A Study of Geographic Information System-Based Watershed Processing for Hydrologic Analysis of Ungauged Watersheds

Philip Adanbe Adalikwu
South Dakota State University

Follow this and additional works at: https://openprairie.sdstate.edu/etd

Part of the Geographic Information Sciences Commons, Hydraulic Engineering Commons, and the Water Resource Management Commons

Recommended Citation


This Dissertation - Open Access is brought to you for free and open access by Open PRAIRIE: Open Public Research Access Institutional Repository and Information Exchange. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of Open PRAIRIE: Open Public Research Access Institutional Repository and Information Exchange. For more information, please contact michael.biondo@sdstate.edu.
A STUDY OF GEOGRAPHIC INFORMATION SYSTEM-BASED WATERSHED PROCESSING FOR HYDROLOGIC ANALYSIS OF UNGAUGED WATERSHEDS

By

PHILIP ADANBE ADALIKWU

A dissertation submitted in partial fulfillment of the requirements for the

Doctor of Philosophy

Major in Civil Engineering

South Dakota State University

2021
This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Suzette Burckhard
Advisor

Nadim Wehbe
Department Head

Nicole Lounsbery, PhD
Director, Graduate School
This dissertation is dedicated to the following special people: my dear wife Neche, mom Elizabeth, late dad, brothers, and sisters.
ACKNOWLEDGEMENTS

My profound gratitude goes to my advisor, Dr. Suzette R. Burckhard for her guidance and support throughout the program. She inspired me to pursue a PhD degree in Civil Engineering, coming from a similar background in Physics. And she has been relentless in making sure that this research is of high quality. Thank you so much for committing your time and resources. My sincere appreciation to the other members of my dissertation committee, Dr. Schmit, Dr. Hua and Dr. Gu, who were very committed to ensuring that project milestones were met. Their questions and comments have greatly improved this work. To my dear wife, Neche, who has provided a shoulder to lean on during the low moments of this journey, I love you and thank you so much. Special thanks to my mom and biggest fan for all her love, support, and encouragement. She could not wait to call me “Dr. Phil”. To my brothers and sister who have walked this path before me for their inspiration, motivation, and support: Dr. Chris, Dr. Paul, and Dr. Justy, thanks a million. Many thanks and appreciation to sister Martina, brothers John and Rico and their families for their love and encouragement. Finally, thanks to my colleagues in Dr. Burckhard’s research group for providing the opportunity for rigorous and productive discussions on watershed modeling and related hydrologic concepts.
# TABLE OF CONTENTS

ABBREVIATIONS .................................................................................................................. viii

LIST OF TABLES .................................................................................................................... ix

LIST OF FIGURES .................................................................................................................... xi

ABSTRACT ................................................................................................................................. xiv

1. Chapter One: Background and Motivation ................................................................. 1
   1.1. Introduction ..................................................................................................................... 1
   1.2. Research Objectives ..................................................................................................... 4
   1.3. Overview of Dissertation ............................................................................................ 5

2. Chapter Two: Literature Review of Issues Associated with Modeling
   Ungauged Watersheds ........................................................................................................... 7
   Abstract ................................................................................................................................. 7
   2.1. Introduction ..................................................................................................................... 8
   2.2. Watershed Subdivision Practice ................................................................................... 9
   2.3. Regionalization and Modeling of Ungauged Watersheds ........................................... 11
   2.4. Geographic information system (GIS) Datasets ......................................................... 14
      2.4.1. Digital Elevation Model (DEM) Issues ................................................................. 15
      2.4.2. Resolution/Grid Cell Size/Resampling ................................................................. 17
      2.4.3. Creating a Soil Conservation Service Curve Number (CN) Grid ...................... 18
   2.5. Conclusions ................................................................................................................... 20

3. Chapter Three: Evaluating Watershed Subdivision Effect on Runoff
   Characteristics for Improved Hydrologic Analysis of Ungauged
   Watersheds ......................................................................................................................... 21
Abstract ......................................................................................................................... 21

3.1. Introduction ........................................................................................................... 22

3.2. Methodology ....................................................................................................... 25

  3.2.1. Materials ......................................................................................................... 25

  3.2.2. Methods .......................................................................................................... 41

3.3. Results .................................................................................................................. 46

  3.3.1. Simulation Results for W1 ............................................................................. 46

  3.3.2. Simulation results for W2 .............................................................................. 51

  3.3.3. Simulation results for W3 .............................................................................. 54

  3.3.4. Simulation results for W4 .............................................................................. 56

  3.3.5. Comparison of peak discharge values for W1 and W4 .................................. 62

3.4. Discussions ......................................................................................................... 62

