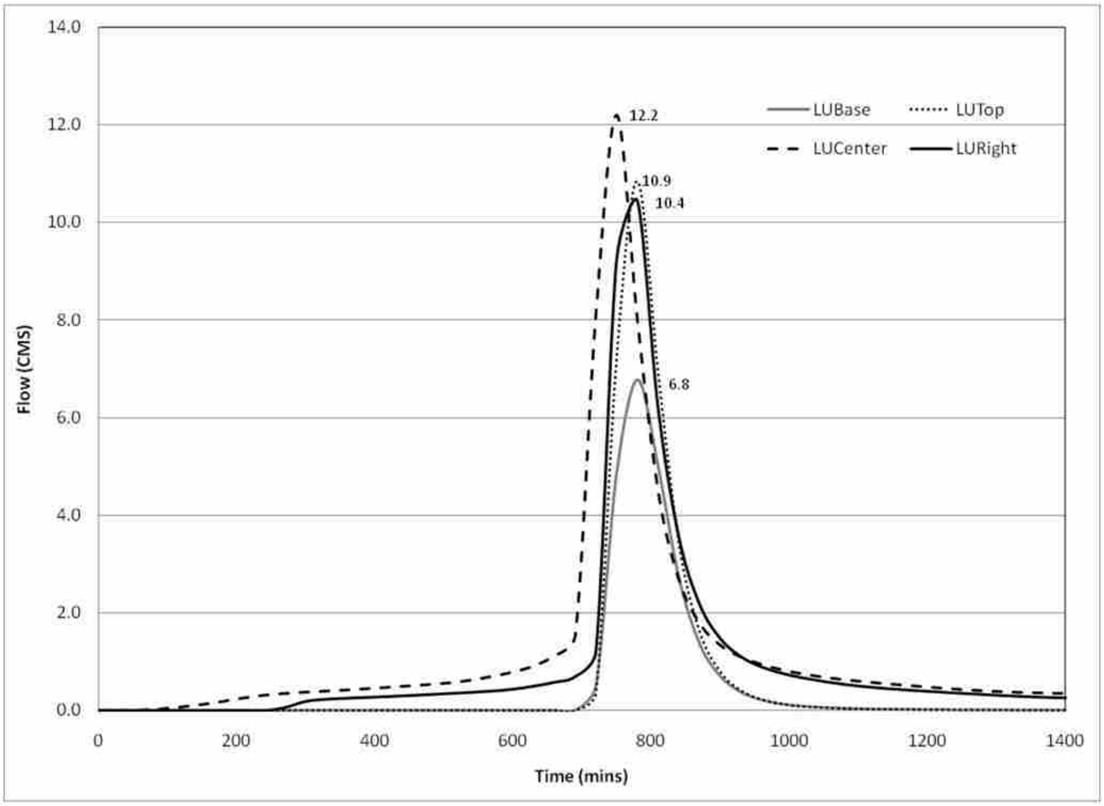


Figure 4.7: GSSHA Models Outflow Comparison at Different Scenario for Synthetic Watershed

Runoff Volume Comparison in Tifton Watershed

Using the synthetic watershed, it was observed that the GSSHA response varied for the different scenarios and that the variation was intuitively correct. In an attempt to validate these observations, the simulation results from the Tifton watershed are presented. In contrast to the synthetic watershed, Tifton has a natural heterogeneity with highly varying terrain slope, land use, and soil types. The watershed shape and streams further influence watershed response. This heterogeneity makes it more difficult to isolate the effects of changing land use on a system response when compared to the synthetic watershed.

Figure 4.9 shows the pre-development scenario (LU_{Base}), in which the base models are calibrated to approximately match the observed flow.

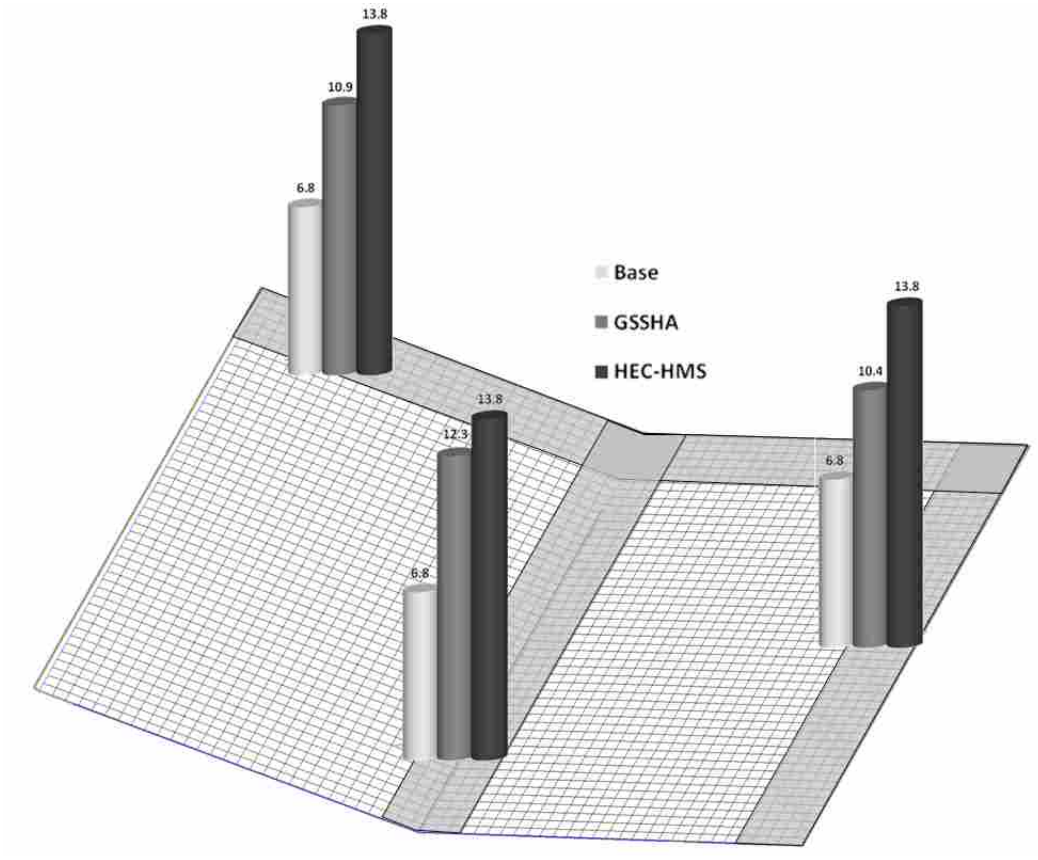


Figure 4.8: Peak Flow (cms) Comparison in HEC-HMS and GSSHA Models at Different Scenario in the Synthetic Watershed

The simulation of the post-development scenario in HEC-HMS for an 11% increase in impervious land use (LU_{Post}) resulted in the increase of the runoff volume by 89% of the pre-development scenario (Table 4.3 and Figure 4.10).

With GSSHA, the volumes are different for each scenario. The maximum runoff volume was produced by the model in which the impervious area was closer to the stream and directly connected. The relative increase in the runoff volume between the base case and the case that produced maximum runoff volume was 124%.

Peak Flow Comparison in Tifton Watershed

The peak flows from the HEC-HMS models are shown in Table 4.4 and Figure 4.11. The smaller hydrograph represents the flow in the HEC-HMS base model (LU_{Base}) in

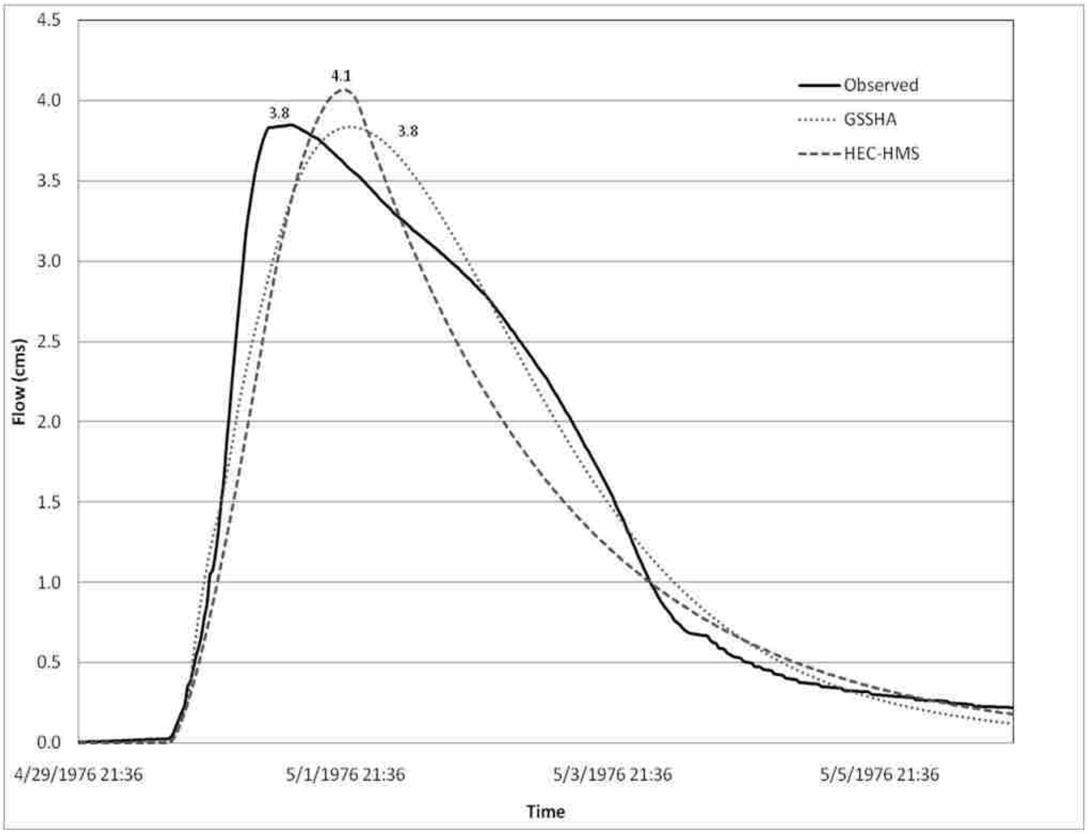


Figure 4.9: Comparison of Observed Flow and Calibration Results from GSSHA and HEC-HMS for Tifton

Figure 4.11. With the introduction of impervious land use, the peak flow increased from 4.04 cms to 7.37 cms.

The results (Figure 4.12) show that GSSHA simulates the peak flows in different scenarios as would be intuitively expected, even with such heterogeneity in a complex real-world problem. These results are similar to those observed with the synthetic watershed

Table 4.3: Runoff Volume Comparison at Different Scenario for Tifton Watershed

Model	Scenario	Volume (m^3)	% difference
GSSHA	LU_{Base}	900107	—
	LU_{Top}	1610856	67.2
	LU_{Center}	2015220	123.9
	LU_{Right}	1504935	79.0
HMS	LU_{Base}	817305	—
	LU_{Post}	1545306	89.1

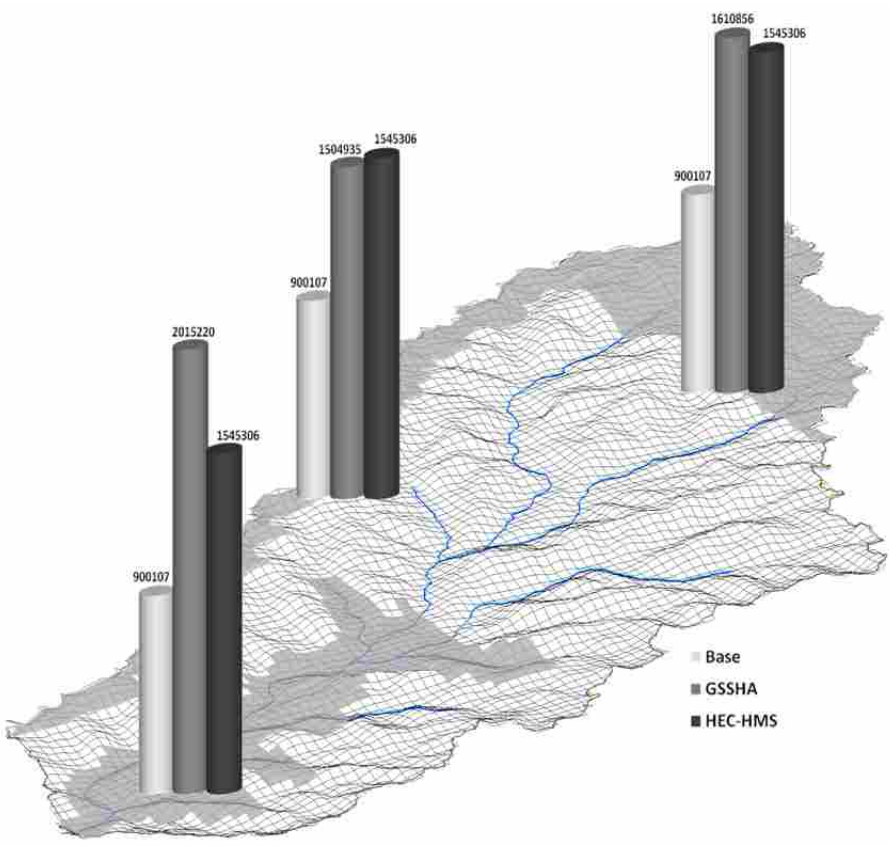


Figure 4.10: Runoff Volume (m^3) Comparison in HEC-HMS and GSSHA Models at Different Scenario for Tifton Watershed

because both the peak and runoff volume increased in the post-development scenario. The relative difference in the peak flow and runoff volume in the Tifton model is similar to that in the synthetic model because LU$_{Center}$ resulted in both a higher peak and a higher runoff volume as compared to other post-development scenarios in both watersheds. Even though the Tifton model has greater complexity and heterogeneity than the synthetic case,

Table 4.4: Peak Flow Comparison at Different Scenario for Tifton Watershed

Model	Scenario	Peak Flow (cms)	% difference
GSSHA	LU$_{Base}$	3.84	—
	LU$_{Top}$	5.87	52.9
	LU$_{Center}$	9.38	144.3
	LU$_{Right}$	5.58	45.3
HMS	LU$_{Base}$	4.04	—
	LU$_{Post}$	7.37	82.4

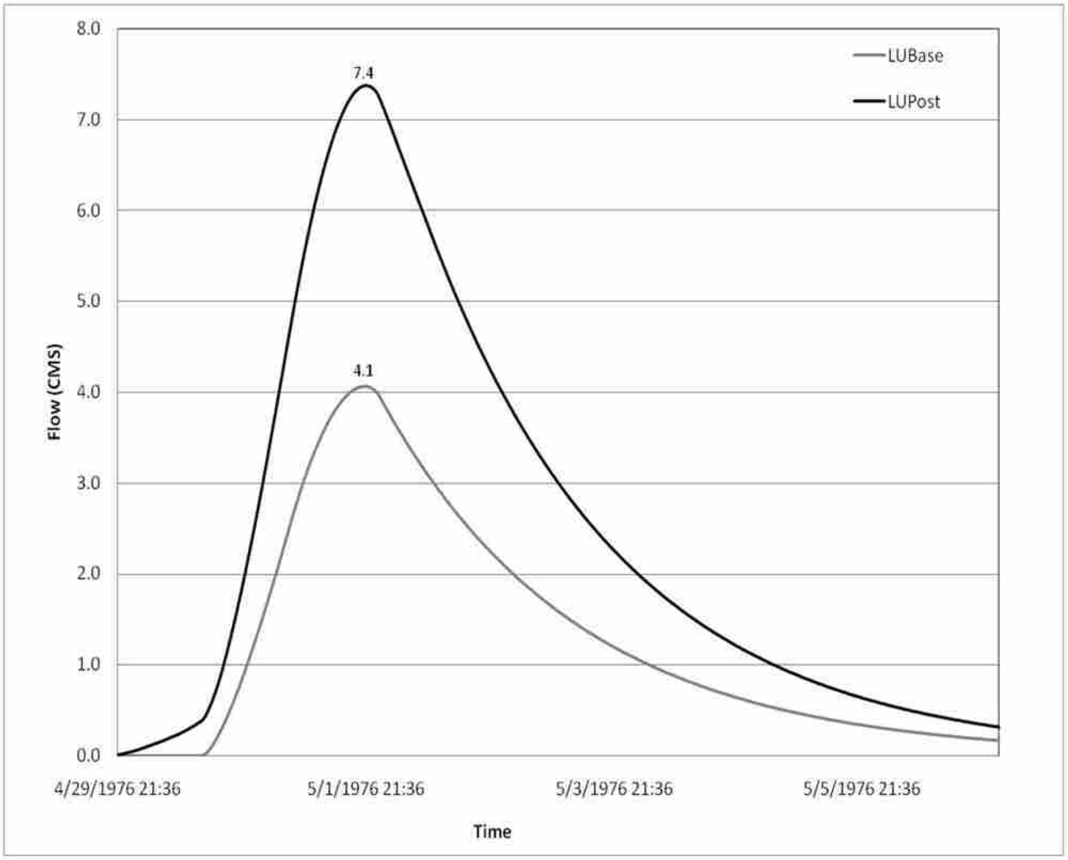


Figure 4.11: HEC-HMS Models Outflow Comparison in Tifton Watershed

the results from GSSHA indicate that the distributed modeling approach can realistically analyze complicated watershed features because of its ability to explicitly include spatial differences.

4.5.2 GSSHA and ModClark Models Conceptual Comparisons

The results (Figure 4.13) show that GSSHA simulates the peak flows from different scenarios as would be intuitively expected, even with such heterogeneity in a complex real world problem. These results are similar to what was observed with the synthetic watershed because both the peak and runoff volume increased in the post-development scenario. The relative difference in the peak flow and runoff volume in the Tifton model is similar to that in the synthetic model because LU_{Center} resulted in higher peak as well as higher runoff volume as compared to other post-development scenarios in both

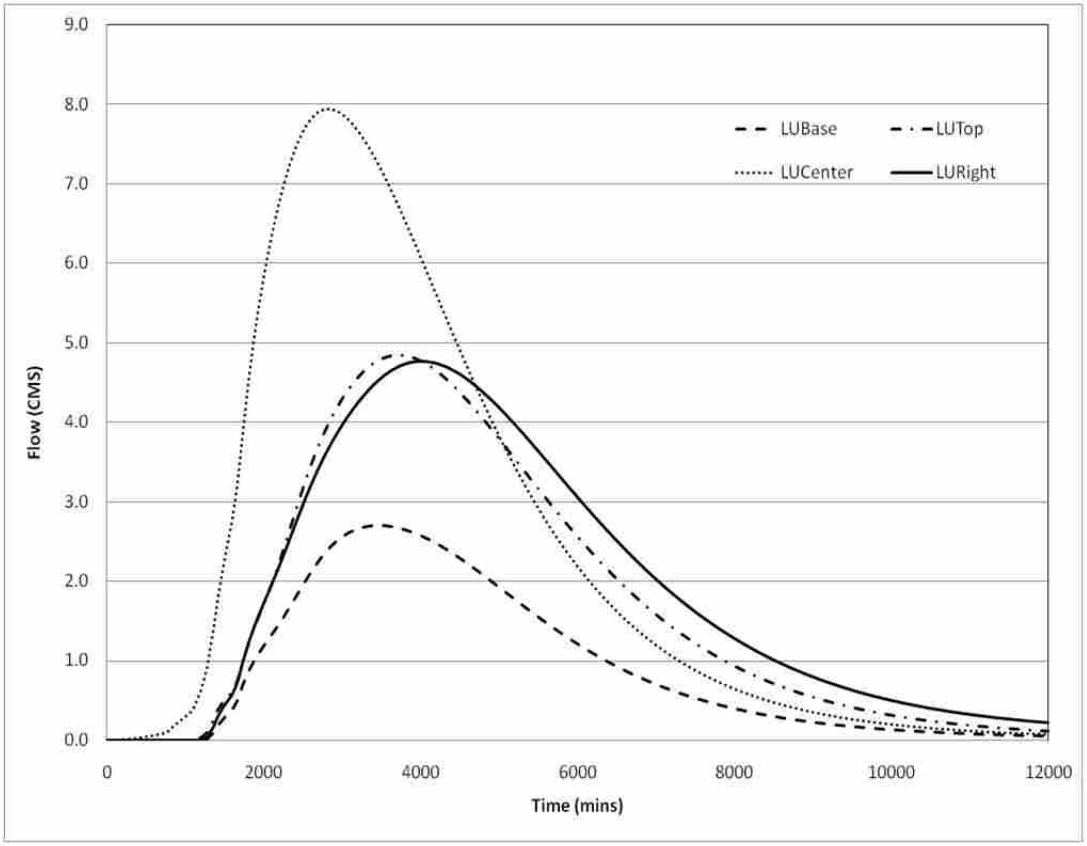


Figure 4.12: GSSHA Models Outflow Comparison in Tifton Watershed

watersheds. Even though the Tifton model has greater complexity and heterogeneity than the synthetic case, the results from GSSHA indicate that the distributed modeling approach can realistically analyze complicated watershed features because of ability of GSSHA to explicitly include spatial differences.

4.5.3 GSSHA and ModClark Models Comparisons

The simulation results of the experiment on the synthetic watershed by using ModClark methods are presented below. The peak flow and runoff volumes are discussed first, and their comparison with the observations made from GSSHA models will be discussed afterwards.

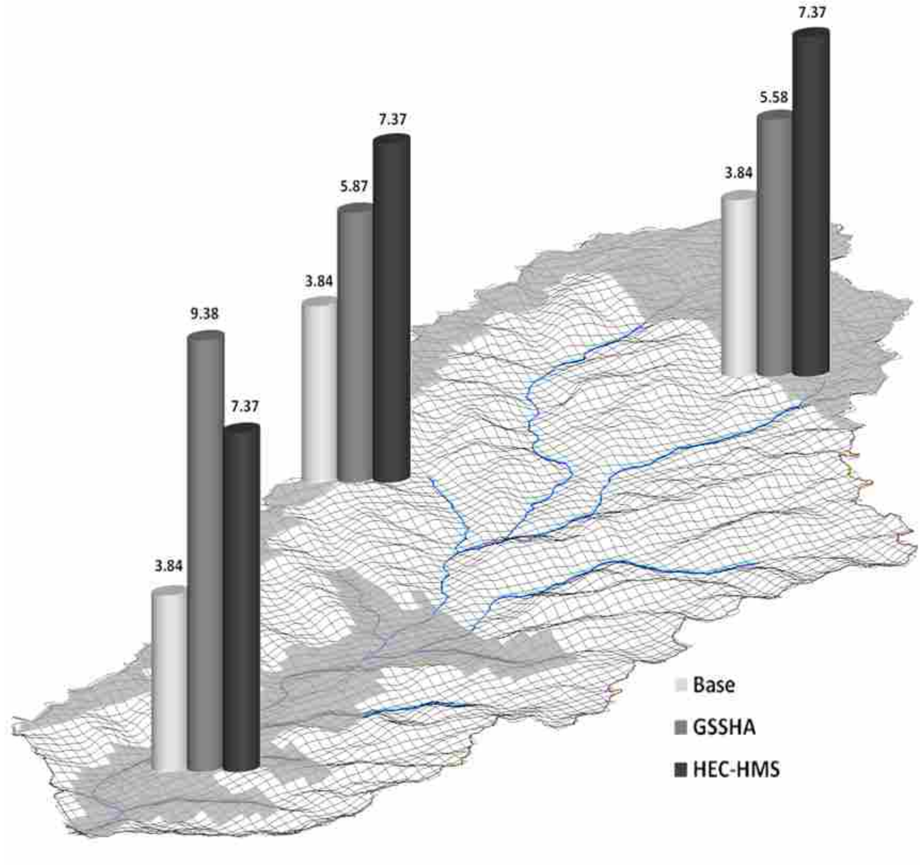


Figure 4.13: Peak Flow (cms) Comparison in HEC-HMS and GSSHA Models at Different Scenarios for Tifton Watershed

Peak Flow Comparison in Synthetic Watershed (ModClark)

Figure 4.14 shows the variation in peak in different scenarios. The model results for base case has peak flow of 3.24 cms. Once the land use is changed, the peak flow increases considerably. As intuitively expected, the peak flows are different for different scenarios. Peak flow with LU_{Top} is 5.61 cms, with LU_{Center} is 5.25 cms and with LU_{Right} is 5.48 cms (Figure 4.14). It is obvious that changing a portion of land to a relatively impervious area means reducing the infiltration from that portion, which results in an increased amount of surface runoff. The Peak flow is sensitive to the location of the cells with such increased surface runoff. Because of the fact that the peak flow simulation in the ModClark model accounts for time of travel from each cell to the outlet, the location of change in land use makes a difference in peak flow.

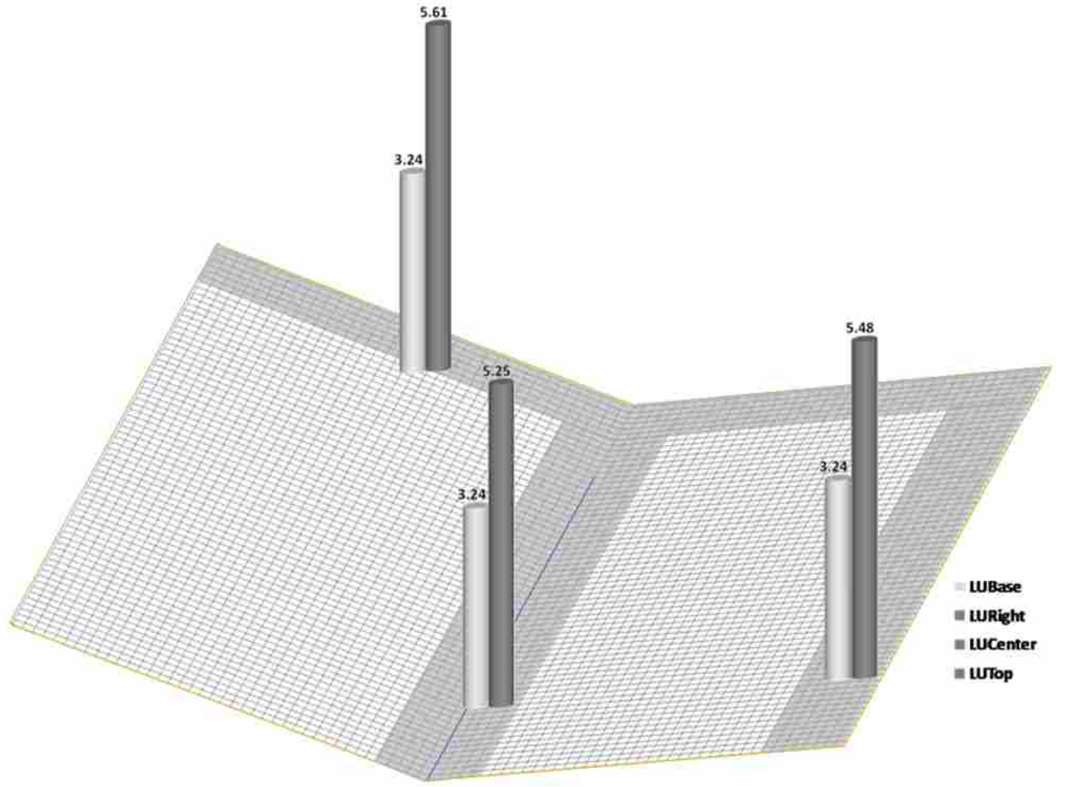


Figure 4.14: ModClark Model Peak Flow (cms) from the Synthetic Watershed

The runoff volume is another parameter to describe the watershed response. Figure 4.15 shows the runoff volumes from the scenarios. The base model (LU_{Base}) has 158,996 m^3 of runoff volume. When the impervious area is inserted in the rest of the scenarios, the volume increases considerably. Unlike the peak flows, runoff volume from all the post-development scenarios remains constant. There are two basic reasons that cause the volume to be constant. As already stated, the ModClark model allows the precipitation and infiltration to vary spatially within each grid cell, but the surface runoff from one cell does not flow to another cell; rather, it is directly transferred to the watershed outlet. So the first reason is that the total number of cells that are converted to impervious is the same in each scenario. The second is that the runoff from the cells is not routed to an adjacent cell and allowed to infiltrate there. So the total amount of water that is flowing to the outlet is the same in all the post-development scenarios; only the location inside the watershed that holds that water changes. The peak flow takes the travel time into

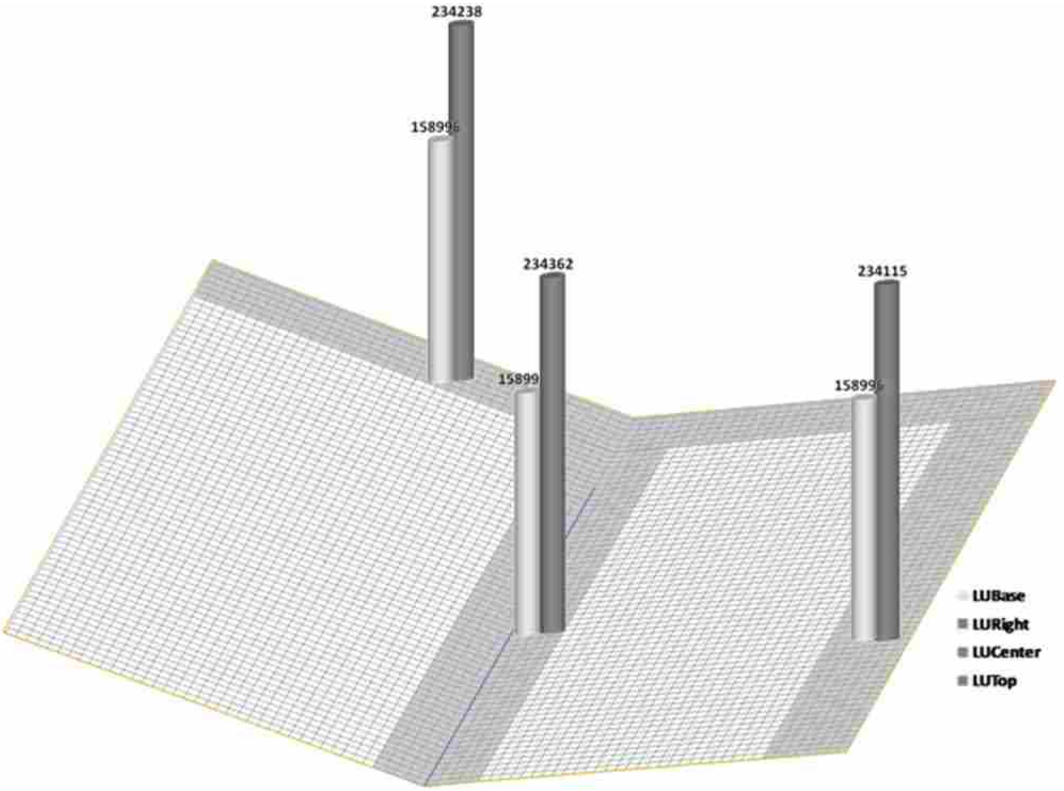


Figure 4.15: ModClark Model Runoff Volume (m^3) from the Synthetic Watershed

consideration, and thus even with the same volume, water reaches the watershed outlet at different times, resulting in varied peak flows.

4.6 Conclusions

This chapter focuses on the study of varied watershed responses from the lumped and distributed modeling approaches while simulating the variations in spatial location of a land use change scenario. The GSSHA model was used to represent the watershed with distributed infiltration and surface runoff characteristics, while the HEC-HMS model was used to represent the watershed with lumped infiltration and conceptual surface runoff characteristics. The main point of this research was to study the variations in peak flow and the runoff volume from different land use change scenarios while using these two model categories. Along with this, the ModClark model with gridded CN was used in the synthetic watershed to emphasize the importance of distributed surface transformation methods. For this purpose the observations made from GSSHA were compared with those from the ModClark models.

A synthetic watershed was used to gain insight into the response of various scenarios, and the outcomes were further tested on an actual heterogeneous watershed in Tifton, Georgia. The results from the Tifton watershed corroborated the results of the synthetic watershed. Owing to the unavailability of observed flow records for the post-development scenarios, the relative accuracies of the results from two models could not be evaluated qualitatively; however, from the relative differences in the results, it is concluded that a distributed model behaves in an intuitively realistic manner as compared to the lumped models. The relative differences in the results from different scenarios have been presented. The following are the specific findings of this research:

1. The spatial location of the changed land use is quite sensitive, as observed from the lumped and distributed model results. The observations are summarized as the following:

    - In the lumped approach, runoff volume and peak flow are the same for each of the post-development scenarios because the amount of impervious area is the same in each case and the approach does not lend itself to analysis of varying spatial positions of the altered land use.
    - In the distributed modeling approach with GSSHA, both peak flow and runoff volume vary when the land use is changed at different locations. This is because in this approach the infiltration/losses are calculated in each grid cell at each time step, and the transformation is done by routing from cell to cell, which makes the peak flow as well as the runoff volume computation dependent on both the amount and the location of the impervious area.
    - If the ModClark model is used, which allows for the distributed precipitation and infiltration but does not have distributed surface runoff transformation, it results in varied peak flow while it fails to catch the variation in the amount of surface runoff.

2. In the real-world watershed, the relative positioning of the impervious area with respect to the stream and watershed outlet holds prime importance. While simulating such a scenario with the distributed model (GSSHA), the following was observed:
    - When the impervious area is both closer to and connected to the stream, increases in both peak discharge and runoff volume occur (LU_{Center} and LU_{Top}).
    - Similarly, when the impervious area is not connected to the stream, the peak flow increases but the runoff volume might not increase significantly. This is because if the impervious area is not connected to the stream, then the flow from such areas has to pass through the relatively pervious areas where it can be captured as infiltration before reaching the stream ($LU_{Left/Right}$).
3. The capability of the distributed model (GSSHA) with suitable grid resolution to locate the position of change in land use is verified. The following observations were made:
    - With the lumped model, while it is possible to represent that a certain percentage of the watershed has been converted to an impervious area, the location of where that change occurred cannot be distinguished and is always represented as if it is directly connected to the stream. Further, if the land use changed such that it is not impervious, but the rate of infiltration is reduced (e.g. wet lands), then it is difficult to represent this case in a lumped model because of the difficulty in adjusting calibrated parameter values.
    - With an empirically-distributed model like HEC-HMS ModClark, it is possible to incorporate the spatial variation in the precipitation as well as infiltration/loss methods. But it lacks the distributed surface transformation which makes it less efficient compared to the physically based distributed models like GSSHA, but it is still better than lumped models.
    - With the distributed modeling approach it is possible to represent both the area and location of the changed land use. This enables better simulation of "what if" analysis of the watershed, which is important for analyzing design alternatives.

> With a lack of observed flow records for post-development scenarios, we could not qualitatively verify that the results from distributed model are accurate when compared to the lumped model results. Moreover, it is verified that the distributed model is sensitive to the spatial location of land use changes and that it provides results that are closer to what is intuitively expected. This demonstrates that the distributed modeling approach may have advantages over the lumped modeling approach for analyzing the hydrologic response to land use change.

Lumped-parameter models are often chosen because of their simplicity in model development and parameterization effort. However, because of the limitations inherent in the formulation of these simpler models, this research indicates that they are insensitive to changes in the landscape that intuitively would produce different results; therefore, they may not be ideally suited to simulate some complex problems such as the spatial location of land use change scenarios. This research also indicates that distributed models, while relatively more complex to develop, calibrate, and run, are more sensitive to the location of spatial heterogeneity and therefore may have the capability to solve advanced hydrologic problems where the spatial location of different processes is critical.

A comparison of the simulated results with empirical flow data (upon availability) for post-development scenarios would be one of the future scopes of this research. In this research test watersheds were simulated as either fully lumped or fully distributed using two USACE modeling tools. However, many models, including the ones employed in this study, allow varying representations of the watershed in terms of its complexity and its sub division. Another area of future research would be to investigate how the complexity and sub division of watersheds affects the model response to land use change or similar scenarios. This study compares the results from a distributed and a lumped model in analyzing the effects of land use change, which is one of several applications where a distributed model like GSSHA might be advantageous over the lumped models. Further study can be conducted on exploring the differences in the performance of such models in analyzing other complex hydrologic issues.

CHAPTER 5. INVESTIGATING THE PARAMETERIZATION ISSUES IN GSSHA MODELING

5.1 Abstract

As discussed previously, distributed hydrologic models have not been used frequently in practice despite their capabilities to solve complex hydrologic problems. There is much in the literature that explain that such models are complex to develop as compared to the lumped models. This chapter the identifies issues that make a distributed modeling difficult to develop. GSSHA is used to identify issues that an engineer with a fundamental background in hydrologic modeling faces while developing distributed models. GSSHA models are developed in WMS using publicly available geospatial data. The model formation process was broken down into several sequential steps, and prominent issues with each of the steps were studied. One of the important results of this research has been the evolution of an efficient hydrologic modeling wizard now implemented in WMS. This wizard provides a step-by-step guide through basic steps of creating a model in GSSHA while still allowing the user to adapt the workflow to the problem at hand.

Distributed models by their very nature require much input data, and it is cumbersome to enter such data manually into the program. Most of the infiltration parameters are derived from the land use and soil data pattern of the watershed. A spreadsheet macro was developed (and later implemented into WMS) that processes the SSURGO soil data to extract important infiltration parameters. This helped in simplifying as well as expediting the initial model parameterization process.

Similarly, while defining the GSSHA 1-D channel model with stream arcs, some inconsistency in the workflow was identified that resulted in erroneous grid-stream interaction in some cases. The workflow was modified and an alternative algorithm was

proposed to solve this issue. It is expected that the findings of this research have improved GSSHA model development with WMS.

5.2 Introduction

Because of rigorous data and computational requirements, distributed models have not enjoyed widespread usage. As a result, few published studies discuss such models as SHE (Abbott *et al.*, 1986a,b), CASC2D (Julien *et al.*, 1995), and r.water.fea (Vieux and Gauer, 1994). As a result of evolving computational capacity and availability of the geospatial datasets that can be readily used in parameterizing the models, development and testing of distributed models have become easier. The importance of using distributed models has been well understood as such models are advantageous, not only for better flow simulation at basin outlets, but also for providing flow simulation at interior locations. Distributed models can become a better foundation of other environmental models, such as for water quality, sediment transport, land use change scenario modeling, wetland restoration, irrigation improvement, and cases where spatial variability in physical processes are critical. These environmental models provide information for decision-making in water resources planning and management.

Along with the increased development and use of distributed models, several new issues are emerging. Moreda *et al.* (2006) list the following major challenges:

1. Proper spatial and temporal resolutions of distributed hydrologic modeling must be selected while considering both data availability and resulting in minimal violation of the physical/conceptual assumptions of the model structure.

2. The lack of high space/time resolution model inputs, e.g. it is not worth using a 10m resolution DEM to create a distributed hydrological model if a mean areal precipitation is used.

3. There is a certain level of calibration involved in any model. Estimating, editing, or calibrating such large numbers of distributed model parameters is a severe problem.

4. It is obvious that many basins are still ungauged, and even the gauged ones do not have sufficient data to evaluate the performance of distributed models. Reed *et al.* (2004) showed that in some basins, the lumped models actually outperformed the distributed models in simulating outlet flow. In such cases, there is always a question for a general practicing engineer: "What is the best model to choose in solving a particular problem?"

Intrinsically, it is neither possible nor advisable to have mastery over all the available models, be they lumped or distributed. The same problem can be efficiently solved using different tools for the same input datasets. The model performance not only depends upon its capabilities and available input data, but it is also governed by the modeler's experience with it. For a practicing engineer in the mainstream hydrologic profession, guidelines for proper model application seem to be necessary.

5.2.1 Model Parameterization and Related Issues

Once the model has been selected and the input data collected, model parameterization is a significant hurdle for distributed modeling (Beven, 2001). In principle, the physics-based distributed hydrological models are developed with an intention of using direct measurements of parameters at the level of grid resolution. But because the real-world watershed is highly heterogeneous and the observed/measured data are generally unavailable at the same grid level, parameters of distributed models are often derived from other available data. Brooks and Corey (1964) developed equations that relate the soil properties to infiltration parameters. These soil properties can be used in relationships to estimate Green and Ampt infiltration equation parameters (Rawls *et al.*, 1983). Recently, Christiaens and Feyen (2001) studied the uncertainty of four methods that relate soil properties to physics-based hydrologic model parameters. In their study, they observed a considerable uncertainty for some parameters derived using these methods for the MIKE-SHE model. However, Vieux and Moreda (2003) used the Map Information Assembly and Display System (MIADS), a three-layer composite of data derived from county soil surveys, to estimate parameters of the physics-based model arc.water.fea

(Vieux, 2001). This study concluded that with a minor adjustment to derived parameters the model performances can be considerably improved. Regardless of the magnitude of adjustments made to a priori parameters to obtain improved simulation, the underlying spatially varied parameters are essential components of distributed models.

In general, field data such as geological information from well-logs, pumping test analysis, maps of soil profiles, soil analysis (texture, density, retention curves), and vegetation maps are used to define the spatial patterns of model parameters. The challenge is to formulate a relatively simple model parameterization in order to provide a better and quicker calibration, but at the same time to keep it distributed enough so that the spatial variability of the model parameters are captured (Madsen, 2003). This is an important consideration as the overall model performance, as well as the efficiency of calibration, is governed by the quality of initial parameterization. But from the modeler's perspective, it is always desirable to have a model that requires lesser input. In many situations, the modelers can become discouraged too easily and quit trying to use a distributed model if it is too complex. To facilitate such complex parameterization as well as conceptualization of a distributed model, a GIS-based processing system is an absolute requirement. In general, such GIS-based tools help process the geospatial data from which the model parameters are extracted. For several distributed models, these GIS-based tools automate the parameterization process thus reduce a considerable amount of modeling effort.

The model parameterization and model calibration is an iterative process. If the calibration results in poorly defined parameter values, then the initial model parameters need to be reconsidered and a simpler conceptual model that includes fewer calibration parameters should be defined. On the other hand, if the model cannot properly describe the spatial variability of the watershed and of that available in the observed data, then the major model parameters need to be distributed or other process descriptions in the calibration need to be incorporated (Madsen, 2003).

5.2.2 Distributed Modeling with GSSHA

The USACE's next-generation hydrologic model GSSHA is becoming increasingly popular among the researchers owing to its capability to simulate the hydrologic processes using physics-based equations and as-close-as-possible representation of watershed characteristics. The USACE is working to promote GSSHA as one of the standard practice models in solving complex problems such as sediment and nutrient transport modeling, scenario modeling, flood wave and inundation modeling, and groundwater surface water interaction. WMS can be used to process the geospatial data and extract GSSHA parameters. WMS has a comprehensive user-interface for GSSHA modeling, and these two programs interact with each other providing an efficient modeling framework for pre-processing, modeling, and post-processing or visualization (Nelson, 2006; Wiki, 2009; Downer and Ogden, 2006).