  3.4.1. W1 Discussion ................................................................................................. 63

  3.4.2. W2 Discussion ................................................................................................. 65

  3.4.3. W3 Discussion ................................................................................................. 67

  3.4.4. W4 Discussion ................................................................................................. 67

3.5. Conclusions ........................................................................................................... 69

4. Chapter Four: Evaluating Input Data Resolution Effect on Runoff
   Characteristics for Improved Hydrologic Analysis of Ungauged Watersheds .............. 71

Abstract ......................................................................................................................... 71

4.1. Introduction ......................................................................................................... 72

4.2. Methodology ....................................................................................................... 75
4.2.1. Materials ........................................................................................................75
4.2.2. Methods .........................................................................................................87
4.3. Results ..............................................................................................................96
4.4. Discussions ......................................................................................................101
4.5. Conclusions .....................................................................................................105
5. Chapter Five: Overall Conclusions ...................................................................107
  5.1. Chapter Two ...................................................................................................107
  5.2. Chapter Three ................................................................................................108
  5.3. Chapter Four ..................................................................................................109
6. Chapter Six: Suggestions for Future Research .................................................110
7. References ...........................................................................................................111
ABBREVIATIONS

GIS - Geographic Information System

DEM - Digital Elevation Model

HMS – Hydrologic Modeling System

HEC-HMS - Hydrologic Engineering Center Hydrologic Modeling System

HEC-GeoHMS – Hydrologic Engineering Center Geo-Hydrologic Modeling System

WshSlope – Watershed Slope

AGREEDEM – Agree Digital Elevation Model

Fil – Fill

Fdr – Flow Direction

Fac – Flow Accumulation

Area SqKm – Area Square Kilometer

SCS CN – Soil Conservation Service Curve Number

W1 – Indian Creek Watershed

W2 – Mud Creek Watershed

W3 – Wolf Butte Creek Watershed

W4 – St. Paul’s Church Watershed
LIST OF TABLES

Table 2. 1. Some hydrologic studies implementing watershed subdivision. ......................... 10
Table 2. 2. Original NLCD classification and re-classification (USGS, 2013). .................... 19

Table 3. 1. Original NLCD classification and re-classification (USGS, 2013) ...................... 28
Table 3. 2. Showing sizes of study areas and their land use, soil groups and average curve numbers (CNs) ........................................................................................................... 30
Table 3. 3. U.S. Natural Resources Conservation Service criteria for Hydrologic soil groups. ................................................................................................................................... 31
Table 3. 4. Showing dataset types, description, sources, special references, geodetic models, format, source scale denominator and year of processing. ............................. 36
Table 3. 5. Hydrologic parameter processes and methods.................................................... 37
Table 3. 6. Frequency storm simulation results for W1 showing 6 levels of subdivisions. .. 47
Table 3. 7. SCS type 2 storm simulation results for W1 showing 6 levels of ......................... 49
Table 3. 8. NSC type 2 storm simulation results for W2 showing 3 levels of subdivisions.. 52
Table 3. 9. SCS type 2 storm simulation results for W3 showing 6 levels of ......................... 54
Table 3. 10. Frequency storm simulation results for W4 showing seven levels of subdivisions .......................................................................................................................... 57
Table 3. 11. NSC type 2 storm simulation results for W4 showing 7 levels of ..................... 59

Table 4. 1. Original NLCD classification and re-classification (USGS, 2013) .................... 77
Table 4. 2. U.S. Natural Resources Conservation Service criteria for Hydrologic soil groups. .................................................................................................................................... 78
Table 4. 3. Showing size of study area and its land use, soil groups and average curve numbers (CNs)..................................................................................................................79

Table 4. 4. Showing dataset types, description, sources, special references, geodetic models, format, source scale denominator and year of processing...........................................82

Table 4. 5. Hydrologic parameter processes and methods.................................................................83

Table 4. 6. Showing simulation results for different grid size models..............................................97
LIST OF FIGURES

Figure 3. 1. Showing the location of South Dakota on the US map ..............................................26

Figure 3. 2. Showing the study areas (Indian Creek and St. Paul’s Church watersheds) in Perkins and Brookings Counties in South Dakota, respectively ..................................27

Figure 3. 3. Showing (a) HUC12 layer for Perkins County with three study areas, (b) W3, (c) W1, and (d) W2 located in Perkins county ..........................................................29

Figure 3. 4. Showing (a) HUC12 layer for Brookings County and (b) shape and clipped DEM with streams for W4 ..........................................................33

Figure 3. 5. Flowchart showing data preprocessing using HEC-GeoHMS and storm event simulation using HEC-HMS .................................................34

Figure 3. 6. Depicting six (6) WI subdivision scenarios or levels: (a) level 1 (entire watershed), (b) level 2 (3 subdivisions), (c) level 3 (5 subdivisions), (d) level 4 (11 subdivisions), (e) level 5 (25 subdivisions) and (f) level 6 (53 subdivisions) ..........................................................42

Figure 3. 7. Showing subdivision effect on runoff when simulated with a Frequency storm precipitation method for W1 .................................................48

Figure 3. 8. Showing subdivision effect on runoff when simulated with an SCS type 2 storm precipitation method for W1 ..........................................................50

Figure 3. 9. Showing total channel slopes and total flow lengths trends for W1 ..................50

Figure 3. 10. Hydrographs at the outlet of W1 for the respective subdivision levels .................51

Figure 3. 11. Showing subdivision effect on runoff when simulated with SCS type 2 storm for W2 ..........................................................53

Figure 3. 12. Showing total channel slopes and total flow lengths trends for W2 ...............53
Figure 3. 13. Showing subdivision effect on runoff when simulated with an SCS type 2 storm for W3. .................................................................................................................. 55

Figure 3. 14. Showing total channel slopes and total flow lengths trends for W3. .............. 56

Figure 3. 15. Showing subdivision effect on runoff when simulated with a frequency storm for W4. .................................................................................................................. 58

Figure 3. 16. Showing subdivision effect on runoff when simulated with an SCS type 2 storm. .................................................................................................................. 60

Figure 3. 17. Showing total channel slopes and total flow lengths trends for W4. .............. 60

Figure 3. 18. Showing hydrographs at the outlet of W4 for the respective subdivision levels. .................................................................................................................. 61

Figure 3. 19. Showing subdivision in W2 to illustrate how subbasins are merged to resolve the cascading of channel slope errors during subdivision. ......................... 66

Figure 4. 1. Showing the location of study area in Perkins county, South Dakota............ 76

Figure 4. 2. Showing (a) HUC12 layer for Perkins County and (b) shape and clipped boundary extent for W1 ..................................................................................................... 79

Figure 4. 3. Flowchart showing data preprocessing using HEC-GeoHMS and storm event simulation using HEC-HMS. ......................................................................................... 81

Figure 4. 4. Showing an original 10m DEM (DEM10), resampled to 50m (DEM50) and resampled to 100m (DEM100) ......................................................................................... 89

Figure 4. 5. Depicting catchment grids for an original 10m DEM (DEM10), resampled to 50m (DEM50) and 100m (DEM100) ........................................................................... 90
Figure 4.6. Depicting impervious % grids for a 10m (IMP10), 50m (IMP50) and 100m (IMP100) resampled from an original 30m data.................................................91

Figure 4.7. Depicting an original 10m (CN10) CN grid, resampled to 50m (CN50) and 100m (CN100)..................................................................................................................92

Figure 4.8. Showing preprocessed data used for building HMS models.............................................94

Figure 4.9. Showing runoff hydrographs at the outlet of the study area for baseline, 20-, 50-, and 100-m resolution models..................................................................................................................98

Figure 4.10. Showing the impact of data re-sizing on peak discharge relative to drainage area.................................................................................................................................99

Figure 4.11. Showing the impact of data re-sizing on time to peak relative to drainage area. ..................................................................................................................................................100

Figure 4.12. Showing the impact of data re-sizing on runoff volume relative to drainage area.................................................................................................................................100

Figure 4.13. Depicting degraded catchment and flow accumulation grids from an original 10m DEM (DEM10), resampled to 50m (DEM50) and 100m (DEM100). ......104
ABSTRACT