As with other distributed models, GSSHA data requirements are dependent on the problem at hand and on desired model complexity. For a simplistic rainfall runoff simulation model, GSSHA requires at least the Green and Ampt parameters, surface roughness (overland roughness), channel roughness, and initial soil moisture at the grid cell level. Besides that, the topography and watershed information are also necessary. If the watershed heterogeneity increases, the number of these parameters also increases proportionately. This research focuses on the identification of potential issues pertaining to pre-processing of geospatial data, initial model parameterization, model run, and result-visualization while using the WMS-GSSHA interface for developing GSSHA models. GSSHA models can be created using other GIS-based tools as well, but similar capabilities as that of WMS would be needed for such GIS systems to pre-process spatial data for GSSHA, or for distributed models in general. Suitable adjustment, updates and workarounds are suggested to overcome such issues. The following sections discuss these aspects in detail.

GSSHA has enormous potential to be a very effective tool in solving complex hydrologic problems. The facts that GSSHA is new to the industry and that it is still seen as an academic research model limit its widespread usage. It was understood that there are several tools in GSSHA that need to be explored and documented so as to promote its effective use for a wider range of problems.

Another objective of the current research has been to establish the creditability of GSSHA as a better tool for hydrologic modeling, in both practice and in the literature. Developing tools and methodology for pre- and post-processing as well as for parameterizing GSSHA models has been an ongoing process, and this research has made a considerable contribution to it. Identifying the modeling issues, upgrading the workflow, and developing tools and methods to overcome such issues have enhanced the usability of GSSHA.

5.3 Methodology

This section identifies common problems of developing GSSHA models. While these problems are unique to GSSHA, they represent similar issues that would be faced in developing other distributed models from geospatial information. The most important fact to consider while evaluating model usability is the user's familiarity of the model being tested. A general practicing engineer will not be as efficient as the model (software) developer. In addition to the actual problem-solving capability of a model and the user, graphical interface and other programming issues play vital roles in increasing or decreasing the model usability. This research intends to identify some of these issues pertaining to the WMS-GSSHA modeling platform.

5.3.1 Information Collection

GSSHA has not been used or tested in practice as rigorously as other USACE models. It has been typically used as a research model or has been applied to a few specific problems by the Corps of Engineers. Because of this, the literature does not have enough information about the problems that people have faced in the past or are currently facing. In this regard, the literature survey was not successful in assimilating the information or feedback on GSSHA usability. Another approach was implemented to collect information that included personal testing of the interface, collecting information from a graduate level class and from professional training course.

Personal Testing

Since GSSHA was selected as the modeling tool for this research, the author performed a lot of modeling and testing with it. This gave a great deal of experience with its capabilities as well as a thorough understanding of the strengths and weaknesses in the approach to develop GSSHA models with the WMS interface. Initially, there were several instability issues while running GSSHA, and the parameterization process was cumbersome. The author's first impression of GSSHA was not so favorable because of such problems, but with time, both familiarity and continuous improvements in GSSHA have changed the perception of it. The author's learning experience was one of the sources of information of the usability of GSSHA.

Hydrologic Modeling Class Feedback

The intent of this part of the research was to investigate the problems and issues that a practicing engineer with a fundamental background in hydrology and hydrologic modeling might find. The students at a graduate level course in the Civil and Environmental Engineering Department at Brigham Young University were assumed to represent such a class of engineers. The advanced hydrologic modeling class was designed in such a way that the students first learned basic hydrologic principles and the use of digital spatial data to delineate watershed and parameterize models. Then they performed traditional lumped hydrologic modeling with HEC-HMS, and after that they were exposed to GSSHA. Each student independently and in groups developed GSSHA models from scratch using the same geospatial data that they used to develop the lumped models with HEC-HMS. The students were asked to report both the conceptual and modeling problems they faced in each of the projects they worked on. The students were also asked to keep track of the time spent on them.

Although a large number of the issues that the students submitted were related to the interface, there was a substantial amount of feedback on the problems faced when parameterizing a model. The students compared the modeling experience with HEC-

HMS and GSSHA in terms of data requirement, pre-processing, knowledge, and time and effort employed.

SWWRP Training Course Feedback

The US Army Corps of Engineers (USACE) under their System Wide Water Resources Program (SWWRP) train engineers within USACE on spatial hydrologic modeling with HEC-HMS and GSSHA. In the training, the trainees were taught about the basics of the HEC-HMS and GSSHA model. They used WMS to parameterize both HMS and GSSHA models. The trainees of this course were experienced hydrologic modelers whose primary experience had been in the application of HEC-HMS lumped-parameter models. At the end of the course the students were asked to complete in a survey form regarding the issues they faced and improvements they suggested to make GSSHA modeling better.

The information from these three sources were taken as the basis of analyzing the usability of GSSHA and of identifying the issues that needed to be addressed in order to leverage the GSSHA modeling in routine hydrologic analysis.

5.3.2 GSSHA Modeling Workflow

Hydrologic modeling comprises several processes, including data pre-processing, model building, and parameterization to post-processing or visualization of the model results. Many of these processes need to be performed in a specific order while others can be done in an order at the modeler's choice. GSSHA modeling begins with the watershed delineation and characterization, which, defines the problem domain.

Performing distributed hydrologic modeling with GSSHA basically involves the following sequential steps.

1. Collecting digital elevation data for the watershed of interest
2. Computing flow direction and accumulation
3. Selecting an outlet location
4. Delineating the watershed

5. Defining and smoothing the stream vectors for use in the 1D channel model
6. Creating a 2D grid
7. Defining job control parameters for GSSHA
8. Creating index maps from land use and soil data
9. Establishing initial parameter values for the index maps
10. Defining precipitation
11. Running the model
12. Visualizing results

Further steps are often necessary to refine the model performance or to use the model for solving advanced problems. By articulating the individual steps this way, it was very easy to isolate the problems and issues that otherwise would seem to be interconnected. This also helped in defining a better work-flow, which has evolved in the form or a hydrologic modeling wizard in WMS.

The outlined steps are used to create a basic working model, and such a model is a good starting point for further hydrologic analysis including calibration and design. More on each of these processes is discussed in WMS user manual (Nelson, 2006) or GSSHAwiki (Wiki, 2009).

5.4 Results and Discussion

Information collected from the three sources mentioned above was taken as the basis of analyzing the usability of GSSHA and of identifying the issues that needed to be addressed in order to improve the process of developing a basic GSSHA model. This section first discusses the general issues faced while developing GSSHA models and elaborates on how to solve two of the prominent issues.

5.4.1 General Issues

While performing distributed hydrologic modeling, a large quantity of geo-spatial data has to be processed in order to attain the model parameters. Coming up with a basic distributed model using publicly available geo-spatial data is often discouraging because of the tedious nature of the process, and this problem becomes severe if the data-processing tool has been inefficiently implemented. Although having a working model is a preliminary step in hydrologic modeling, in most cases, a modeler quits because of a problem in the modeling framework. This section lists some of the issues that were identified to have significant impact in demoralizing a GSSHA modeler. These issues were solved without much effort but they had substantial impact in breaking the modeler‘s confidence. The following are the issues:

1. *Bug fixes and interface enhancement*

   At the initial stage of this research, there were several programming bugs that were introducing model instabilities as well as model errors. These resulted in a great deal of setbacks in GSSHA modeling. With an extensive testing of WMS-GSSHA modeling by the graduate engineering students and USACE trainees, most of such issues were resolved. Although these issues do not hold an academic merit as a new finding, solving these issues has resulted in improvement of the modeling experience.

2. *Grid development*

   In most of the distributed models that use the gridded approach, watershed discretization and grid/gridded data management is a complicated process. Few GIS-based programs are available that help in this task.

   With WMS-GSSHA modeling, grid data management are has been efficiently managed. Most of the grid tools necessary for creating GSSHA model are already supported in WMS but at the initial stage of this assessment there were issues with grid management.

   The following gridded information is necessary to develop a basic hydrologic model in GSSHA:

- Elevation grids
- Precipitation grids
- Overland roughness
- Infiltration grids

  Infiltration grids are used to define the infiltration parameters that are necessary to solve the Green and Ampt equations. Each cell potentially has different parameter values. A soil type index map is created in GSSHA that stores soil type information at each grid cell. The mapping table lists the unique soil types that are available in the watershed. The parameters listed below need to be defined for each soil type:

  - Hydraulic conductivity
  - Capillary head
  - Porosity
  - Pore distribution index
  - Residual saturation
  - Field capacity

  These parameters are generally obtained by comparing standard tables with to soil classifications. Most often, such parameters are determined from the Rawls and Brakensiek table, which includes the Green and Ampt parameters related to the soil textural classifications (Rawls *et al.*, 1983). Entering these data by looking at the Rawls and Brakensiek table for each unique soil type is one of the most cumbersome jobs in model developing. This step of data entry was reported to be the most tedious by the student survey as well as the training course feedbacks. This part was studied elaborately and is discussed later in this section.

- Initial soil moisture grid

  Initial soil moisture content is one of the most important but most uncertain parameters because its value not only depends upon the soil but also on the ambient climatic conditions, such as wet and dry years, time of the year, and antecedent moisture. Most of the time, the initial moisture is considered one of the calibration parameters owing to the uncertainty involved in its estimation. GSSHAwiki suggests performing a long-term simulation so that estimating soil moisture will not be a severe problem (GSSHAWiki). In doing so, the initial model predictions might show some deviation from the observed data because of the incorrect initial moisture estimation, but this problem improves as the model redistributes the soil moisture in the watershed domain in successive time steps.

3. *Work Flow Guidelines*

Hydrologic modeling is not only a science but an art. A modeler's experience with modeling and, knowledge of physics, as well as the limitations of the implementation being used in the analysis, play an important role in developing an efficient model. Owing to this, each modeler might follow his or her own work sequence to achieve similar, if not the same, final result.

Although the basic steps of delineating the watershed, selecting and parameterizing a model, running and result visualization seem to be straightforward, there are many details of developing a distributed model that will cause problems if not handled correctly. During testing of WMS-GSSHA modeling, it was clear that a lack of guidelines not only caused improper interaction between data at different stages, but it also resulted in varied model output. For instance, defining the GSSHA stream network before creating the 2D grid makes a significant difference in the results (discussed in more detail below). Similarly, it is necessary to create an index map prior to defining the model parameters; smoothing the channel thalweg is better done prior to using the cleandam utility etc.

Extensive personal testing as well as the analysis of feedback from the class and training courses helped conclude that following a specific work flow not only helps being time-efficient, but it also helps in getting more accurate results. Without it modelers would be likely to give up or lose confidence in their overall ability to solve routine hydrologic modeling problems. As a result of this study, an optimal work flow was identified which has now been implemented in WMS as a 'Hydrologic Modeling Wizard'(Figure 5.1. This improvement has become possible as a combined effort of this research, of the observations made by BYU students, and the SWWRP trainees, and of the help of the programmers at Aquaveo LLC.

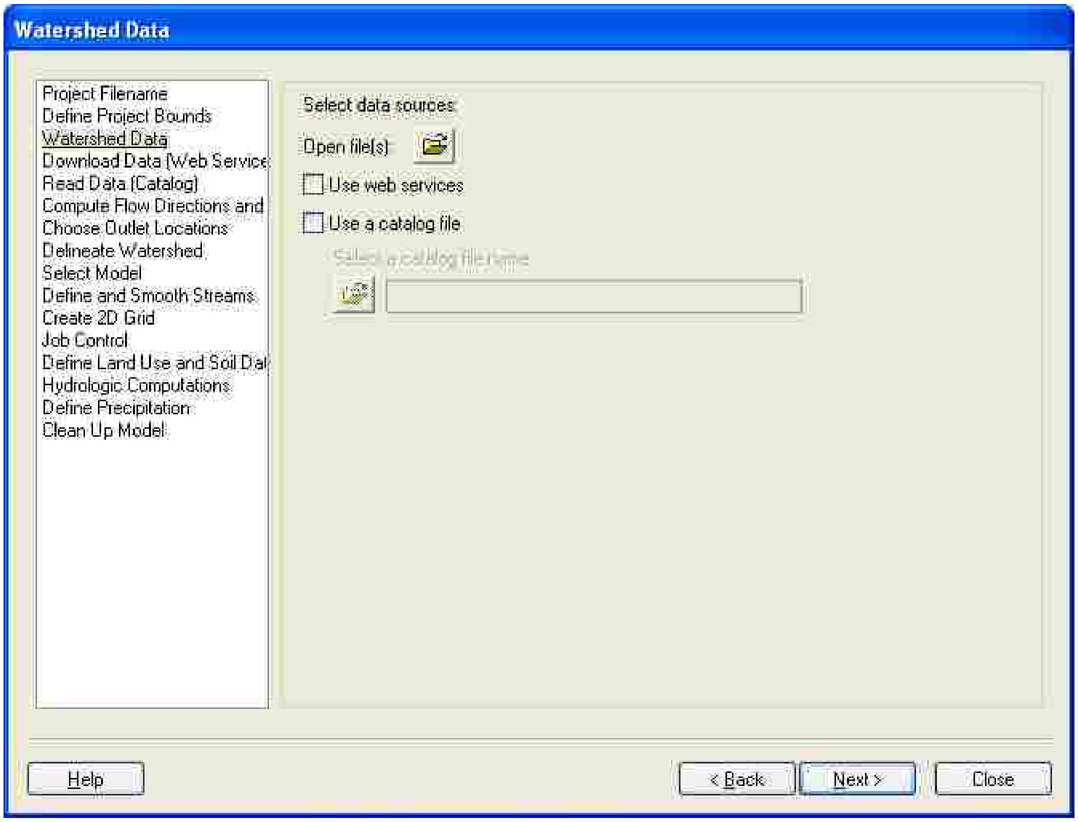


Figure 5.1: WMS-Hydrologic Modeling Wizard

4. *Handling results*

   A large amount of input data is required to create a GSSHA model, and evidently large amount of datasets are generated as model output data. Managing such output data is often referred to as post-processing. WMS has efficient ways to handle such data, and newer tools are evolving continuously. The results can be viewed as animations, graphics, or as tabular formats. During the usability test, it was identified that it is necessary to develop a better guideline on using such output data. There are many useful datasets that GSSHA generates, and in lack of such guidelines, they are underutilized.

5. *Enhancing scenario-modeling environment*

   Scenario modeling is a popular practice in hydrologic modeling because the decision-makers desire to compare alternatives. In order to perform "what if" analysis in different practical problems, scenario modeling is an important and popular tool. While performing a scenario analysis, a minor change is often made among alternatives, and variations in results are compared. In terms of GSSHA modeling, in many situations, the grid can be the same, with just the parameters changed, the precipitation changed or land cover updated in certain portion of the watershed. That means the majority of the project remains the same while only a small portion of it changes. In the absence of a scenario-modeling environment, it was a complicated process using the WMS-GSSHA interface. The need for scenario-modeling tools became obvious while performing the land use change scenario-modeling discussed in chapter 4.

   In the previous versions, each of the scenarios had to be created separately, and it was not possible to have two GSSHA projects open at the same time. The results from each scenario had to be compiled out of WMS, making important comparisons complicated.

   With the evolution of the multiple–scenario–modeling tools in WMS, these simulations have been simplified. Currently, multiple GSSHA models using the same 2D grid can be managed within a single instance of WMS. The models are displayed in the data tree, where the user can edit the job control, precipitation, GSSHA coverage, index maps, and continuous maps.

   This research identified the need for these tools, especially while performing the land use change scenario-modeling. However, the programming and implementation aspects of it were done by the group of experts at Aquaveo LLC.

5.4.2 Parameterization Problems

GIGO (Garbage in Garbage Out) is a quite common term used in numerical modeling. This term refers to the fact that the better is the model input, the better the result will be. In GSSHA modeling, getting the best initial estimates of the parameters is equally important as making the model complex enough to capture the spatial variation.

GSSHA stores the soil type information in a watershed in the form of an index map. The index map is a raster dataset that stores the soil type and other attributes for each grid cell. WMS has pre-processing tools that overlay the soil information from a shapefile over the grid, and each grid cell that falls within a specific soil category is assigned a soil type ID. Each unique soil type is displayed with a different color code as shown in Figure 5.2. This shows that higher resolution geospatial data can be used in parameterizing GSSHA because such resolutions can be better captured to the size levels of the grid cells.

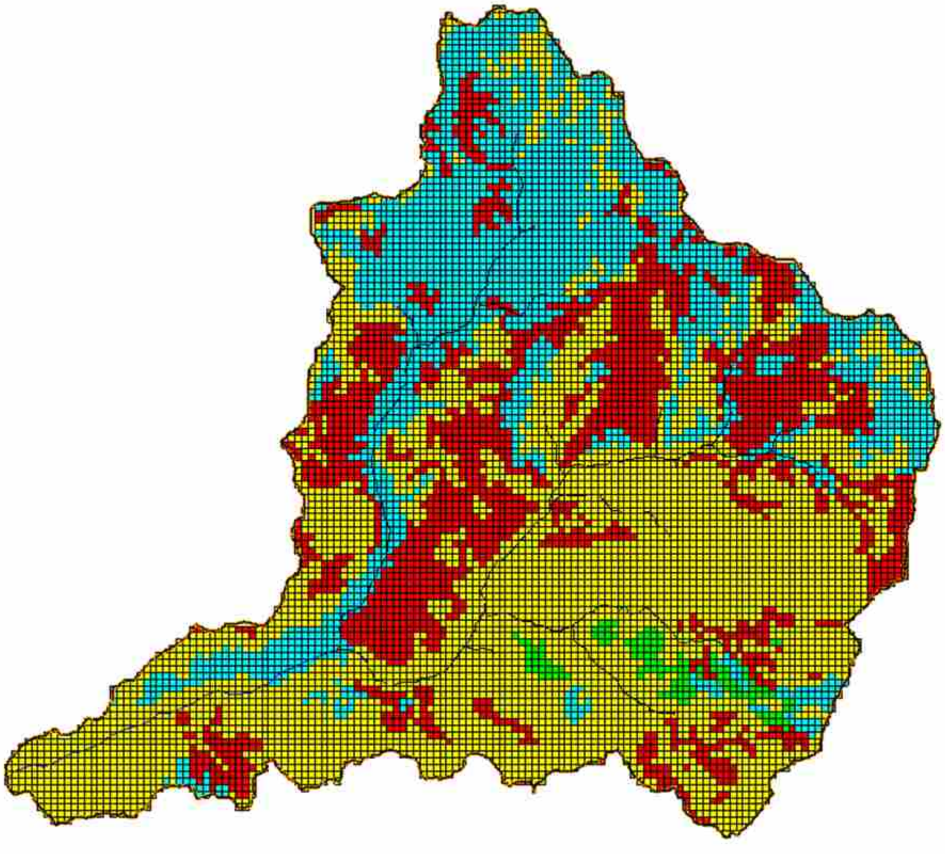
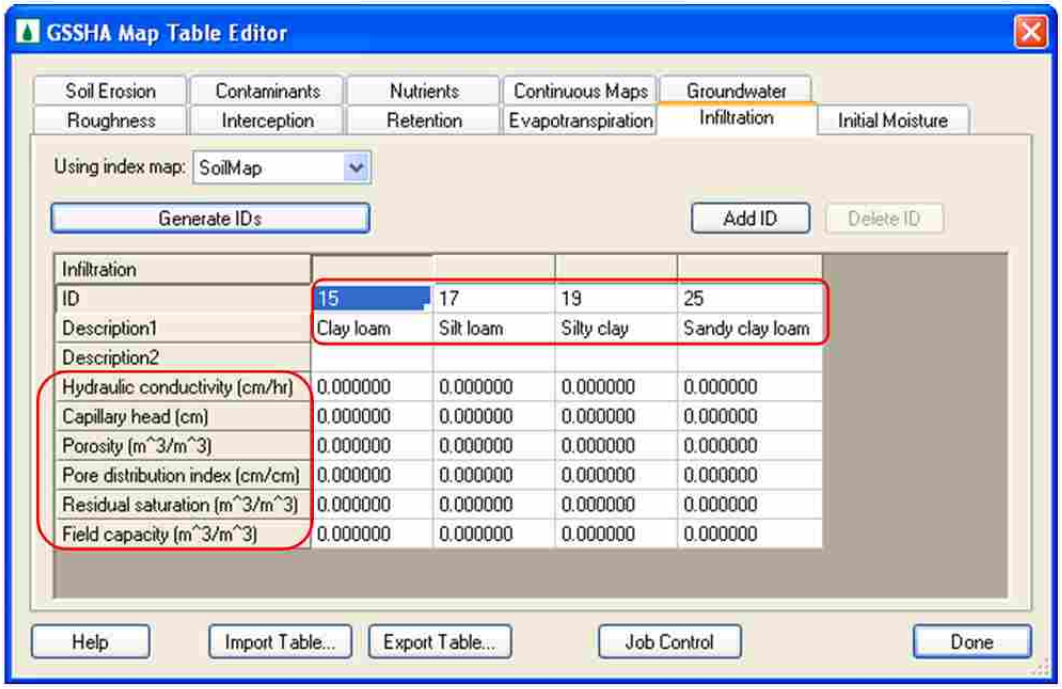


Figure 5.2: An Index Map Showing Soil Types

Each unique soil ID, which was defined while creating an index map, is now summarized into a mapping table where the parameters pertaining to each soil types are entered (Figure 5.3).