A STUDY OF GEOGRAPHIC INFORMATION SYSTEM-BASED WATERSHED PROCESSING FOR HYDROLOGIC ANALYSIS OF UNGAUGED WATERSHEDS

PHILIP ADANBE ADALIKWU

2021

The increasing application of geographic information system (GIS) technology in watershed modeling makes it necessary to further evaluate its impacts on runoff characteristics as a basis for improved hydrologic analysis in ungauged watersheds. Experts in the field of water resources and hydrology have recommended the practice of subdivision when modeling a watershed, and the use of observed data from hydrologically similar watershed to calibrate and validate an ungauged watershed’s model. However, previous studies have failed to adequately address the issues of watershed heterogeneity, spatial and temporal variability in physical parameters, GIS data resolution issues, including artifacts in automated extraction of topographic attributes from elevation datasets. This study utilized the US Army Corps of Engineers Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) to evaluate the effects of watershed subdivision and input data resolution on peak discharge in ungauged watersheds. To better understand the underlying processes in ungauged watershed hydrology, runoff hydrographs were simulated at the outlets of study areas located in different hydrological subregions and subdivided into different subdivision scenarios or levels. Simulation results show that total channel slopes and total flow lengths increased with further subdivision, resulting in high peak discharges. Similarly, runoff hydrographs at the outlets of different resolution models were simulated and analyzed. Simulation results indicate that peak discharge values increased as finer
resolution datasets were resampled to coarser resolutions with a slight reduction in the sizes of drainage areas. A better understanding of a watershed’s runoff characteristics is a basis for improved hydrologic analysis of ungauged watersheds.
1. Chapter One: Background and Motivation

1.1. Introduction

Challenges associated with modeling ungauged watersheds have been of great concern to experts in the field of water resources, especially water engineers, watershed managers and governmental agencies tasked with policy decisions, over the years. These challenges have been amplified by incessant destruction to the environment due to climate change and changes in land use globally. Flooding has been identified as the single most concerning problem, especially in the least developed parts of the world. As Douglas et al., (2008) stated, “many urban poor in Africa face growing problems of flooding. Increased storm frequency and intensity related to climate change are exacerbated by such local factors as growing occupation of floodplains, increased runoff from hard surfaces, inadequate waste management and silted-up drainage”.

Several Asian and African countries in recent years have suffered from severe flooding. Nigeria is a country in Africa that was hit by devastating floods as recently as 2012 and 2016. The 2012 floods were reported to be the worst in forty years, causing widespread damage to homes, impacting economic and agricultural activities, and in some cases, loss of lives. Specifically, these floods affected thirty out of the thirty-six states of that country, killed over three hundred and sixty people, and displaced over two million more, with an estimated cost of three trillion naira (₦3 trillion) in flood impacts and damages (Agada & Nirupama, 2015; Akankali & Jamabo, 2012; Aloysius, 2012; Kayode, Yakubu, Ologunorisa, & Kola- Olusanya, 2017; Loveline, 2015; Mmom & Aifesehi, 2013; Tami & Moses, 2015). The 2016 floods were equally as devastating as those in 2012 and consequently, several studies have been conducted to examine current
approaches by private and government agencies at all levels. For instance, Adelekan (2016) discussed the devastation by floods to Lagos, Nigeria’s most populous and economic nerve center of the country and suggested that flood risks management be integrated into future sustainability plans. Also, Adelekan & Asiyanbi (2016) and Daramola, Oni, Ogundele, & Adesanya (2016) have discussed the perception of flood risks in affected communities and response strategies to floods and concluded that current efforts by government may neither be proactive nor effective in lowering citizens’ flood risk vulnerabilities.

In the United States and elsewhere around the world, floods have also recently occurred, causing massive damage with huge financial costs and impacts to man and the environment (Lott & Ross, 2015; Ross & Lott, 2003; Smith & Matthews, 2015). The magnitude of these impacts underscores the need for further investigation of the factors affecting peak discharge, a major parameter in watershed flood modeling. Proper understanding of the dynamism and factors driving runoff processes would enhance the formulation of proactive responses and mitigation mechanisms by policy makers and flood managers, even more so for undeveloped parts of the world where ungauged watersheds predominate.

A major problem associated with modeling ungauged watersheds is availability of observed historical data for model calibration and validation. As a remedy, most experts propose a practice known as regionalization, where observed data from a gauged watershed with hydrologically similar characteristics is utilized for calibration of an ungauged watershed’s model (Chiang, Tsay, & Nix, 2002). The understanding and quantification, therefore, of how the land surface responds to rainfall and its consequent
runoff is heavily reliant on river gauging. Since historical data is imperative to modeling, it becomes challenging when dealing with ungauged watersheds.

Studies have investigated and suggested that the best approach at modeling and simulating a watershed’s hydrologic response, water quality, best management practices and model assessment is to subdivide the watershed into smaller hydrologic units or subbasins despite its impact on simulation results (Amore, Modica, Nearing, & Santoro, 2004; Arabi, Govindaraju, Hantush, & Engel, 2006; Bingner, Garbrecht, Arnold, & Srinivasan, 1997; Chang, 2009; Chang & Chao, 2014; Chapiot, 2014; Chiang & Yuan, 2015; FitzHugh & Mackay, 2000, 2001; Gong, Shen, Liu, Wang, & Chen, 2010; Han, Huang, Zhang, Li, & Li, 2014; Jha, Gassman, Secchi, Gu, & Arnold, 2004; Kumar & Merwade, 2009; Norris & Haan, 1993; Nour, Smith, El-Din, & Prepas, 2008; Rouhani, Willems, & Feyen, 2009; Tripathi, Raghuwanshi, & Rao, 2006; Wang, Chen, Huang, Xiao, & Shen, 2016). The general assumption is that these subbasins are homogeneous and their individual characteristics represent the entire watershed. However, simulation results are affected by spatial and temporal variability among multiple subbasins within a watershed.

In recent years, advances in computers, availability of downloadable Geographic Information System (GIS) data and watershed modeling software means that complex watersheds can be spatially analyzed and modeled when integrated with GIS technology. Information derived from GIS data include elevation, drainage networks, slopes, spatial characteristics variability. The spatial variability in these data can be summarized for a watershed to produce useful information for modeling and management decisions purposes. But integrating GIS technology in watershed modeling affects the level of
detail required for high quality model simulations because much of the spatial variability that influences hydrologic responses is lost due to averaging of the data, either at watershed or subbasins level (Chaubey, Cotter, Costello, & Soerens, 2005; Cotter, Chaubey, Costello, Soerens, & Nelson, 2003; Kienzle, 2004). Therefore, there is a lack of general agreement in the literature as to what the resolution of input GIS data should be when utilized in watershed modeling (Lorite, Mateos, & Fereres, 2005; Muleta, Nicklow, & Bekele, 2007; Singh, 1997; Warwick & Litchfield, 1993).

1.2. Research Objectives

This dissertation aims to evaluate the factors that affect peak discharge values in GIS-based watershed models for improved hydrologic analysis of ungauged watersheds. The following are specific research objectives for this research.

1. Literature review: this objective evaluates aspects of hydrologic modeling that are fundamental to ungauged watershed modeling. Topics considered include watershed subdivision, practice of regionalization and the role of Geographic Information System (GIS) in watershed modeling.

2. Evaluate watershed subdivision effect: This objective is to evaluate the effect of watershed subdivision on peak discharge in ungauged watersheds. Specific tasks include:

i. Generating HMS models for different levels of subdivision, with the entire watershed-as-one subbasin as the first model scenario,

ii. Creating HEC-HMS projects with respective subdivision levels or scenarios as basin models.
iii. Evaluating the effect of subdivision on simulation results

3. Data resolution effect on model results: This objective is to evaluate the effect of input data resolution on peak discharge in an ungauged watershed. Specific tasks include:

i. Resampling or resizing of data from their native or original resolutions.

ii. Generating HMS models for different data resolution scenarios, with the first model scenario being the one with data in their native or original resolutions.

iii. Creating HEC-HMS projects with respective resolution scenarios as basin models.

iv. Compare different model scenarios to one with native/original data resolutions.

v. Evaluating the effect of data resolution on simulation results.

Utilizing HEC-HMS, this study reviewed aspects of watershed modeling ensemble that specifically affect ungauged watershed modeling. The practice of watershed subdivision and utilization of GIS datasets in their native and resampled resolutions were further evaluated for a better understanding of runoff characteristics as a basis for improved hydrologic analysis in ungauged watersheds.

1.3. Overview of Dissertation

This dissertation is comprised of six chapters. Chapter One is the overall introduction and includes the background and research objectives of the study. Chapter Two is the literature review of relevant topics in watershed modeling. Particularly, it
discusses the practice of watershed subdivision, application of regionalized data in ungauged watershed modeling, integration of GIS in watershed modeling and associated GIS data issues, and steps involved in geoprocessing of data. Chapters Three and Four cover the two research objectives highlighted in Section 1.2. These two chapters, with their respective abstracts, research questions, materials and methods, results and discussions, and conclusions, are related to the overall goal of improved hydrologic model analysis of ungauged watersheds by evaluating the effects of subdivision practice and data resolution on peak discharge values. Chapters Five and Six are a summary of the overall conclusions and suggestions for further research, respectively.
2. Chapter Two: Literature Review of Issues Associated with Modeling Ungauged Watersheds