Using index map: SoilMap

Infiltration				
ID	15	17	19	25
Description1	Clay loam	Silt loam	Silty clay	Sandy clay loam
Description2				
Hydraulic conductivity (cm/hr)	0.000000	0.000000	0.000000	0.000000
Capillary head (cm)	0.000000	0.000000	0.000000	0.000000
Porosity (m^3/m^3)	0.000000	0.000000	0.000000	0.000000
Pore distribution index (cm/cm)	0.000000	0.000000	0.000000	0.000000
Residual saturation (m^3/m^3)	0.000000	0.000000	0.000000	0.000000
Field capacity (m^3/m^3)	0.000000	0.000000	0.000000	0.000000

Figure 5.3: Sample Mapping Table

As seen in Figure 5.3, the infiltration parameters such as hydraulic conductivity, capillary head, etc. need to be entered for each soil category. If the watershed is fairly large with higher variation of soil types, the mapping table shown here grows in size, making parameterization a time-consuming process.

At the same time, if the soil data used in creating such index map does not have soil texture information (e.g. sand, clay loam, etc), such as the STATSGO data, parameterization becomes complicated beyond the point that most modelers are able to tolerate, even if they understand well the processes involved in arriving at a good parameterization. This is because most of the standard infiltration parameters are related to the soil textural classification. This difficulty was identified as one of the most significant setbacks in developing a basic GSSHA simulation wherein calibration could be performed. Both personal experience and the feedback from the class and training courses supported the fact that simplifying this parameterization process would help leverage the use of GSSHA for routine hydrologic analyses, which could lead to more advanced applications.

A literature review suggested that the Soil Survey Geographic (SSURGO) soil database has very high-resolution soil data available for most parts of the United States. Another important aspect of SSURGO data is the standard textural information that can be utilized to relate the infiltration parameters with standard tables such as Rawls and Brakensiek.

SSURGO Data

SSURGO data are made available by the USDA from the soil datamart for free. This data is well suited for hydrologic modeling applications, particularly GSSHA, where the suggested parameters for infiltration could be derived from the soil texture information contained in the SSURGO data. SSURGO is a complicated database that stores a lot of data in a series of relational tables. Each map unit in the data is identified by a 'mukey,' which relates the map unit with its attributes stored in several other files (Figure 5.4).

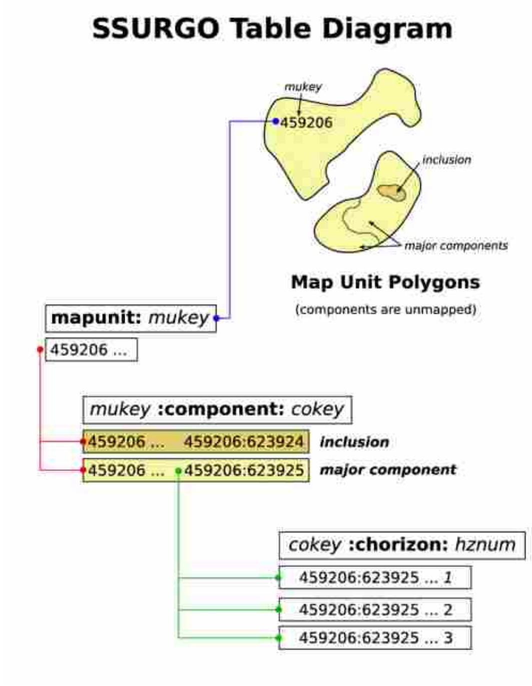
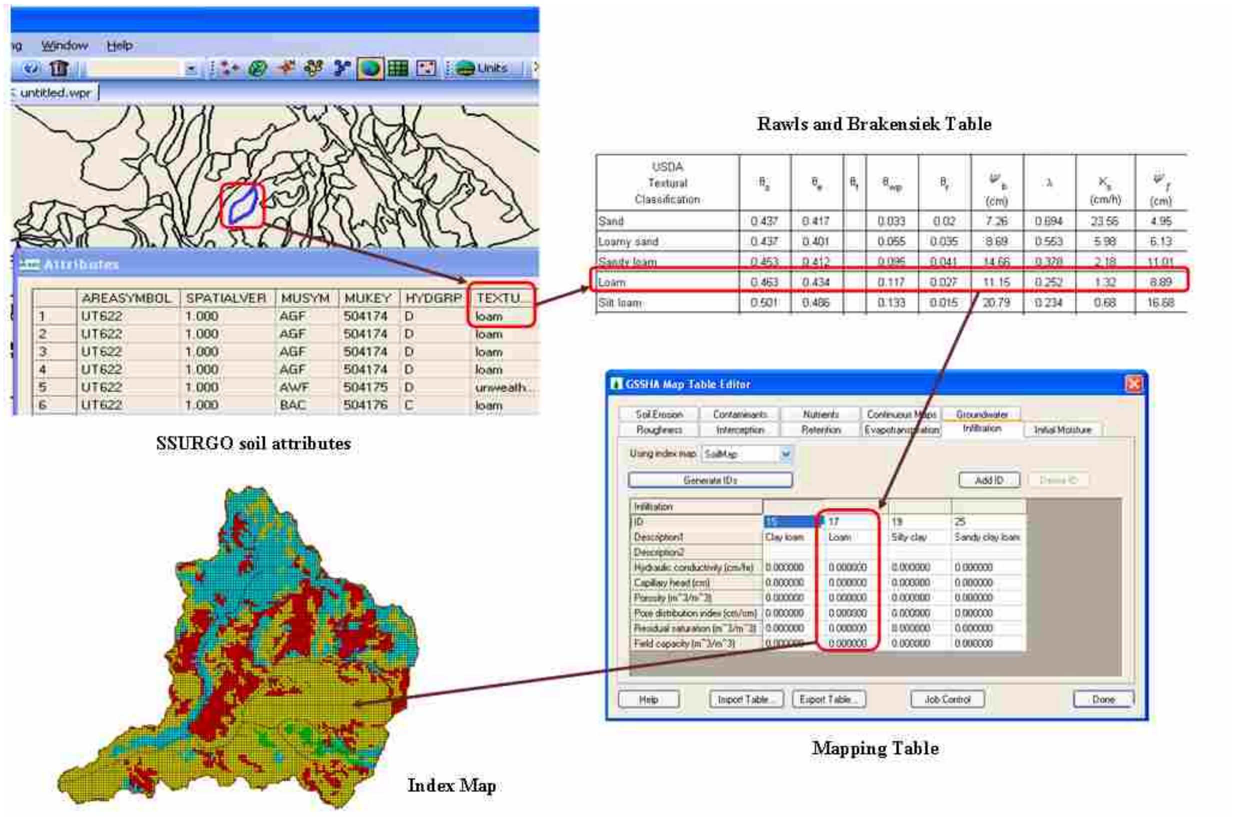


Figure 5.4: SSURGO Data Storage

For hydrologic modeling, all the information stored in SSURGO database is not required. More particularly, for GSSHA modeling, the textural classification of the soil is of prime importance because that information could be compared with the Rawls and Brakensiek table to obtain the infiltration parameters. There are values such as hydraulic conductivity, wilting point, field capacity, etc. for each SSURGO soil polygon that can also be extracted and used in conjunction with the mapping table of soil parameters developed from the Rawls and Brakenseik estimates. This study focuses on using the SSURGO data with the mapping table concept.

Soil Texture and Rawls-Brakensiek Table

The soil texture information obtained from SSURGO data can be related to Rawls and Brakensiek parameter estimates (Appendix A, Table A.1).



	AREASYMBOL	SPATIALVER	MUSYM	MUKEY	HYDGRP	TEXTU
1	UT622	1.000	AGF	504174	D	loam
2	UT622	1.000	AGF	504174	D	loam
3	UT622	1.000	AGF	504174	D	loam
4	UT622	1.000	AGF	504174	D	loam
5	UT622	1.000	AWF	504175	D	unweath...
6	UT622	1.000	BAC	504176	C	loam

SSURGO soil attributes

Rawls and Brakensiek Table

USDA Textural Classification	θ_s	θ_e	θ_t	θ_{wp}	θ_r	ψ_b (cm)	λ	K_s (cm/h)	ψ_f (cm)
Sand	0.437	0.417		0.033	0.02	7.26	0.694	23.56	4.95
Loamy sand	0.437	0.401		0.055	0.035	8.69	0.553	5.98	6.13
Sandy loam	0.453	0.412		0.095	0.041	14.66	0.378	2.18	11.01
Loam	0.463	0.434		0.117	0.027	11.15	0.252	1.32	8.89
Silt loam	0.501	0.486		0.133	0.015	20.79	0.234	0.68	16.68

Using index map: SoilMap

Infiltration				
ID	15	17	19	25
Description1	Clay loam	Loam	Silty clay	Sandy clay loam
Description2				
Hydraulic conductivity (cm/hr)	0.000000	0.000000	0.000000	0.000000
Capillary head (cm)	0.000000	0.000000	0.000000	0.000000
Porosity (m^3/m^3)	0.000000	0.000000	0.000000	0.000000
Pore distribution index (cm/cm)	0.000000	0.000000	0.000000	0.000000
Residual saturation (m^3/m^3)	0.000000	0.000000	0.000000	0.000000
Field capacity (m^3/m^3)	0.000000	0.000000	0.000000	0.000000

Mapping Table

Figure 5.5: Assigning Infiltration Parameters Based on SSURGO Attributes and Rawls & Brakensiek Table

As shown in Figure 5.5, the soil texture is extracted from the SSURGO database for each soil polygon that is within the watershed. Then such textures are compared with the Rawls and Brakensiek table to get the infiltration parameters such as hydraulic conductivity, capillary head, and porosity. These values need to be entered into the mapping table, which allows GSSHA to appropriately reference these values to each individual grid cell that has the same soil texture. This process facilitates the initial parameterization of GSSHA models and allows a modeler to get to the point in a modeling effort where sensitivity studies, calibrations, and design simulations can be performed.

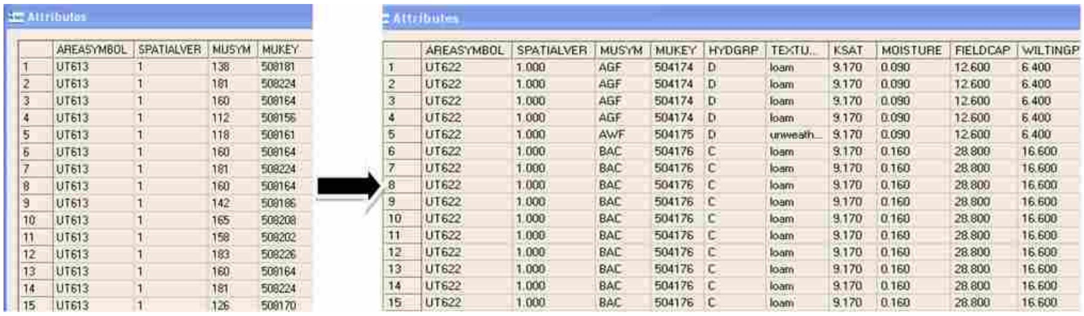
One important consideration here is that the parameters entered into the GSSHA model using this algorithm are only "initial estimates". The initial parameters need to be modified during model calibration or manual tune-up to make the model reflect the watershed condition that is being modeled. The better initial parameters, however, ensure better model performance resulting in significantly reduced effort in model calibration.

SSURGO Data Processing

The State Soil Geographic (STATSGO) Database is one of the most popularly used soil data source in hydrologic analysis. This data is derived from the SSURGO database and stored in readily usable GIS-shapefiles format. STATSGO data do not contain as much detailed information as can be found in SSURGO data, but it is still popular mainly because of its usability.

Several tools are developed to view and analyze SSURGO data, such as USDA soil data viewer. The majority of these tools are developed based upon the developer's need. For the purpose of GSSHA parameterization, no such useful tool was found, and an Excel spreadsheet macro was developed to join the necessary tables and extract these parameters.

WMS has an interface to read GIS shapefiles and map them to the coverages. The SSURGO data shapefiles, if opened in WMS, are not linked to the important information that is necessary to parameterize a GSSHA model (Figure 5.5).



	AREASYMBOL	SPATIALVER	MUSYM	MUKEY
1	UT613	1	138	508181
2	UT613	1	181	508224
3	UT613	1	160	508164
4	UT613	1	112	508156
5	UT613	1	118	508161
6	UT613	1	160	508164
7	UT613	1	181	508224
8	UT613	1	160	508164
9	UT613	1	142	508186
10	UT613	1	165	508208
11	UT613	1	158	508202
12	UT613	1	183	508226
13	UT613	1	160	508164
14	UT613	1	181	508224
15	UT613	1	126	508170

	AREASYMBOL	SPATIALVER	MUSYM	MUKEY	HYDGRP	TEXTU...	KSAT	MOISTURE	FIELDCAP	WILTINGP
1	UT622	1.000	AGF	504174	D	loam	9.170	0.090	12.600	6.400
2	UT622	1.000	AGF	504174	D	loam	9.170	0.090	12.600	6.400
3	UT622	1.000	AGF	504174	D	loam	9.170	0.090	12.600	6.400
4	UT622	1.000	AGF	504174	D	loam	9.170	0.090	12.600	6.400
5	UT622	1.000	AWF	504175	D	unweath...	9.170	0.090	12.600	6.400
6	UT622	1.000	BAC	504176	C	loam	9.170	0.160	28.800	16.600
7	UT622	1.000	BAC	504176	C	loam	9.170	0.160	28.800	16.600
8	UT622	1.000	BAC	504176	C	loam	9.170	0.160	28.800	16.600
9	UT622	1.000	BAC	504176	C	loam	9.170	0.160	28.800	16.600
10	UT622	1.000	BAC	504176	C	loam	9.170	0.160	28.800	16.600
11	UT622	1.000	BAC	504176	C	loam	9.170	0.160	28.800	16.600
12	UT622	1.000	BAC	504176	C	loam	9.170	0.160	28.800	16.600
13	UT622	1.000	BAC	504176	C	loam	9.170	0.160	28.800	16.600
14	UT622	1.000	BAC	504176	C	loam	9.170	0.160	28.800	16.600
15	UT622	1.000	BAC	504176	C	loam	9.170	0.160	28.800	16.600

Figure 5.6: Adding SSURGO Attributes

The spreadsheet macro reads the "mukey" from this shapefile, extracts soil textural classification from another data file in the database, and finally combines them together (Figure 5.6). The details of using this spreadsheet can be found in Appendix B.

Once these attributes are joined together, WMS automatically populates the values into the mapping table as well as into the index map. This spreadsheet macro has now been implemented in WMS interface 8.2 or later.

5.4.3 GSSHA Stream-Grid Interaction

As discussed earlier, overland flow in GSSHA is solved in a 2D grid, whereas a 1D channel-routing technique is used for stream routing. The stream and surface grid interact with each other in such a way that as soon as the water that flows from the 2D grid as overland flow reaches a grid cell containing a stream channel, all of the water is "dumped" into the stream and will then be routed to the watershed outlet (Figure 5.7). There are algorithms in GSSHA to allow the stream to flow back onto the overland flow plane when the water surface elevation in the stream is greater than the adjacent grid cell. Because of such sophisticated interaction, the stream and grids need to be constructed carefully to avoid as much discontinuity as possible.

Upon careful evaluation of this process, it was determined that building the stream model after having first defined the overland flow on the grid introduced error and resulted in unnecessary complexity in the development of a model.

GSSHA streams are generally derived from the stream networks that are delineated from the DEM using TOPAZ. If such stream cross-sections are backed up by surveyed data

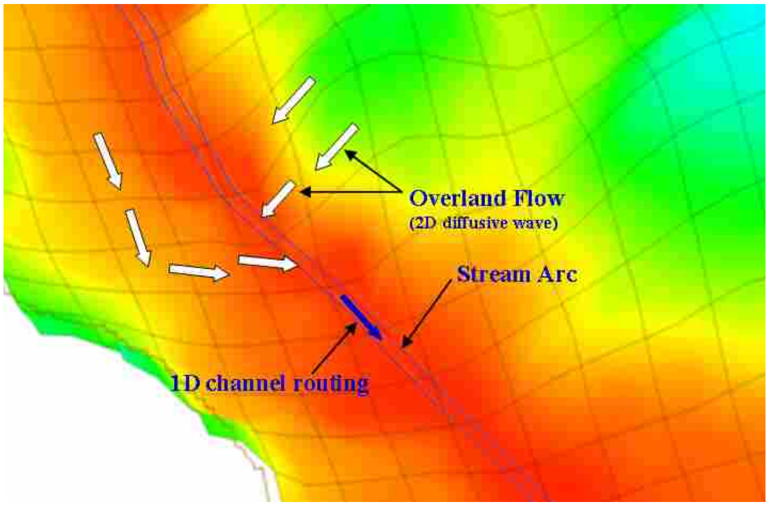


Figure 5.7: 2D Grid and Stream Interaction

for the channel corridor, that fully defines the stream geometry for the 1D routing. However, for larger watersheds, surveyed cross-section data for an entire drainage network are costly and not practical.

As discussed earlier in this section, the order of stream and grid definition in WMS-GSSHA modeling can make a significant difference in model performance. The problem was to define the streams well after the grid was in place. Although the tools to make appropriate adjustments were already in the WMS interface, they were not used in the right order, resulting in cumbersome stream-grid adjustment. Because the model was difficult to build, it obviously affected overall model performance. This section will discuss this issue and the heuristics developed through this research to make model development more efficient.

Before Improvement

WMS delineates the watershed as well as the stream network from digital data using an automated tool called TOPAZ. The following was the sequence of work steps in creating a GSSHA model:

1. Delineate the watershed and stream network.

2. Create a 2D grid in which the elevation of each grid cell is interpolated from the DEM.

3. Run Cleandam to remove digital dams (if any). Digital dams are artificial depressions in the digital elevation data that pond a lot of surface water creating an error in simulation. Most of the time, a digital dam is a result of interpolating the DEM to a relatively coarse grid resolution. The fact that flow on the GSSHA finite difference grid only occurs in the x-y (left-right and up-down) directions further exacerbates the digital dam problem.

   Cleandam uses an automated algorithm to trace the best flow path from the digital dam to a lower elevation by starting from the digital dam and randomly searching from cell to cell until it finds a lower cell elevation. A cost function is then calculated, which is the difference between the current cell elevations along the path and a linear sloping path from the digital dam and the cell with the lower elevation (GSSHAWiki). Once the best one is selected, the cell elevations in the grid are adjusted so that “flow” along the new path can occur.

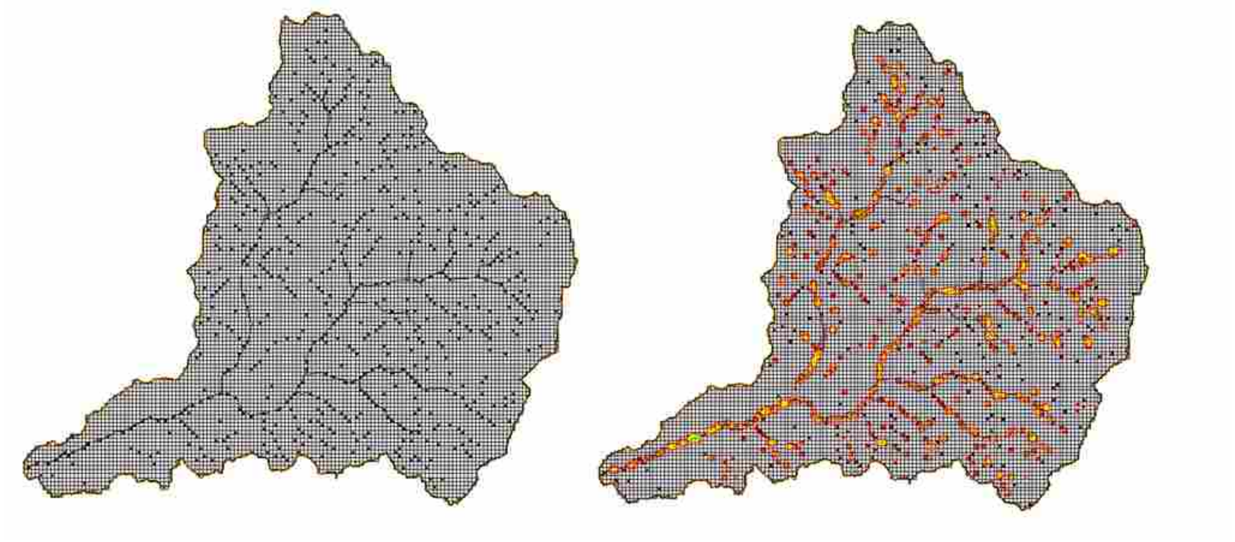


Figure 5.8: Digital Dams and Overland Flow Ponding

The black dots in the left image (Figure 5.8) represent the cells that are identified as the digital dams. Similarly, the image on the right shows, the overland flow depth contours that are concentrated at the cells designated as the digital dams.

4. Once digital dams were removed (a process that often resulted in numerous iterations and tended to be very time consuming) the GSSHA streams are defined by joining the cells with minimum elevations on an adjusted 2D grid that represented the stream thalweg.

5. Such streams are then smoothened to avoid any adverse slope and to make sure that the stream bed conforms to the grid (Figure 5.9). GSSHA is capable of handling flow through an adverse slope channel bed, but it is better to remove such slope to eliminate probable numerical instability.

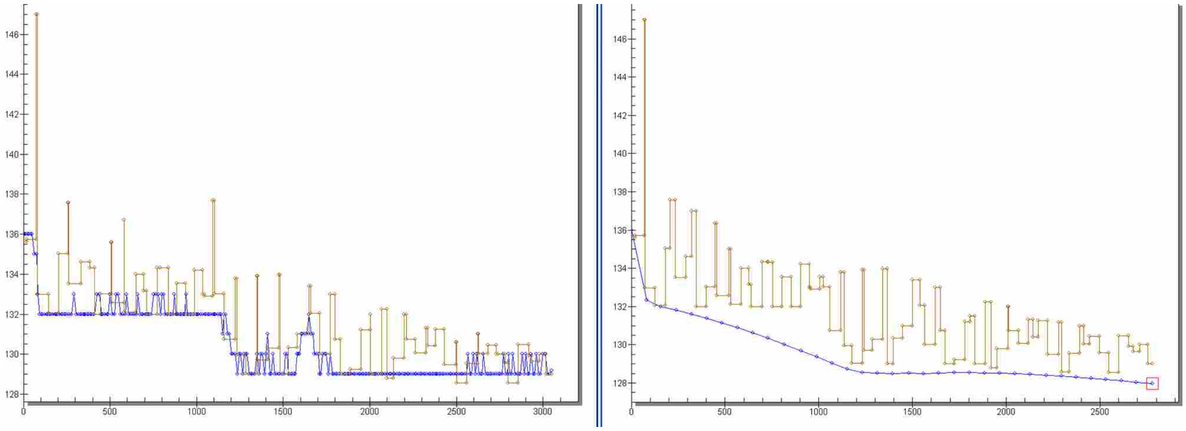


Figure 5.9: Stream Bed Smoothening

Problems with This Approach

If the number of digital dams is high and Cleandam is used to fix them, a considerable change in the grid elevation may be expected. This makes the grid elevation different from the DEM, and the streams that were delineated from the DEM and GSSHA streams that were created from a modified grid might not overlay laterally, resulting in two parallel flow paths as shown in Figure 5.10.

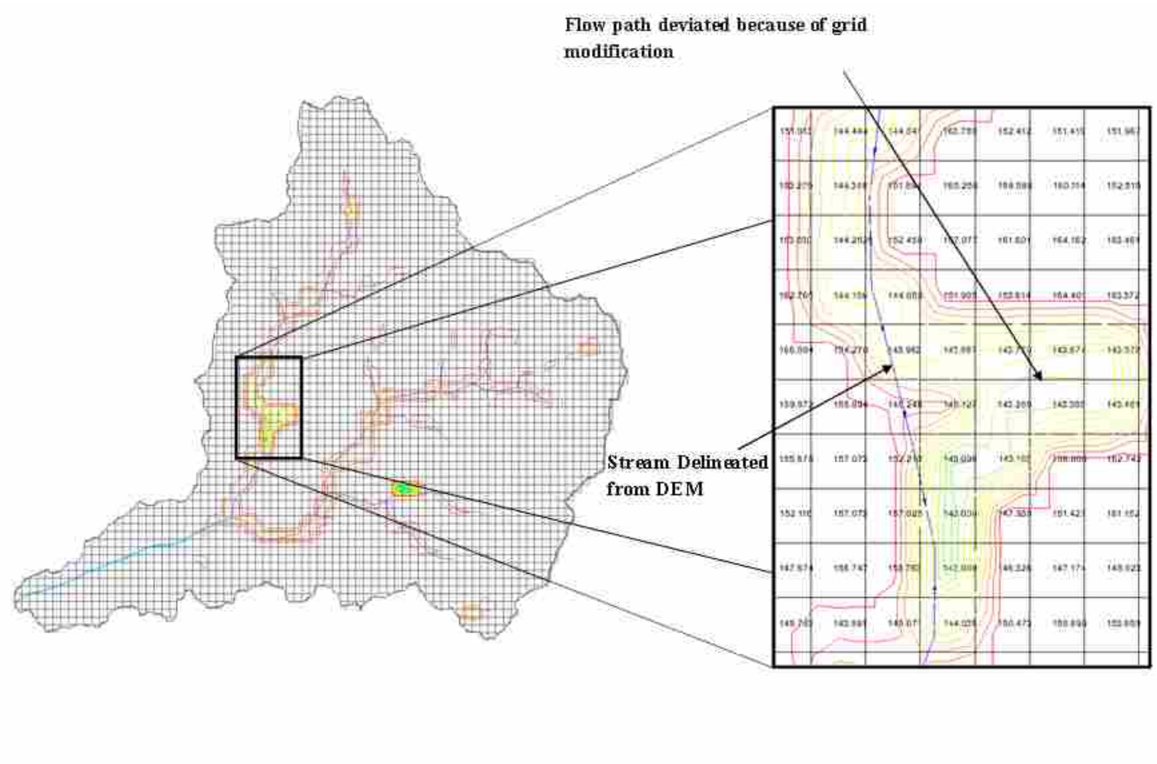


Figure 5.10: Flow Path Deviation from the Original Stream Due to Grid Modification

To resolve this problem of parallel flow paths, generally it was suggested that the stream be laterally shifted to match the overland flow contours (in this case a shift to the right) so that the stream arcs are aligned with the grid cells of lower elevations. Shifting the stream as suggested would solve the modeling problem, but at the same time it would add an approximation to the model, as the new location of the stream might be different from what it really is. More importantly, this involves a deeper insight into the model behavior that beginning modelers such as the students in the BYU class and the SWWRP training course did not possess. Because of that, they often became discouraged and gave up or lost confidence in the model's abilities before arriving at an adequate solution. As can be seen in Figure 5.11, the original stream arc runs straight downward (left arc) while the proposed stream arc shifted in order to match the flow contours is deviated toward forming a little loop (right arc). When the locations are compared with the background image, it can be clearly seen that the original stream follows the actual stream where there is a highway intersecting the shifted stream (See Figure 5.11).

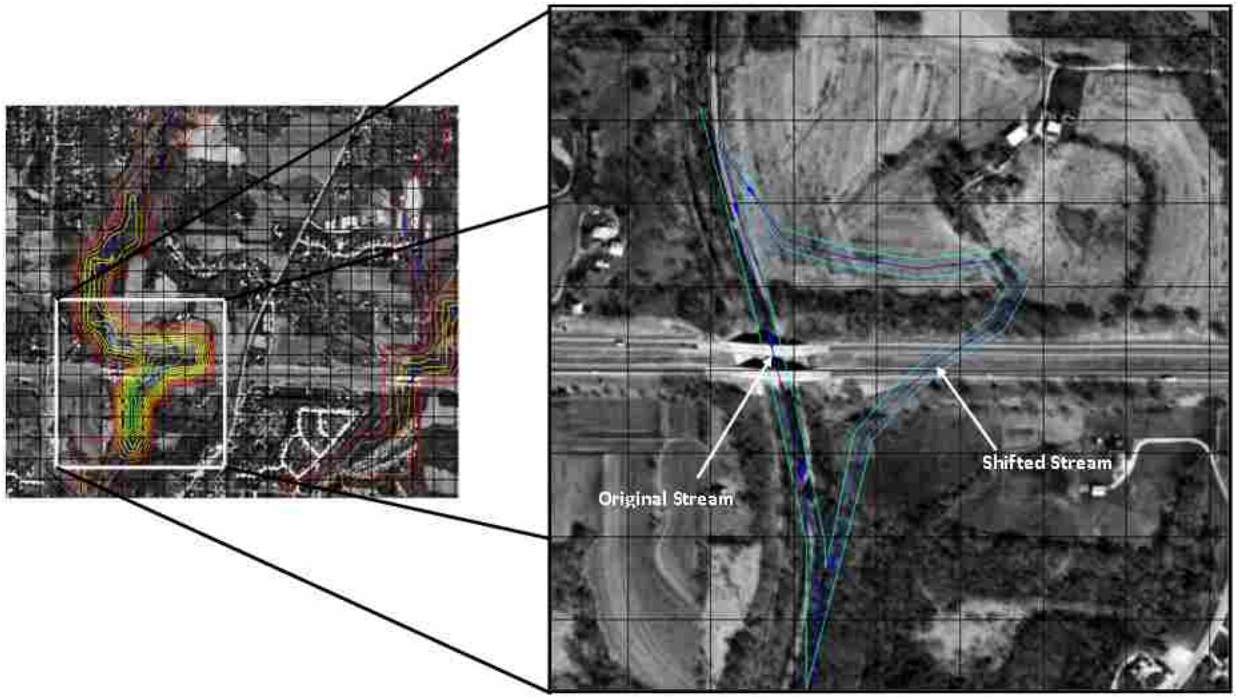


Figure 5.11: Stream Location with Background Image

Another problem with this approach is that the stream bed elevation is derived from adjusted grid elevations. If there were too many digital dams that were fixed using Cleandam, this might either lower or raise the stream bed as compared to what it really is, or at least it will be different from the stream bed delineated from the DEM.

These issues could be avoided by more selective use of Cleandam (i.e. not fixing the digital dams in the area of a stream arc), but by doing so, most of the surface water will be trapped in these digital dams resulting in excessively low runoff. It was also observed that if GSSHA is run without cleaning the digital dam, the simulation time increases significantly. This problem was confusing to modelers because someone being trained to use a distributed model for the first time and because necessary tools to solve this problem did not exist, making any proposed solution complicated and tedious.

Modified Approach

Because of the overwhelming feedback received from those using GSSHA, the following modified approach to developing a model was proposed:

1. Delineate the watershed and stream network.
2. Set up the stream arcs to define the GSSHA channel model prior to grid creation by assigning channel properties. Then redistribute the stream vertices with a general rule of thumb that no two vertices will lie on the same cell (i.e. the interspacing of the vertices needs to be equal to or greater than the grid cell size). Finally, smoothen the thalweg to avoid any adverse gradients as shown in Figure 5.9.
3. Create a 2D grid in which the elevation of each grid cell that is not on the stream arc is interpolated from the DEM. For the grid cells coincident with the stream arc, the elevation is derived from the stream bed elevation.
4. Run Cleandam to remove digital dams. If any digital dam falls on the stream cells, it is neglected and the elevation of that cell is unaltered. It does not affect the surface runoff because as soon as water flows onto a grid cell in the stream, the flow is transferred to the 1D channel model.

One important point to mention here is that GSSHA has an option to have streams flow overbank in case of a flood surge or high channel flow. The problem discussed above is for general modeling when the overbank flow option is turned off. If one were to develop a model with the bank overflow option turned on, extra care should be taken to make the grid and overland grid cell elevation consistent (Merrell, 2009).

Figure 5.12 illustrates the improvement in the stream and overland simulation by following this approach. Since the same sets of stream arcs delineated by TOPAZ are used to define GSSHA streams, there is little possibility of developing parallel channels. Because the grid modification (running Cleandam) is performed after defining the stream arcs, the issue discussed above is largely eliminated.

The accuracy of the streams delineated from DEM is still in question, but this is the best possible way to developing a basic model. Field validation is always suggested whenever possible.

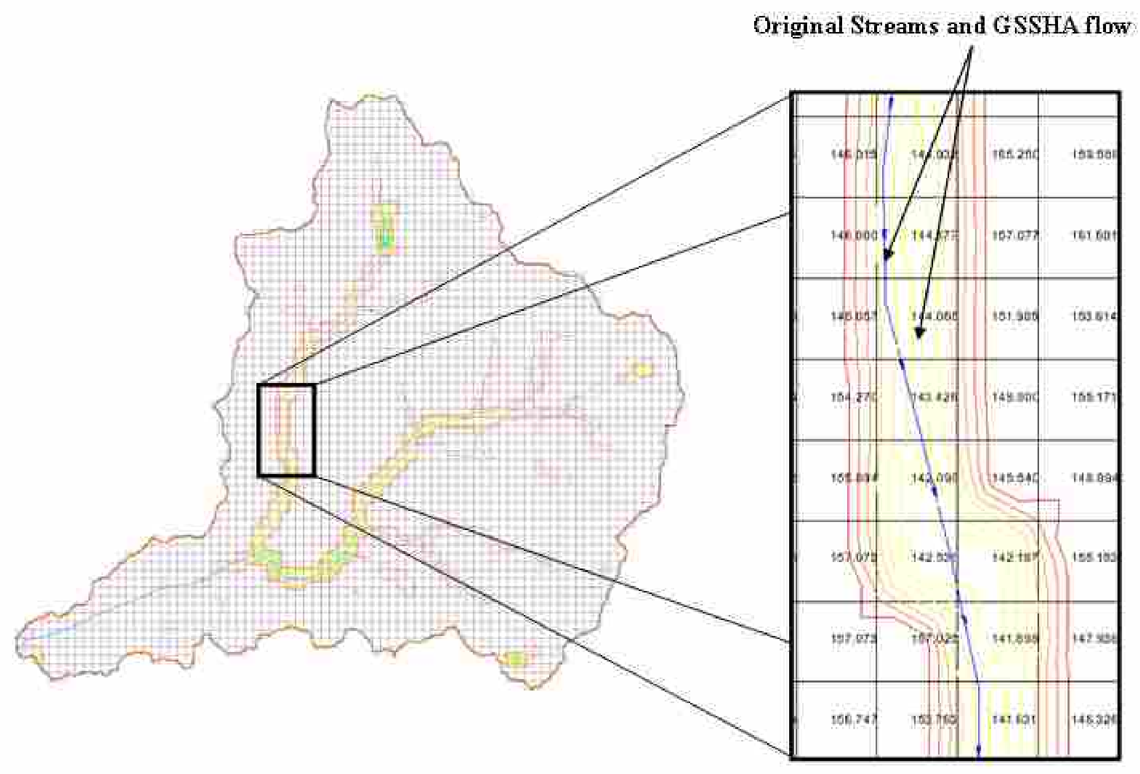


Figure 5.12: Flow Path and Stream Arc after Grid Modification

5.4.4 Adjusting Infiltration Parameters Based on Land Cover

The watershed characteristics are governed by basic factors such as prevailing topography, soil type, and land cover existing on the watershed. The surface roughness is fully determined by the land cover, while the infiltration parameters, although largely dependent upon the existing soil, are influenced by overlaying land cover.

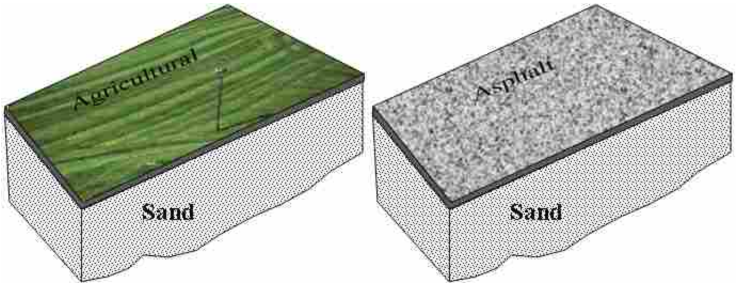


Figure 5.13: Schematic Diagram Showing Soil and Land Cover

Figure 5.13 shows a portion of a watershed where the soil type is identified to be sand, but the overlaying land cover varies with location. The picture on the left shows an agricultural land over the sandy soil where on the right there is impervious asphalt. In such a situation, if the infiltration parameters are derived solely on the basis of the underlying sandy soil, a serious over-approximation in infiltration will be introduced.

In order to consider the effect of land cover on the soil parameter, a combined index map is needed rather than using a simple soil index map. This combined map finds a unique combination of land use and soil. This feature is available in the WMS interface. Once such a combined index map is created, the values of the infiltration parameters from Rawls and Brakensiek table are used. It should be noted that the values available in Rawls and Brakensiek table are based upon the soil characteristics on bare earth, so the effect of land cover are not taken into consideration. This solicits the necessity of infiltration parameter modification based upon the land cover and use of “effective parameters”.

A literature review was done to figure out if there is a scientifically established method to modify the soil parameters obtained from standard tables such as the Rawls and Brakenseik table. Unfortunately, no such method or guidelines were available. Currently, WMS interface provides a way to identify what land cover is overlaying different soil textures, but the parameter modification guideline is missing. At present, this is achieved based on the modeler’s experience or by calibration.

In an attempt to address this issue, the students in class CE531 were asked to generate calibrated models with GSSHA. The purpose of this assignment was to compare their initial set of parameters with the calibrated parameter values. It was expected that an assessment of several such comparisons, would identify a relationship or methodology for the parameter modification. Unfortunately, this approach failed because of the following two reasons:

- The calibration tools available in WMS-GSSHA modeling were not yet ready to be used by the group of engineers represented by the students. There were some programming bugs as well as lack of consistency between GSSHA requirements and WMS interface.

- There were not enough test cases with sufficient sets of observed data to come up with a discrete relationship between the initial parameters and calibrated parameters values

This experience highlighted the necessity of evaluating the calibrating capabilities of WMS-GSSHA modeling, an evaluation that was carried out in research for a master's thesis (Shurtz, 2009). Although the current research identifies the necessity of a methodology or guidelines for parameter modification, it does not address the issue. The methodology and guidelines for parameter modification is left as a future scope to the study.

5.4.5 Extended Research

The current research encompasses the broader objective of validating the use of a distributed model as well as of establishing GSSHA as a promising distributed hydrologic model. In the process of investigating the issues with GSSHA modeling, several other prominent issues have been identified. Two important research projects were carried as a master's thesis (Shurtz, 2009) and a master's project (Merrell, 2009). The first research, carried out by Kayosn Shurtz, focused on studying the GSSHA calibration tools and effects of initial parameterization on the overall calibration results. Similarly, the second study, conducted by Clinton Merrel, analyzed an important aspect of regional to local model linkage, and it validated the usability of the GSSHA overbank flow module.

5.5 Conclusions

As a result of the current research, various tools have evolved in WMS as pre- and post-processing tools for distributed hydrologic/hydraulic modeling. Some of these include improving the stream representation, developing multiple–scenario–modeling tools, using high-resolution SSURGO data, and using textural classifications with standard infiltration properties to seed the initial model development. The actual programming for the WMS and GSSHA programs was not the objective of this research; the objective was identifying the issues, developing modeling guidelines, and testing their usability so that the models can be verified and to prepare publications related to their core functionality strengths. The development and improvement of the interface have been and are being done by Aquaveo LLC. The outcome of this research has been the guidelines for such improvements that pave the way for more application in routine hydrologic modeling, which can lead to use of more complex situations that depend on the distributed modeling philosophy.

Summarizing the Issues

The specific issues identified in WMS-GSSHA modeling interface involve establishing proper work flow, initial parameterization, stream and 2D grid interaction, adjusting infiltration parameters based on land cover, calibration and optimization tools for GSSHA, and exploration and documentation of other capabilities of GSSHA. These issues were identified as a result of personal testing as well as the feedback from the hydrologic modeling classes (C531 2008 and C531 2009) and SWWRP GSSHA training courses (2008 and 2009). The feedback was extremely useful and resulted in a great deal of improvement of WMS-GSSHA modeling experience.

Improvements Made

Not all of these issues have been completely solved, but the majority of them have been resolved. The issues of the establishment of proper workflow, initial parameterization, stream and grid interaction and multiple–scenario–modeling issues have been resolved, and these tools are now performing well in facilitating GSSHA modeling with WMS interface. Similarly, two other studies were carried out that evaluated the GSSHA calibration (Shurtz, 2009), examined GSSHA overbank flow routine, and explored regional-to-local model linkage (Merrell, 2009).

Shortcomings and Future Scope

There are problems and issues as well as ways to work around them for every tool that is used in hydrologic modeling today. Many issues were identified in the WMS-

GSSHA modeling interface during this study, some have been fixed, some are in the process of being fixed and some are still unsolved. Some of the issues that were not resolved in this research such as infiltration parameter modifications based on land cover data, Cleandam raising the stream cells above the ground if the watershed is particularly flat, expediting the GSSHA calibration process as it is extremely time consuming, improving model results while performing event simulation which might include ground water and sub-surface flow interacting with the overland flows, exploring other capabilities of GSSHA such as wet land simulation, hydraulics structures, and sediment and nutrient transport modeling.

CHAPTER 6. CONCLUSION

Much research has been carried out in mainstream hydrology to promote a transition from the traditional lumped hydrologic modeling paradigm to a more sophisticated and comprehensive physically based distributed hydrologic modeling system. In earlier days, hydrologic modeling was performed by solving the mathematical equations manually. Because of the modeling techniques and available data resources at that time, such a solution procedure was feasible. In the 1960s, as computer technology began evolving, such manual computations were quickly replaced by simpler computer programs that expedited the computational time by an order of magnitude. The computer models, basically the concepts, which were created in the earlier days of automated computation, were established as standard practice and they have a strong influence in the mainstream hydrologic analyses today. Such conventional models are referred to as lumped-parameter hydrologic models.

In the past few decades, computer technology, database management techniques, and numerical methods to solve complicated equations have immensely evolved. In conjunction, several hydrologic models have been developed that are capable of simulating the watershed behavior by making maximum utilization of the available geo-spatial data and technological resources. But contrarily, such new generations of hydrologic models are rarely used, and mainstream hydrology is still extrapolating the capabilities of the traditional lumped model even to solve extremely complicated problems.

The objective of this research is to establish the credibility of the distributed hydrologic models of the USACE in solving complex problems. The present-day engineering community must solve many complicated problems that were once not a priority nor did the engineers at that time conceive they could be solved. Thus, this research is intended to evaluate the possibility that HMS-ModClark and GSSHA could live up to the claims of being capable in distributed modeling. The credibility of these models has been established by publishing the findings of this research in peer-reviewed journals.

It was identified from the earlier days that the distributed models are more powerful and perform better than the traditional lumped models in simulating the water resources problems that are spatially sensitive. However, these models are still rarely used in routine hydrologic analyses. The current research aims at establishing the usability of the distributed model by identifying the reasons that have been hindering the greater use of the distributed models and developing suitable solutions to these problems. Despite the availability of sophisticated tools, high-resolution data, advanced numerical methods, and easily accessible literature, the usage of distributed hydrologic modeling is still underdeveloped. Having understood their capabilities and potential uses to solve current and future water resources problems, agencies such as USACE are trying to promote these advanced tools.

Two of the US Army Corps of Engineers (USACE) hydrologic modeling tools, GSSHA and HEC-HMS were used as the modeling tools for the study because the types of models that were intended to be compared are available in these softwares. GSSHA is USACE's next-generation hydrologic modeling tool capable of simulating complex watershed behavior using physics-based equations. Being a gridded model, GSSHA can incorporate the spatial heterogeneity of the watershed characteristics while simulating a rainfall response of the watershed. Similarly, HEC-HMS is USACE's most popular hydrologic modeling tool that is being considered as the current state-of-art in hydrologic modeling. WMS was used as the modeling framework to pre-process the data, to create and parameterize the models and to visualize the results.

6.1 Accomplishments

One way of validating the necessity of using distributed hydrologic models is to compare their performances with the lumped models. As the first part of this research, lumped and distributed approaches available in HEC-HMS were evaluated. The lumped curve number method has been quite popular from the earlier days in determining watershed response and thus was used as a representative lumped model. Similarly, there is another methodology that discretizes the watershed into grid cells, and instead of averaging the curve number, allows it to vary spatially over the watershed domain. The method is called ModClark in HEC-HMS. ModClark model also allows spatially varying precipitation to be used. While ModClark model has existed in HEC-HMS since its earliest versions, the application of the ModClark model has been limited by the necessity of using radar rainfall. Current research established that employing some specific GIS tools, it is actually possible to use it even with the rain gauge or synthetic precipitation. A comparison between lumped and distributed curve number methods concluded that using a distributed model (gridded curve number) results in more conservative results. The simulation results supported the fact that using the gridded curve number method employs the weighted discharge method and NEH 63 states that this method is more accurate than using the lumped curve number method.

Another part of this research analyzed the effectiveness of GSSHA as a distributed hydrologic model. Results from the traditional lumped methods in HEC-HMS were compared against the results from GSSHA while simulating a developing urban landscape. Land use change scenarios were created in which a portion of the watershed was assumed to be converted to a residential area, making the land relatively impervious as compared to its pre-development state. A lumped model that used Green and Ampt infiltration equation was developed in HEC-HMS and both the pre- and post-development scenarios were simulated. Similarly, GSSHA was used in its fully distributed mode using Green and Ampt infiltration equation to simulate the development scenarios. Results concluded that GSSHA simulation were intuitively correct and reflected the watershed behavior better than the lumped models in HEC-HMS. In order to see if overland flow transformation method being distributed or lumped makes any difference in scenario modeling, ModClark model was developed for the synthetic watershed. Pre- and post-development scenarios were simulated using the ModClark model which uses the gridded curve number method and empirical surface runoff transformation. The results from ModClark model were not directly comparable to GSSHA owing to the use of different loss methods. But an implicit comparison of the observations made from the two models concluded that even if the infiltration and precipitation methods were distributed in the ModClark model, because of empirical surface transformation method, ModClark model was efficient enough to simulate the watershed response to the land use changes. GSSHA results were intuitively correct over other models under comparison because of its capability to incorporate the spatial variations of watershed parameters, to use the physics-based equations, and to explicitly model the flow path all over the watershed domain. The research established the necessity of using GSSHA or similar distributed models to analyze complex hydrologic problems such as problems with the land use change modeling tested here.

A literature review revealed that the distributed models and their capabilities are somehow underutilized, but no research was carried out to investigate the underlying reasons. Another aspect of the research was to investigate the common hurdles in the development and the initial parameterization of a distributed hydrologic model and to explore the suitable solutions for such hurdles. It is intrinsically not possible to analyze all available lumped or distributed models to investigate such roadblocks that restrict the distributed models from being properly utilized. So, this study selected GSSHA as a representative distributed model and restricted the study on investigating the issues while developing the GSSHA models. Feedback from a graduate-level hydrologic modeling class and US Army Corps of Engineers training courses, supported by the author's own personal experiences was used as the basis for identifying such issues. Many problems were identified that were most likely to be faced by a general practicing engineer if he/she were to develop the GSSHA models by employing the publicly available geospatial data. Some of the prominent issues identified during this test were the stream and 2D grid interaction, order of work flow, and initial model parameterization. Suitable solution methods were proposed to take care of these issues, most of which are already implemented in the WMS-GSSHA modeling framework, and some of them are still under development. the possibility of using high resolution SSURGO soil database was explored and an algorithm to extract, process, and populate the values from the database as model parameters was developed. An Excel spreadsheet macro was created to extract and process SSURGO data, and it is successfully being used. It is expected that identifying and exploring suitable solutions to such problems have helped and will continue to help promote the use of GSSHA in solving applicable hydrologic problems.

The current research has identified that the suitable area of application of distributed hydrologic modeling is in analyzing complex water resources problems. Currently used lumped models are not capable of solving such problems in the way that distributed models can. The distributed models can be developed quite easily using GIS-based pre-processing tools such as WMS by better utilizing publicly available high-resolution geo-spatial data. There is no necessity of finding any specialized set of information or extremely sophisticated data to develop such models, as it is often thought to be. It must be acknowledged that distributed models are data-hungry and take some effort, time, and knowledge to come up with a better-working model, but the availability of better guidelines, powerful sets of pre- and post-processing tools, and easily available input datasets make them usable. Developing a distributed hydrologic model to solve extremely huge watersheds (regional models) or to solve fairly simple problems such as estimating a flood hydrograph at the watershed outlet for some arbitrary storm might not be a wise choice. Lumped models perform better in such situations. At the same time, the lumped models should not be extended beyond their capabilities to solve complex hydrologic or environmental problems because the distributed models perform superior in those situations.

The following table (Table 6.1) summarizes the observations made about the distributed and lumped hydrologic models.

6.2 Limitations

It is not justifiable to have mastery over all the available modeling tools, because there is often a significant overlap in the capabilities as wells as conceptualization of such tools. The present research focuses on comparing the lumped and distributed hydrologic models, taking GSSHA and HEC-HMS as test cases that are models representative of most of the cases but not for all. The author acknowledges that considering more distributed and lumped modeling tools in the comparison would add further strength to this research.

Table 6.1: Relative Strengths and Weaknesses of Lumped and Distributed Hydrologic Models

Model	Relative Strengths and Weaknesses
Lumped	– Ease in development but inefficient to represent the spatial variation – Ease in calibration but does not work well with other storms – Fewer parameters but these parameters are not related to watershed physics – Incapable of simulating scenario as these models cannot simulate the overland flow path
Distributed	– Complex in development but represents the spatial variation efficiently – Complex in calibration but work well with other storms – Require a lot of parameters and the parameters are physically based – Efficiently simulate scenario as these models simulate the overland flow path

Because the current version of HEC-HMS does not support a gridded Green and Ampt infiltration model, it was not possible to compare lumped and empirically distributed models in HEC-HMS with the fully distributed models in GSSHA. That would have offered a better comparison of how distributed or non distributed infiltration and surface transformation methods make a difference.

Whether a model is better developed or parameterized, it is always desirable to compare the model results with the observed data. It is well understood that there is always some amount of empiricism involved in any level of distributed models and that some uncertainty is introduced in input data measurement. So, analyzing the closeness of the simulated results with the ground truth would increase the confidence level in the model results. Owing to unavailability, some of the test cases presented in the current research miss the observed flow data, and it is identified as one of the limitations.

Similarly, the usability assessment of distributed modeling is performed taking the WMS-GSSHA modeling framework as a test case. Inclusion of another modeling environment would have added more insight into the usability issues. But again as previously discussed, there are countless tools and models, many of which are customized to meet specific requirements. It is assumed that the USACE models are good representatives of current state-of-art hydrologic modeling practice.

6.3 Products

The current research has made a significant contribution in hydrologic engineering practices. The outcomes of the research have been published in peer-reviewed scientific journals and presented at international conferences. The following are publications that this research produced:

1. Assessment of Lumped, Quasi-Distributed and Distributed Hydrologic Models of the US Army Corps of Engineers, EWRI conference, Kansas City, May 2009
2. Comparison of Lumped and Quasi-Distributed Clark Runoff Models Using the SCS Curve Number Equation, ASCE Journal of Hydrologic Engineering, October 2009. 1098-1106
3. Evaluation of distributed and lumped-parameter models on analyzing the effects of land use change, EWRI conference, Rhode Island, 2010 (scheduled)
4. Assessing the capability of a distributed and a lumped hydrologic model on analyzing the effects of land use change, Journal of Hydroinformatics, HYDRO-D-09-00100, Accepted for publication with date pending.

Besides these formal publications, the following are other forms of deliverables that are expected to make a significant contribution to mainstream hydrologic analyses:

- This dissertation which fulfills the requirements for the doctoral degree from Brigham Young University.
- Material was developed for a graduate-level course (CE531) in conjunction with Civil and Environmental engineering Department at Brigham Young University. This course is currently being taught in its 3rd semester. This is expected to introduce the capabilities of semi-distributed and distributed modeling approaches to the evolving generation of engineers.
- USACE's SWWRP training course materials for the 2008 and 2009 courses were developed as a conjunctive part of the research. This material has spread the importance and usability of the distributed hydrologic modeling to a set of practicing

engineers who have a strong influence in spreading the use of distributed modeling in routine hydrologic analyses.

- The experiences of using GSSHA from this research have been summarized into the form of tutorials and guidelines have been added to GSSHAWiki.
- An Excel spreadsheet macro to process SSURGO data has been developed and is a useful tool for model developers who do not have access to new versions of WMS.

Two important sets of research topics evolved out of this research on the capabilities of GSSHA; one formed a master's thesis and the other a masters project. The first research carried out by Kayosn Shurtz focused on studying the GSSHA calibration tools and effects of initial parameterization on the overall calibration results (Shurtz, 2009). Similarly, the second study conducted by Clinton Merrel analyzed an important aspect of regional-to-local model linkage, which developed a runoff hydrograph from a regional model (HEC-HMS lumped model) and fed it as an input to a more sophisticated local model (GSSHA model) (Merrell, 2009). These studies have made a significant contribution to the overall goal of the current research.

Much enhancement and improvement have been made in WMS-GSSHA interface by implementing the feedback from the current research. Development of a hydrologic modeling wizard, improvement of 2D grid and stream interaction process, development of automatic initial parameterization tools, and the SSURGO data processing tool, implementation of multiple–scenario–modeling environment, and improvement of calibration tools are some of the major contributions of this research. Along with these, many interface bug fixes were made, which, although are not documentable, make a significant difference in modeling experience.

All the materials discussed thus far have already been available. Besides that, it is expected that a manuscript for a journal article or technical note will developed by summarizing the overall understanding of the current research.

6.4 Future Scope

Several aspects of distributed versus lumped modeling as well as of the WMS-GSSHA modeling interface has been explored in this study. Although the current research meets all the research goals established at the beginning, there is abundant research potential in this area.

The distributed versus lumped model comparison aspect can be carried further to incorporate other prominent models, Mike SHE for instance, that would further leverage the suitable usage of distributed hydrologic models. A comparison of each individual component such as precipitation input, infiltration or loss methods, and surface-transformation method in both lumped and distributed models, would distinguish the capabilities and potentiality of the use of distributed models in solving complex problems.

In addition, GSSHA itself can be explored for many of its capabilities. It is still important to validate several tools that are available in GSSHA by performing scientific tests and publishing technical papers to establish its creditability. Further research can be carried out on exploring overbank flooding scenario modeling, ground water surface water interaction modeling, exploring the potential usage of regional to local model connectivity, and examining sediment and nutrient transport modules. Besides these areas of improvement, investigation on improving the model calibration process for an event simulation can be another important aspect of future study.

Changing the engineering practice from using traditional lumped models towards the use of distributed hydrologic models cannot be accomplished by the sole efforts of an individual. A team research project such as DMIP would help bring a significant change in the perception of the modelers. Creating a data repository where the modelers from different professions and parts of the world can store modeling data, documentation and resources would help in performing such teamwork. Identifying a proper way of developing such programs and developing better ways to maintain the repository can be another important future research in this area.

REFERENCES

Abbott, M., J. Bathurst, J. Cunge, P. O'Connell, and J. Rasmussen, 1986a. "An Introduction to European Hydrological System : Systeme Hydrologique Europeen, 'SHE', 1, History and Philosophy of a Physically-based Distributed Modeling System". *Journal of hydrology*, 87:45–59. 90

Abbott, M., J. Bathurst, J. Cunge, P. O'Connell, and J. Rasmussen, 1986b. "An Introduction to European Hydrological System : Systeme Hydrologique Europeen, 'SHE', 2. Structure of a Physically-based Distributed Modeling System". *Journal of hydrology*, 87:61–77. 90

Ajami, N. K., H. Gupta, T. Wagener, and S. Sorooshian, 2004. "Calibration of a Semi-distributed Hydrologic Model for Streamflow Estimation Along a River System". *Journal of Hydrology*, 298(1-4):112–135. 44

ARS, 2008. ARS water database. Website. http://www.ars.usda.gov/Main/docs.htm?docid=9696 . 73

Bandaragoda, C., D. G. Tarboton, and R. Woods, 2004. "Application of TOPNET in the Distributed Model Iintercomparison Project". *Journal of Hydrology*, 298:178–201. 23

Bergstrm, S. and L. P. Graham, 1998. "on the Scale Problem in Hydrological Modeling". *Journal of Hydrology*, 211(1-4):253–265. 20

Beven, K. J., 2001. "how Far Can We Go in Distributed Hydrological Modeling?". *Hydrology and Earth System Sciences*, 5(1):1–12. 91

Beven, K. J., M. J. Kirby, N. Schofield, and A. F. Tagg, 1984. "Testing a Physically-based Flood Forecasting Model (TOPMODEL) for Three U.K. Catchments". *Journal of Hydrology*, 69(4):119–143. 23

Beven, K. J. and M. J. Kirkby, 1979. "A Physically Based Variable Contributing Area Model of Catchment Hydrology". *Hydrological Science Bulletin*, 24:43–69. 23

Beven, K. J. and P. E. O'Connell, 1982. "On the Role of Physically-based Distributed Models in Hydrology". Technical Report Institute of Hydrology Report, No 81, Wallingford. 5

Bicknell, B. R., J. C. Imhoff, J. J. Kittle, J. A. Donigian, and R. Johanson, 1997. “Hydrological Simulation Program-FORTRAN, Users Manual for Version 11”. *EPA/600/R-97/080*, page 755. 17, 24

Biftu, G. F. and T. Y. Gan, 2001. “Semi-Distributed, Physically Based, Hydrologic Modeling of the Paddle River Basin, Alberta, Using Remotely Sensed Data”. *Journal of Hydrology*, 244(3-4):137–156. 3, 18

Blackie, J. R. and C. W. O. Eeles, 1985. *“Lumped Catchment Models in Hydrological Forecasting”*, pages 311–345. John Wiley and Sons, Chichester. 3

Bobba, A. G., V. P. Singh, and L. Bengtsson, 2000. “Application of Environmental Models to Different Hydrological Systems”. *Ecological Modelling*, 125(1):15–49. 4, 18, 65

Borah, D. K. and M. Bera, 2003. “SWAT Model Background and Application Reviews”. 19

Brooks, R. and A. Corey, 1964. “Hydraulic Properties of Porous Media”. *Hydrology Paper No. 3*. 91

Burnash, R. J. C., R. L. Ferral, and R. A. McGuire, 1973. “A Generalized Streamflow Simulation System - Conceptual Modeling for Digital Computers”. Technical Report NOAA, and the State of California Depart of Water Resources Tech. Rep, Joint Federal-State River Forecast Center. 23

Butts, M. B., J. T. Payne, M. Kristensen, and H. Madsen, 2004. “An Evaluation of the Impact of Model Structure on Hydrological Modeling Uncertainty for Streamflow Simulation”. *Journal of Hydrology*, 298(1-4):242–266. 2, 64

Calder, I. R., 1993. *“Hydrologic Effects of Land-use Change”*, pages 3.1–3.50. Handbook of Hydrology, D. R. Maidment. McGraw-Hill. 37, 64, 68

Carpenter, T. M. and P. G. Konstantine, 2004. “Continuous Streamflow Simulation with the HRCDHM Distributed Hydrologic”. *Journal of Hydrology*, 298:61–79. 19, 22

Charley, W., A. Pabst, and J. Peters, 1995. “The Hydrologic Modeling System (HEC-HMS): Design and Development Issues”. Technical Paper 149. 44

Chow, V. T., D. R. Maidment, and L. W. Mays, 1988. *"Applied Hydrology"*. McGraw-Hill Book Company, New York. 17

Christiaens, K. and J. Feyen, 2001. "Analysis of Uncertainties Associated with Different Methods to Determine Soil Properties and their Propagation in the Distributed Hydrological MIK SHE Model". *Journal of Hydrology*, 246:63–81. 91

Clark, C. O., 1945. "Storage and the Unit Hydrograph". *Transactions, American Society of Civil Engineers*, 110:1419–1446. 4, 41, 67

Crawford, N. H. and R. K. Linsley, 1966. "Digital Simulation in Hydrology: Stanford Watershed Model IV". Technical Report 39, Stanford Univ. Dept. of Civil Engineering. 23

Davis, D. W., 1993. "The HEC NEXGEN Software Development Project, Technical Paper 138". Technical Report TP-138, US Army Corps of Engineers, Hydrologic Engineering Center. 37, 44

DHI, 1998. "In MIKE-SHE v.5.3 User Guide and Technical Reference Manual". 22

Doan, J., 2000. "Geospatial Dydrologic Modeling Extension HEC-GeoHMS - User's Manual -Version 1.0". 25

Dodson and Associates, 1988. "Hands on HEC-1, Technical Document 88". 42

Downer, C. W. and F. L. Ogden, 2003. "Prediction of Runoff and Soil Moistures at the Watershed Scale: Effects of Model Complexity and Parameter Assignment". *Water Resources Research*, 39(3):SWC 1–1. 29

Downer, C. W. and F. L. Ogden, 2004. "GSSHA: Model to Simulate Diverse Sstream Flow Producing Processes". *Journal of Hydrologic Engineering*, 9(3):161–174. 67

Downer, C. W. and F. L. Ogden, 2006. "GSSHA User's Manual, Gridded Surface Subsurface Hydrologic Analysis Version 1.43 for WMS 6.1". *ERDC Technical Report*. 8, 22, 29, 93

Downner, C. W., F. L. Ogden, and A. R. Byrd, 2008. "GSSHAWIKI User's Manual, Gridded Surface Subsurface Hydrologic Analysis Version 4.0 for SMS 8.1". 29, 30, 33

Downer, C. W., F. L. Ogden, W. D. Martin, and R. S. Harmon, 2002. "Theory, Development, and Applicability of the Surface Water Hydrologic Model CASC2D". *Hydrological Processes*, 16(2):255–275. 22, 28, 29, 66

EPA, 2009. EPA website. Website. http://cfpub.epa.gov/surf/locate/index.cfm . 47, 73

Fitzpatrick, F. A., B. C. Scudder, B. N. Lenz, and D. J. Sullivan, 2001. "Effects of Multi-scale Environmental Characteristics on Agricultural Stream Biota in Eastern Wisconsin". *American water resources association*, 37(1):489–507. 19

Fohrer, N., S. Haverkamp, K. Eckhardt, and H. G. Frede, 2001. "Hydrologic Response to Land use Changes on the Catchment Scale"'. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, 26(7-8):577 – 582. 64

Goodchild, M. F. and D. J. Wright, 1997. "Data from the Deep: Implications for the GIS Community". *International Journal of Geographical Information Science*, 11(6):523. 24

Guertin, D. P., S. N. Miller, and D. G. Goodrich, 2000. "Emerging Tools and Technologies in Watershed Management". *USDA Forest Service, Proceedings RMRS-P-13*, pages 194–204. 6

Hartman, B. R. and E. J. Nelson, 2001. "A Central Method for Geo-spatial Data Acquisition (GSDA)". *Proceedings of the World Water and Environmental Resources Congress, American Society of Civil Engineers (ASCE) and the Environmental Water Resources Institute (EWRI), Orlando*. 45, 69

HEC, 1998. *"HEC-1 Flood Hydrograph Package User's Manual"*. US Army Corps of Engineers Hydrologic Engineering Center. 23, 37, 38, 41

HEC, 2000. *"HEC HMS, Technical Reference Manual"*. US Army Corps of Engineers Hydrologic Engineering Center. 4

HEC, 2008. *"HEC HMS, User's Manual Version 3.3"*. US Army Corps of Engineers Hydrologic Engineering Center. 8, 17, 23, 26, 27, 28, 37

Hernandez, M., S. N. Miller, D. C. Goodrich, B. F. Goff, W. G. Kepner, and C. M. E. K. B. J. and, 2000. “Modeling Runoff Response to Land Cover and Rainfall Spatial Variability in Semi-arid Watersheds”. *Environmental Monitoring and Assessment*, 64(1-4):285 – 298. 64

Hunter, S., J. Jorgeson, M. S., and B. Vieux, 2002. “A Test of two Distributed Hydrologic Models with WSR-88D Radar Precipitation Data Input”. 3, 29

III, K. G. R. and M. Y. Crouse, 2002. “the National Flood Frequency Program, Version 3: A Computer Program for Estimating Magnitude and Frequency of Floods for Ungauged Sites”. Technical Report 02-4168. 23

Ivanov, V. Y., E. R. Vivoni, R. L. Bras, and D. Entekhabi, 2004. 23

J. K. Lrup, J. C. Refsgaard, D. M., 1998. “assessing the Effect of Land use Change on Catchment runoff by Combined Use of Statistical Tests and Hydrological Modelling:Case Studies from Zimbabwe”. *Journal of Hydrology*, 205(3-4):147. 65, 66

Johnson, D. L. and A. C. Miller, 1997. “A Spatially Distributed Hydrologic Model Utilizing Raster Data Structures”. *Computers and Geosciences*, 23(3):267 – 272. 16

Jones, J., 1997. *“Global Hydrology: Processes, Resources and Environmental Management”*. Longman, England. 2, 4, 5, 18

Julien, P. Y., B. Saghafian, and F. L. Ogden, 1995. “Raster-based Hydrologic Modeling of Spatially-varied Surface Runoff”. *Journal of the American Water Resources Association*, 31(3):172–1688. 90

Kalin, L., R. S. Govindaraju, and M. M. Hantush, 2003. “Effect of Geomorphologic Resolution on Modeling of Runoff Hydrograph and Sedimentograph Over Small Watersheds”. *Journal of Hydrology*, 276(1-4):89–111. 19

Kalin, L. and M. M. Hantush, 2006. “Hydrologic Modeling of an Eastern pennsylvania Watershed With NEXRAD and Rain Gauge Data”. *Journal of Hydrologic Engineering*, 11(6):555. 5

Kite, G. W. and P. A., 1996. “Remote Sensing Applications in Hydrological Modelling”. *Hydrological Sciences Journal*, 41(4):563–587. 4

Koren, V., S. Reed, M. Smith, Z. Zhang, and D. J. Seo, 2004. "Hydrology Laboratory Research Modeling System (HL-RMS) of the US National Weather Service". *Journal of Hydrology*, 291:297–318. 22

Kouwen, N., 1988. "WATFLOOD: a Micro-computer Based Flood Forecasting System Based on Real-time Weather Radar". *Canadian Water Resources Journal*, 13(1):62–77. 4

Krajewski, W. F., V. Lakshmi, K. P. Georgakakos, and S. C. Jain, 1991. "A Monte Carlo Study of Rainfall Sampling Effect on a Distributed Catchment Model". *Water Resources Research*, 27(1):119–128. 20

Leavesley, G. H., P. J. Restrepo, S. L. Markstrom, M. Dixon, and L. G. Stannard, 2004. "The Modular Modeling System (MMS)-A Modeling Framework for Multidisciplinary Research and Operational Applications (User's Manual". *USGS home page*. 22

Loague, K. M. and R. A. Freeze, 1985. "A Comparison of Rainfall-runoff Modeling Techniques on Small Upland Catchments". *Water Resources Research*, 21(2):229–248. 19

Loch, R. J., 2000. "Effects of Vegetation Cover on Runoff and Erosion Under Simulated Rain and Overland Flow on a Rehabilitated Site on the Meandu Mine, Tarong, Queensland". *Australian Journal of Soil Research*, 38:299. 65

Luzio, M. D. and J. G. Arnold, 2004. "Formulation of a Hybrid Calibration Approach for a Physically Based Distributed Model With NEXRAD Data Input. *Journal of Hydrology*, 298:136–154. 23

Madsen, H., 2003. "Parameter Estimation in Distributed Hydrological Catchment Modelling Using Automatic Calibration with Multiple Objectives". *Advances in Water Resources*, 26(2):205 – 216. 92

Maidment, D., 2002. *"Arc Hydro: GIS for water resources"*. ESRI, Redlands, CA. 25

Merrell, C. R., 2009. "Modeling Overbank Flow and Creating Regional-to-local Model Using WMS and GSSHA"'. Technical report. Master's Project Report. 114, 117, 118, 128

Michaud, J. D. and S. Sorooshian, 1994. "Effect of Rainfall-sampling Errors on Simulations of Desert Flash Floods". *Water Resources Research*, 30(10):2765–2775. 19

Moore, R. J. and R. T. Clarke, 1981. "A Distribution Function Approach to Rainfall Runoff Modeling". *Water Resources Research*, 17(5):1367–1382. 23

Moreda, F., V. Koren, Z. Zhang, S. Reed, and M. Smith, 2006. "Parameterization of Distributed Hydrological Models: Learning from the Experiences of Lumped Modeling". *Journal of Hydrology*, 320(1-2):218 – 237. The model parameter estimation experiment - MOPEX. 90

Nelson, E. J., 2006. "Watershed Modeling System (SMS), User's Manual". 26, 33, 37, 93, 97

Obled, C., J. Wendling, and K. Beven, 1994. "The Sensitivity of Hydrological Models to Spatial Rainfall Patterns:An Evaluation Using Observed Data". *Journal of Hydrology*, 159:305–333. 20, 21

Ogden, F. L., H. O. Sharif, S. U. S. Senarath, J. A. Smith, M. L. Baeck, and J. R. Richardson, 2000. "Hydrologic Analysis of the Fort Collins, Colorado, Flash Flood of 1997". *Journal of Hydrology*, 228(1-2):82–100. 28

Paniconi, C., S. Kleinfeldt, J. Deckmyn, and A. Giacomelli, 1999. "Integrating GIS and Data Visualization Tools for Distributed Hydrologic Modeling". *Transactions in GIS*, 3(2):1361–1682. 7

Paudel, M., E. J. Nelson, and R. H. H. C. W. Downer, 2010. "Assessing the Capability of a Distributed and a Lumped Hydrologic Model on Analyzing the Effects of Land Use Change. *Journal of Hydroinformatics*. In Press. 18, 65

Paudel, M., E. J. Nelson, and W. Scharffenberg, 2009. "Comparison of Lumped and Quasi-distributed Clark Runoff Models Using the SCS Curve Number Equation". *Journal of Hydrologic Engineering*, 14(10):1098–1106. 20, 67

Peters, J. C. and D. J. Easton, 1996. "Runoff Simulation Using Radar Rainfall Data". *Water resources bulletin*, 32:753–760. 43

Rawls, W., D. Brakensieki, and N. Miller, 1983. "Predicting Green and Ampt Infiltration Parameters from Soils Data". *ASCE Journal of Hydraulic Engineering*, 109:62–70. 39, 91, 99

Reed, S., V. Koren, M. Smith, Z. Zhang, F. Moreda, D.-J. Seo, , and D. Participants, 2004. "Overall Distributed Model Intercomparison Project Results". *Journal of Hydrology*, 298(1-4):27–60. 3, 16, 17, 19, 21, 22, 91

Refsgaard, J., 1997. "[p. 16, 17, 20

Refsgaard, J. C. and J. Knudsen, 1996. "Operational Validation and Intercomparison of Different Types of Hydrological Models". *Water Resources Research*, 32(7):2189–2202. 19, 20

Rockwood, D. M., E. D. Davis, and J. A. Anderson, 1972. "User Manual for COSSARR Model". 23

SCS, 1986. "Urban Hydrology for Small Watersheds, Technical Report 55". Technical Report tr55, USDA, Springfield, VA. xi, 23, 38, 39, 142

Sherman, L. K., 1932. "Streamflow from Rainfall by Unit-graph Method". *Eng. New Record*, 108:501–505. 17

Shurtz, K. M., 2009. "Automated Calibration of the GSSHA Watershed Model: A Look at Accuracy and Viability for Routine Hydrologic Modeling". Technical report. Master's Thesis. 117, 118, 128

Smith, M. B., 1993. "A GIS-based Distributed Parameter Hydrologic Model for Urban Areas". *Hydrological Processes*, 7:45–61. 19

Smith, M. B., D.-J. Seo, V. Koren, S. M. Reed, Z. Zhang, Q.-Y. Duan, F. Moreda, and S. Cong, 2004. "The Distributed Model Intercomparison Project (DMIP): Motivation and Experiment Design". *Journal of Hydrology*, 298:4–26. 16, 18, 19, 20

Sugawara, M., E. Ozaki, I. Wantanabe, and Y. Katsuyama, 1976. "Tank Model and its Application to Bird Creek, Wollombi Brook, Bihin River, Sanaga River, and Nam Mune". *National Center for Disaster Prevention*, 11. 23

Sui, D. Z. and R. C. Maggio, 1999. "Integrating GIS with Hydrological Modeling: Practices, Problems, and Prospects". *Computers, Environment and Urban Systems*, 23(1):33–51. 5, 36

Todini, E., 1996. "The ARNO Rainfall-Runoff Model". *Journal of Hydrology*, 175(1-4):339–382. 23

USACE, 1994. "Flood Runoff Analysis". Technical Report EM 1110-2-1417, US Army Corps of Engineers, Hydrologic Engineering Center. 16, 18, 19, 35, 41

USDA, N., 2004. "National Engineering Handbook". *NEH*, Part 63. 36, 40, 45, 54, 55

USGS, 2009a. USGS website. Website. http://seamless.usgs.gov . 47

USGS, 2009b. USGS website for soil. Website. http://edc2.usgs.gov/geodata/index.php . 73

Vazquez, R. F., L. Feyen, J. Feyen, and J. C. Refsgaard, 2002. "Effect of Grid Size on Effective Parameters and Model Performance of the MIKE-SHE Code". *Hydrological Processes*, 16(2):255. 4, 18

Vieux, B. and N. Gauer, 1994. "Finite Element Modeling of Storm Water Runoff Using GRASS GIS". *Microcomput. Civil Eng.*, 9(4):263–270. 90

Vieux, B. E., 2001. "Distributed Hydrologic Modeling Using GIS". *Water Science and Technology Series*, 38:293p. 92

Vieux, B. E., Z. Cui, and A. Gaur, 2004. "Evaluation of a Physics-based Distributed Hydrologic Model for Flood Forecasting". *Journal of Hydrology*, 298:155–177. 18

Vieux, B. E. and F. G. Moreda, 2003. "Ordered Physics-based Parameter Adjustment of a Distributed Model". *Calibration of Watershed Models Water Science and Application*, 6:267–281. 19, 22, 91

Wanielista, M., R. C. Maggio, and R. Kersten, 1997. *"Hydrology - Water quantity and Quality Control"*, chapter 3, page 68. John Wiley and Sons, Inc., second edition. 47

Ward, G. H. and J. Benaman, 1999. "Models for TMDL Application in Texas Watercourses: Screening and Model Review". Technical Report CRWR-99-7., Center for Research in Water Resources, The University of Texas at Austin, Austin, Texas 78712. 19

Westervelt, J. D., M. Shapiro, W. D. Goran, and D. P. Gerdes, 1992. "Geographic Resources Analysis Support System (GRASS) Version 4.0 User's Reference Manual". 25

Wiki, G., 2009. GSSHAwiki. http://www.gsshawiki.com/gssha/Main_Page . 29, 30, 33, 93, 97

Williams, J. R. and R. W. Hann, 1973. "WatershedHYMO: Problem-oriented Language for Hydrologic Modeling -User's Manual". 23

Woolhiser, D. A., 1996. "Search for Physically Based Runoff Model-A Hydrologic El Dorado?". *Journal of Hydrologic Engineering*, 122(3):122–129. 24

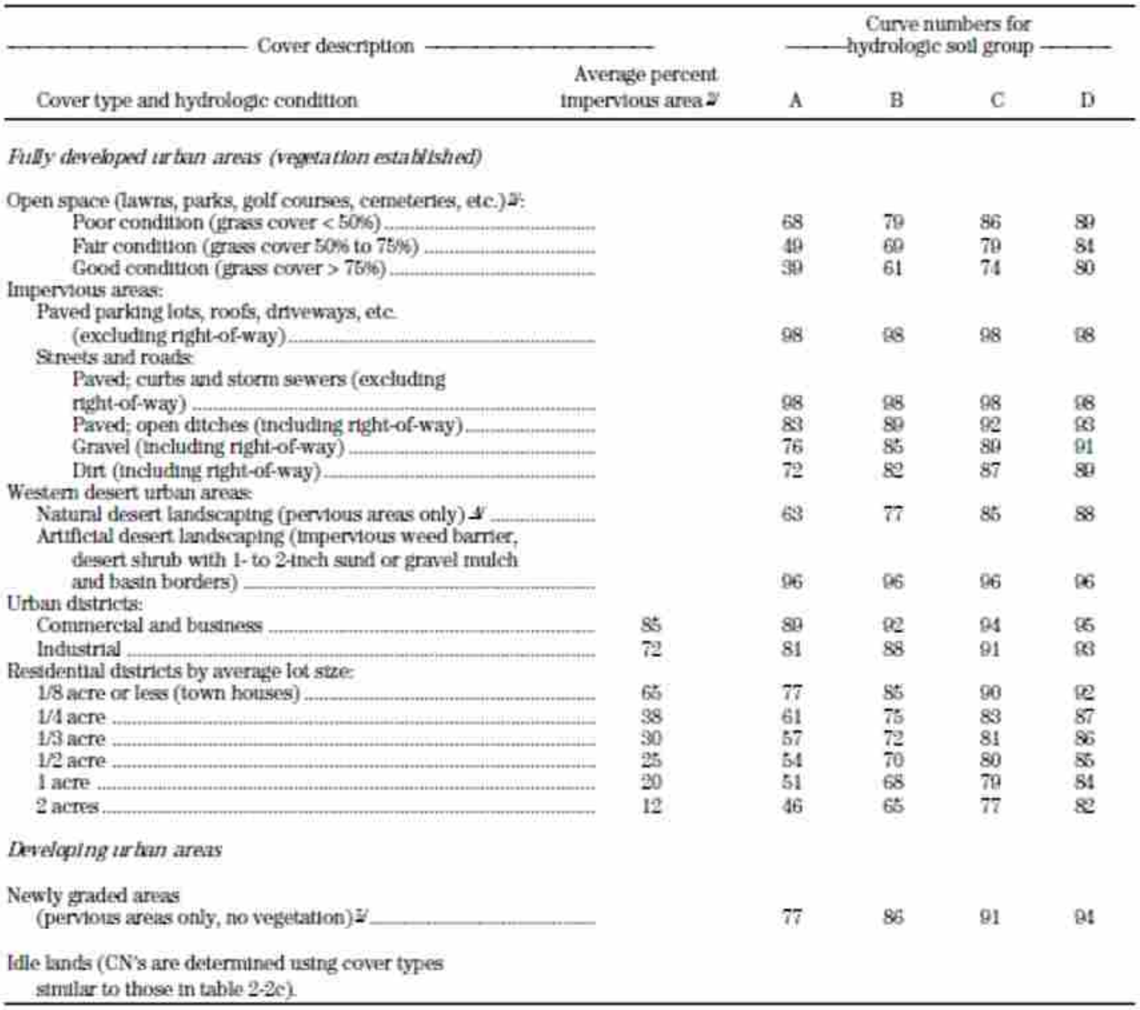
XMSWiki, 2010. XMSwiki. http://www.xmswiki.com/xms/Main_Page . 33

Zhao, R. J., 1984. "Watershed Hydrological Modelling". *Water Resources and Electric Power Press*. 23

APPENDIX A. STANDARD TABLES AND VALUES

Classification Code	Land Use Description
11	Residential
12	Commercial Services
13	Industrial
14	Transportation, Communications
15	Industrial and Commercial
16	Mixed Urban or Built-Up Land
17	Other Urban or Built-Up Land
21	Cropland and Pasture
22	Orchards, Groves, Vineyards, Nurseries
23	Confined Feeding Operations
24	Other Agricultural Land
31	Herbaceous Rangeland
32	Shrub and Brush Rangeland
33	Mixed Rangeland
41	Deciduous Forest Land
42	Evergreen Forest Land
43	Mixed Forest Land
51	Streams and Canals
52	Lakes
53	Reservoirs
54	Bays and Estuaries
61	Forested Wetlands
62	Nonforested Wetlands

Figure A.1: USGS Land Use Codes



Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area[2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only)[4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation)[5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

Figure A.2: Runoff Curve Numbers for Urban Areas (SCS, 1986)

Table A.1: Rawls and Brakensiek Soil Parameter Estimates

USDA Textural Classification	θ_S	θ_e	θ_f	θ_{wp}	θ_r	ψ_b	λ	K_S	ψ_f
Sand	0.437	0.417		0.033	0.02	7.26	0.694	23.56	4.95
Loamy sand	0.437	0.401		0.055	0.035	8.69	0.553	5.98	6.13
Sandy loam	0.453	0.412		0.095	0.041	14.66	0.378	2.18	11.01
Loam	0.463	0.434		0.117	0.027	11.15	0.252	1.32	8.89
Silt loam	0.501	0.486		0.133	0.015	20.79	0.234	0.68	16.68
Sandy clay loam	0.398	0.330		0.148	0.068	28.08	0.319	0.30	21.85
Clay loam	0.464	0.390		0.197	0.075	25.89	0.242	0.20	20.88
Silty clay loam	0.471	0.432		0.208	0.040	32.56	0.177	0.20	27.30
Sandy clay	0.430	0.321		0.239	0.109	29.17	0.223	0.12	23.90
Silty clay	0.479	0.423		0.250	0.056	34.19	0.150	0.10	29.22
Clay	0.475	0.385		0.272	0.090	37.30	0.165	0.06	31.63

APPENDIX B. PREPARING SSURGO SOIL DATA FOR MODELING USE

In this tutorial you will learn how to obtain detailed information from the internet on the soil types located within any watershed in the United States. These properties can be used to more accurately model infiltration in our watershed models. Prior to using the data you obtain, however, you will learn how to format the data to work with the Watershed Modeling System.

As water resources engineers, we often need to understand how a watershed will respond to a particular storm event. In order to make an accurate prediction, we must model many different processes occurring within the watershed such as precipitation, overland flow, stream flow, and infiltration. One of the most important but sometimes neglected processes is infiltration. Infiltration is the process by which water seeps into the soil covering an area. Once water has infiltrated into the soil, it percolates through the soil, perhaps lost from the watershed to the water table or perhaps only to reappear in the watershed runoff as it exits the ground through a spring.

In order to properly model infiltration we need to know some of the properties of the soil located within the watershed of interest. Soil is not a homogenous substance and often many different types of soil with very different properties are found within the same watershed. WMS allows us to model this spatial distribution of different soil types within a watershed. First, we obtain surveyed data which describes the soils within the watershed. This data is most often found in the form of a shapefile, a common form of data exchange for geo-spatial data. Next, we format this data for use in WMS. Then, we import this data into the watershed model to specify the parameters for the infiltration model and run the model. The diagram below provides an overview of this process:

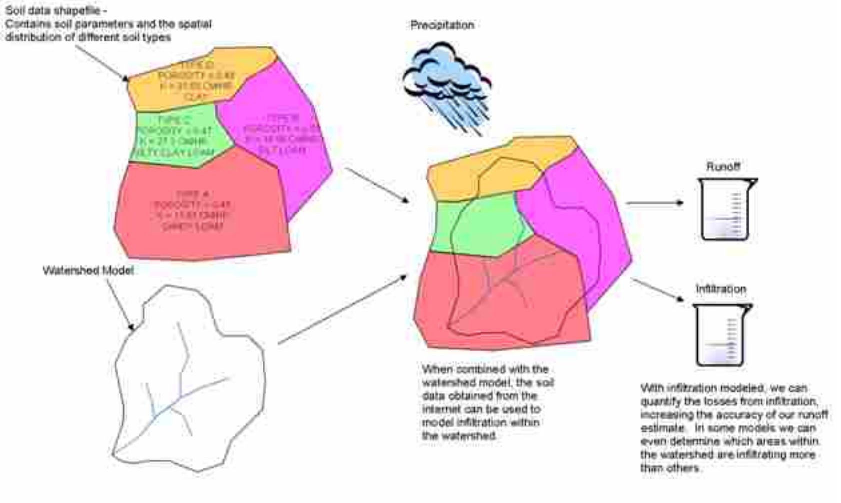


Figure B.1: Using a Shapefile to Define Soil Properties in a Watershed

B.1 Obtain Soil Properties Data from the Internet

Geospatial soil data exists on the internet in a variety of formats from different sources. The most detailed soil data is provided by the Natural Resources Conservation Services (NRCS). The data provided by the NRCS is broken up into individual counties within each of the fifty United States. This detailed data is often referred to as SSURGO data and is the most useful soil data readily available for hydrological modeling.

1. Open a Web browser such as Microsoft Internet Explorer or Mozilla Firefox. Navigate to the Geospatial Data Acquisition website at: http://www.emrl.byu.edu/gsda/

2. Scroll down the page to the Surface Characteristics section and click on the picture which has "Soil Type" written underneath it. Then on the next page, click on the "Obtain Soil Type Data" button.

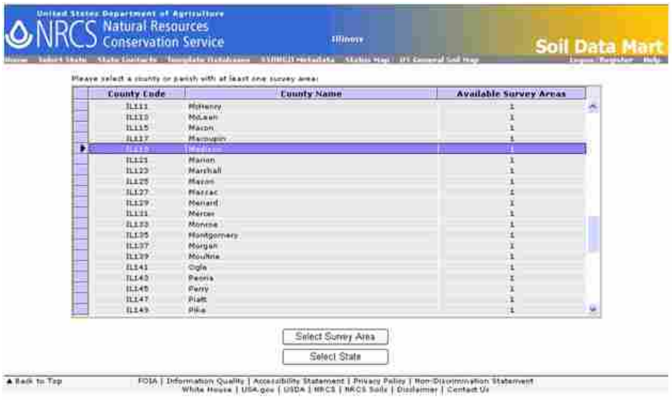
   This will take you to a page with descriptions of and links to the different agencies that provide soil type data. Data from the NRCS can be obtained from two locations: the NRCS's own, Soil Data Mart, and the United States Department of Agriculture's (USDA's), Geospatial Data Gateway. The Soil Data Mart is the easiest way to acquire SSURGO data.

3. Click on the "Click Here" button located beneath the Soil Data Mart description. You should now see the Soil Data Mart web page in your browser. The welcome page explains the purpose and function of the web site and provides you with access to a more detailed explanation in an Adobe PDF file which you may be interested in.

4. Click the "Select State" button.

   The watershed we would like to model is the Judy's Branch watershed located in Madison County, Illinois.

5. Select Illinois from the list, then click the "Select County" button at the bottom of the list. A list of the counties in Illinois should appear (see Figure B.2).



Please select a county or parish with at least one survey area:

County Code	County Name	Available Survey Areas
IL111	McHenry	1
IL113	McLean	1
IL115	Macon	1
IL117	Macoupin	1
IL119	Madison	1
IL121	Marion	1
IL123	Marshall	1
IL125	Mason	1
IL127	Massac	1
IL129	Menard	1
IL131	Mercer	1
IL133	Monroe	1
IL135	Montgomery	1
IL137	Morgan	1
IL139	Moultrie	1
IL141	Ogle	1
IL143	Peoria	1
IL145	Perry	1
IL147	Piatt	1
IL149	Pike	1

Figure B.2: List of Counties in Illinois on the Soil Data Mart Webpage

6. Scroll down through the list and select "Madison" (as shown in Figure 1 above), and then click on the "Select Survey Area" button beneath the list. A list of the available areas for which soil properties were surveyed in Madison County will now appear.

   Note: In this example, only one survey area is available within Madison County. In other areas of the United States, more than one survey may have been performed within a county. If this is the case with your area of interest you must use the name of the surveyed area and your knowledge of the area to determine which surveyed area includes your watershed.

7. Select “Madison County, Illinois” from the list and then click on the “Download Data” button beneath the list.

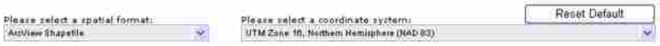
   Although we are primarily concerned with obtaining soil texture information for hydrological modeling, the SSURGO database located at the Soil Data Mart provides much more information if you need it. The page which you see now has many options which must be selected correctly for the data to be downloaded in a format easily recognizable by WMS.

8. Select the button next to “Tabular and Spatial Data” at the top of the page (See Figure B.3).

○ Tabular Data Only ● Tabular and Spatial Data ○ Spatial Data Only ○ Template Database Only

Figure B.3: Screenshot of Data Class Selection Options

9. Confirm that the spatial format is set to “ArcView Shapefile” and the coordinate system is set to “UTM Zone 16, Northern Hemisphere (NAD 83)” (See Figure B.4).



Please select a spatial format: ArcView Shapefile

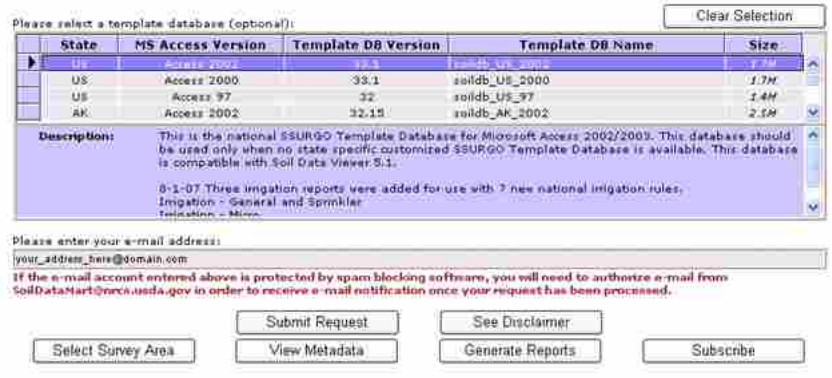
Please select a coordinate system: UTM Zone 16, Northern Hemisphere (NAD 83)

Figure B.4: Screenshot of Spatial Format and Coordinate System Options

   Note: If your model is in a different coordinate system, you can select the system used in your model.

10. Select the entry in the list with “soildb-US2002” listed in the column titled “Template DB Name.” It should be the first entry in the list (See Figure B.5).

    Tip: If there is more than one file available for download for your watershed, follow these general guidelines for selecting a file:



Please select a template database (optional):

State	MS Access Version	Template DB Version	Template DB Name	Size
US	Access 2002	33.1	soildb_US_2002	1.7M
US	Access 2000	33.1	soildb_US_2000	1.7M
US	Access 97	32	soildb_US_97	1.4M
AK	Access 2002	32.15	soildb_AK_2002	2.5M

Description: This is the national SSURGO Template Database for Microsoft Access 2002/2003. This database should be used only when no state specific customized SSURGO Template Database is available. This database is compatible with Soil Data Viewer 5.1.

8-1-07 Three irrigation reports were added for use with 7 new national irrigation rules.
Irrigation - General and Sprinkler
Irrigation - Micro

Please enter your e-mail address:

your_address_here@domain.com

If the e-mail account entered above is protected by spam blocking software, you will need to authorize e-mail from SoilDataMart@nrcs.usda.gov in order to receive e-mail notification once your request has been processed.

Figure B.5: Screen shot of Template Database Selection Options

- If there is no file listed with a state that matches the one where the watershed is located, select the file with ”US” listed as the state (as in this tutorial).
- Select the file with the most recent year listed in the “MS Access Version” column.
- If you still can’t decide, refer to the Soil Data Mart webpage Help section.

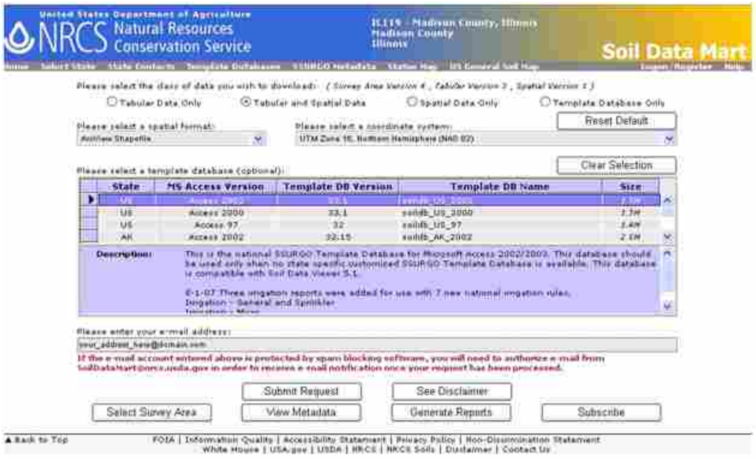
In order to download the data, you must provide an email address.

11. Enter your email address, make sure it is typed correctly, and that all the other settings are correct. You should have the same options selected as in the screenshot shown in Figure B.6 below. Click the “Submit Request” button.

    This brings up a notification displaying your “place in line” and guidelines for estimating the time before the data will be ready to download.

12. Click “OK” to close the notification. At this point, you can close your internet browser.

    Depending on the number of people trying to download from the Soil Data Mart servers, you may have to wait between a couple of minutes to a couple of hours. Eventually you will receive an email from SoilDataMart@nrcs.usda.gov containing a link to a zip file with all the SSURGO data you need.



IL119 - Madison County, Illinois
Madison County
Illinois

Please select the class of data you wish to download: (Survey Area Version 4 , Tabular Version 3 , Spatial Version 1)

○ Tabular Data Only ● Tabular and Spatial Data ○ Spatial Data Only ○ Template Database Only

Please select a spatial format: ArcView Shapefile

Please select a coordinate system: UTM Zone 16, Northern Hemisphere (NAD 83)

Please select a template database (optional):

State	MS Access Version	Template DB Version	Template DB Name	Size
US	Access 2002	33.1	soildb_US_2002	2.1M
US	Access 2000	33.1	soildb_US_2000	2.7M
US	Access 97	32	soildb_US_97	2.4M
AK	Access 2002	32.15	soildb_AK_2002	2.1M

Description: This is the national SSURGO Template Database for Microsoft Access 2002/2003. This database should be used only when no state specific customized SSURGO Template Database is available. This database is compatible with Soil Data Viewer 5.1.

6-1-07 Three irrigation reports were added for use with 7 new national irrigation rules.
Irrigation - General and Sprinkler

Please enter your e-mail address: your_address_here@domain.com

If the e-mail account entered above is protected by spam blocking software, you will need to authorize e-mail from SoilDataMart@nrcs.usda.gov in order to receive e-mail notification once your request has been processed.

Figure B.6: Completed Download Screen for SSURGO Data

13. Click on the link in the email and your browser should begin downloading the file. Save the file as soil-il119.zip to a convenient location such as C:/Temp. You may need to create the folder if it doesn't already exist.

    WARNING - The file will be a relatively large file (approx. 20-40 MB) so make sure you wait till the file is entirely downloaded before you move to the next step.

B.2 Processing and Formatting the SSURGO Data

Once you've completed the previous steps, you will have the raw data necessary to define the soil properties in your model. Next, you will learn how to properly format this data for use in WMS.

The file you just downloaded is a compressed folder filled with other files. WMS needs three files to map soil properties correctly. These three files must have the same name, but different extensions. A summary of these files is given below:

- Shapefile (.shp extension)

  Specifies the position of polygons representing areas of soil with different properties within the selected survey area.

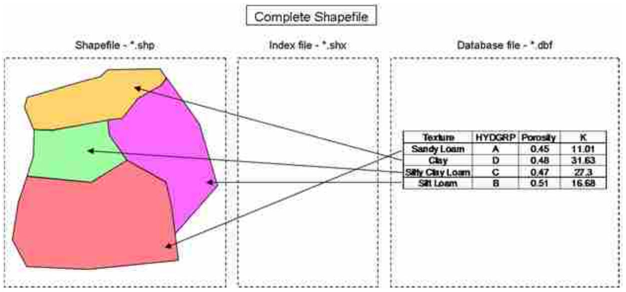
- Database file (.dbf extension)

Contains various attributes such as soil type and porosity for each polygon specified in the shapefile.

- Index file (.shx extension)

  Specifies how to link the shapefile and database file together.

  This relationship can be visualized as in the Figure B.7.



Texture	HYDGRP	Porosity	K
Sandy Loam	A	0.45	11.01
Clay	D	0.48	31.63
Silty Clay Loam	C	0.47	27.3
Silt Loam	B	0.51	16.68

Figure B.7: Diagram of a Complete Shapefile

Although the data you obtained contains the three necessary files, you must make some changes to these files before you can use them in WMS. The default database file does not contain the soil texture information you need to correctly define infiltration parameters in the model. This soil texture information is instead located in a separate ASCII text file located in the zip file downloaded from the Soil Data Mart. You will now use a previously developed Microsoft Excel Spreadsheet to add the soil texture information to the database file.

Before you can do anything with the data, you have to extract the files from the zip file. You can do this either with a program like WinZIP or in Windows 2000 or later by opening or right-clicking the zip file and selecting "Extract all files." Make sure to extract them to a location you will remember. For this tutorial extract the files to C:/Temp.

1. Open Microsoft Excel 2003. To use the spreadsheet, we must first enable macros. Select Tools/Macro/Security On the "Security Level" tab, make sure the "Medium" option is selected, then click "OK".

WARNING - The current version of the spreadsheet only functions in Microsoft Excel 2003. The 2007 version does not support editing of database files (.dbf extension).

2. Select File/Open and open the sssurgoImport.xls from wherever you saved it previous to beginning the tutorial. Click on "Enable Macros" when the warning prompt appears to ensure the spreadsheet works correctly.

   Next, a notification will appear telling you "ssurgoImport.xls" should be opened as read-only.

3. Select "Yes" to open the file as read-only.

   The "Basic" tab at the bottom of the page should be selected. If not, switch to the "Basic" tab. You should now see a spreadsheet that looks similar to the screen shot in Figure B.6. There are instructions included in the spreadsheet itself which you can refer to if you need a reminder or clarification.

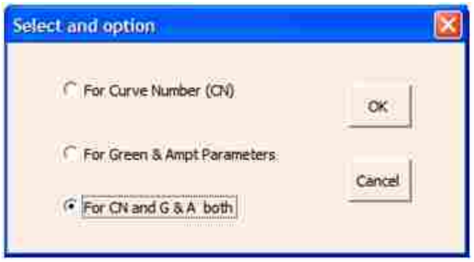
Figure B.8: The SSURGOImport.xls Spreadsheet

4. Click the "Refresh" button to make sure any old data is cleared from the other tabs in the spreadsheet.

5. Click on the "Initiate" button.

   This will open the dialog box shown below. You can specify if you want to format the data for using the SCS Curve Number (CN) or the Green and Ampt (G&A) method or both for modeling infiltration. These options simply control which properties are extracted from the text file for inclusion in the database file.

6. Select the option “For CN and G&A both.” Then click “OK” to close the dialog box. This will allow you to use either the CN or G&A method when you build your watershed model.



○ For Curve Number (CN)
○ For Green & Ampt Parameters
● For CN and G & A both

Figure B.9: Infiltration Modeling Method Options

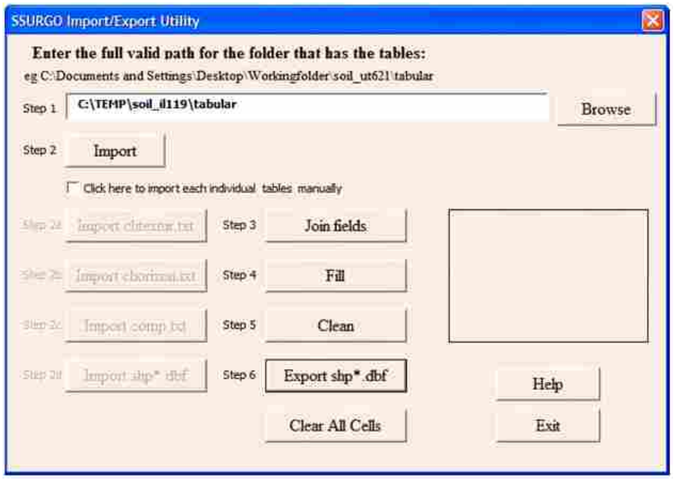
A new Dialog box titled “SSURGO Import/Export Utility” will open. This dialog box will guide us through the rest of the process.

Note: There are six steps outlined in the dialog box itself. These steps correspond to steps 8 through 15 in this tutorial.

WARNING - If you close this dialog box or click the “Exit” button, you will need to click the “Initiate” button in the spreadsheet again and resume the tutorial from step 7.

First, we must browse to the location of the tables which contain the soil property information we want to add to the database file. This file is named “tabular” and is one of the folders we extracted from the zip file earlier.

7. Click the “Browse” button and navigate to the location of the “tabular” folder and click “OK”. If you’ve followed this tutorial up to this point, the folder is located in C:/Temp/soil-il119/tabular. (Step 1)



SSURGO Import/Export Utility

Enter the full valid path for the folder that has the tables:

eg C:\Documents and Settings\Desktop\Workingfolder\soil_ut621\tabular

Step 1 C:\TEMP\soil_il119\tabular

☐ Click here to import each individual tables manually

Figure B.10: "SSURGO Import/Export Utility" Dialog Box

8. Click the "Import" button. This will copy the contents of the shapefile database file, the "chtexture.txt" file, "chorizon.txt" file, and "comp.txt" file, to their respective tabs in the spreadsheet. (Step 2)

   At this point, each tab in the spreadsheet should contain information about the soils. There is a large amount of information in these tables. You only need a few properties for each soil, such as texture, hydrologic soil group, porosity, etc. The "shp" tab contains the information currently in the database associated with the soils shapefile you will use in WMS. If you click on the "shp" tab at the bottom of the screen you will notice that the sheet contains four columns with values in them, but none of these values look like the properties you need in your shapefile. The next steps will add the properties you need to this tab.

   Each table in your spreadsheet has an entry named "MUKEY" which is a unique identifier for the soil type. The "Join fields" button will copy the soil properties from the other tabs that have an "MUKEY" that matches the "MUKEY" in the "shp" tab and then it will add them to the "shp" tab.

9. Click on the "Join fields" button. You will see a progress bar dialog box like the one shown below. Be patient as the joining process may take several minutes. (Step 3)

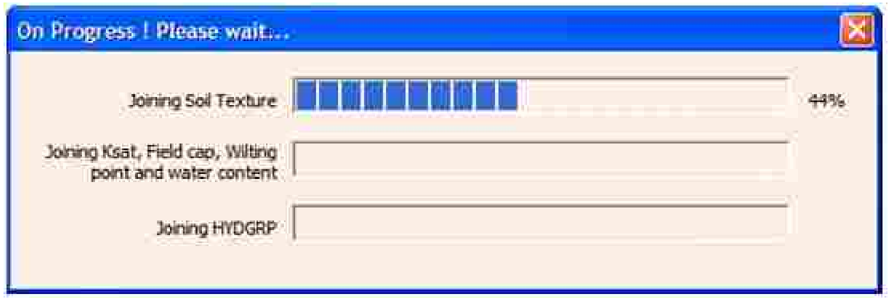


Figure B.11: Join Fields Progress Dialog Box

When the field joining process is complete, the ”SSURGO Import/Export Utility” dialog box will reappear. There are some fields in the ”shp” that may still be lacking values because there was no data for them in the other tables.

10. Click the “Fill” button. (Step 4)

    A new box appears, asking you to select a soil type from a list. Pick a soil type from the dropdown menu that you think is the predominant type of soil in your watershed.

11. Choose “silt loam” (the predominant soil type in the Judy’s Branch watershed) and click “Ok.” This will assign the properties of the soil type you selected to the blank fields in the ”shp” tab.

    Some of the HYDGRP fields which specify the hydrologic soil group contain a value such as “A/B” or “B/C.” WMS will only recognize a single character value in this field.

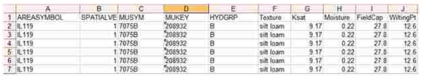
12. Click the “Clean” button. This will change any combination HYDGRP fields to a single character. (Step 5)

    Note: The “SSURGO Export/Import Utility” does not indicate if anything was done when you clicked on the “Clean” button. You can confirm that the operation was completed successfully in the next step. The values in the HYDGRP column should all be single character values of A, B, C, or D.

13. Move the "SSURGO Import/Export Utility" window to the side of your monitor and click on the "shp" tab.

    You can see now that the tab contains all the soil properties you need for your watershed model. Your "shp" tab should look similar to the figure below.

    Note: More rows of data will be visible on your screen but the number and name of the columns should be the same as Figure B.12.



	A	B	C	D	E	F	G	H	I	J
1	AREASYMBOL	SPATIALVE	MUSYM	MUKEY	HYDGRP	Texture	Ksat	Moisture	FieldCap	WiltingPt
2	IL119	1	7075B	208932	B	silt loam	9.17	0.22	27.8	12.6
3	IL119	1	7075B	208932	B	silt loam	9.17	0.22	27.8	12.6
4	IL119	1	7075B	208932	B	silt loam	9.17	0.22	27.8	12.6
5	IL119	1	7075B	208932	B	silt loam	9.17	0.22	27.8	12.6
6	IL119	1	7075B	208932	B	silt loam	9.17	0.22	27.8	12.6
7	IL119	1	7075B	208932	B	silt loam	9.17	0.22	27.8	12.6

Figure B.12: Completed "shp" Tab

14. Click on the "Export shp*.dbf" button. Save the file in a convenient location. For Judy's Branch, name the file "ssurgoSoils.dbf" and save it in the C:/Temp/soil-il119/spatial folder. (Step 6)

    You have now created a new database file which contains the soil properties you need for you watershed model, but for WMS to associate that database file with the correct polygons in the shape file, it must have the same name as the .shp and .shx files.

15. In a Windows Explorer navigate to the C:/Temp/soil-il119/spatial folder and copy and rename the soilmu-a-il119.shp and soilmu-a-il119.shx files as ssurgoSoils.shp and ssurgoSoils.shx respectively.

    Note: Some of the file extensions may not be shown in the Windows Explorer. If they are not shown, refer to the Windows Help to learn how to make them appear.

    Tip: If you download data for a different watershed than Judy's Branch, the files will not be named "soilmu-a-il119". They will be named "soilmu-a-xx123" where "xx123" is the same as the two-letter, three-number combination as in the name of the zip file you download from the Soil Data Mart (e.g. "il119" in "soil-il119.zip).

WARNING - If all three files do not have the exact same name (excluding their unique extensions), WMS will import the shapefile and soil properties incorrectly. In addition, all three files must be located in the same folder.

16. You can now exit the "SSURGO Import/Export Utility" dialog and exit Microsoft Excel. Do not save the changes to the ssurgoImport.xls file when prompted.

You have now properly formatted the soils data for use in WMS. You now have a complete shapefile which you can import into WMS to spatially define the soil properties within your watershed model. Refer to Chapter 5 on Infiltration in WMS Tutorial Volume 2 for instruction on importing a shapefile into the WMS interface and setting up your infiltration model.