Abstract

Water resources engineers and scientists are regularly confronted with issues associated with hydrologic modeling of ungauged watersheds that impact simulation outcomes. Without reliable and accurate model simulation results, project costs can be overestimated or underestimated and, in some cases, lead to loss of lives and property. Previous studies have not adequately addressed the issues of watershed heterogeneity, including spatial and temporal variability in physical parameters, GIS data resolution issues, including artifacts in automated extraction of topographic attributes from elevation datasets associated with modeling ungauged watersheds. This review highlights the ensemble of materials and methods utilized in hydrologic modeling of ungauged watersheds. Therefore, practices of watershed subdivision and regionalization, the use of GIS datasets and issues related to their resolutions were further evaluated. For improved hydrologic analysis of ungauged watersheds, a better understanding of the factors that affect their hydrologic response is important.
2.1. Introduction

Watershed managers, waters resources engineers, hydrologists and government agencies utilize watershed model results to formulate policies and make decision on sustainable watershed management. But they also are faced with the possibility of underestimating or over estimating project costs, a problem that underscores the importance of reliable and accurate simulation results (Garbrecht & Martz, 2000). This problem emphasizes the need to further review factors that play important roles in watershed modeling. Generally, observed historical data is used for model calibration and validation (Chiang, Tsay, & Nix, 2002). But where data is scarce or non-existent, experts have recommended the practice of regionalization, in which data from a gauged watershed is used to calibrate a model for an ungauged watershed with similar hydrologic and geomorphologic characteristics (Gottschalk, 1985).

However, the innovative integration of computers and GIS in watershed modeling means that simulation results are affected by a combination of factors that include computer artifacts, model processes and input data configuration. Specifically, studies have shown that watershed heterogeneity, spatial and temporal variability in physical parameters, GIS data resolution issues and common practices associated with automated extraction of topographic attributes from elevation datasets affect model simulation results (Chaubey, Cotter, Costello, & Soerens, 2005). Policy and decision makers rely on accurate model results to make proper watershed management decisions. GIS-based watershed modeling is generally an ensemble of methods and materials. Methods such as watershed subdivision, use of regionalized historical data for model calibration and validation, and materials such as GIS data are all critical components of
watershed modeling and studies show that they affect simulation results. This section discusses some relevant methods and materials associated with watershed modeling. To better understand a watershed’s hydrologic response to changes and for improved hydrologic analysis of ungauged watersheds, it is therefore important to further evaluate the factors that affect GIS-based watershed modeling.

2.2. Watershed Subdivision Practice

Watershed subdivision is a common practice in hydrologic watershed modeling used to estimate and/or quantify the impacts of changes in a watershed. These estimated or quantified impacts are vital information necessary in climate change studies, hydrologic/hydraulic design projects, flood and drought mitigation planning, and policy and decision making. Specifically, in hydrologic studies, watershed subdivision is implemented to isolate a portion of a watershed impacted by changes in land use or other factors, for instance.

Over the years, watershed subdivision practice has been implemented in several environmental and hydrologic studies (Table 2.1). These include studies by Norris & Haan (1993) who studied the impacts of subdivision on estimated hydrographs and concluded that peak discharge stabilized for five subdivisions but fluctuated for fewer. A sediment load study by Momm et al. (2017) examined automated watershed subdivision for simulations using multi-objective optimization methodology found that some reference layers had more significance that others. On their part, Kamran & Rajapakse (2018) investigated the effect of subdivision and antecedent moisture condition on HEC-
HMS model performance in the Maha Oya Basin in Sri Lanka and concluded that subdividing a watershed impacted flow predictions.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Study</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norris &amp; Haan (1993)</td>
<td>Impacts of subdivision on estimated hydrographs</td>
<td>Peak discharge stabilized for five subdivisions but fluctuated for fewer</td>
</tr>
<tr>
<td>Momm et al. (2017)</td>
<td>Automated watershed subdivision for simulations</td>
<td>Reference layers had more significance than others</td>
</tr>
<tr>
<td>Kamran &amp; Rajapakse (2018)</td>
<td>Effect of subdivision and antecedent moisture condition on HEC-HMS model performance</td>
<td>Subdividing a watershed impacted flow predictions</td>
</tr>
<tr>
<td>Cho et al. (2010)</td>
<td>Effect of watershed subdivision and filter width of a coastal plain watershed</td>
<td>Streamflow was slightly affected by subdivision</td>
</tr>
<tr>
<td>Tripathi, Raghuwanshi, &amp; Rao (2006)</td>
<td>Effect of subdivision on estimating water balance components</td>
<td>No variation in annual runoff values in the Nagwan watershed</td>
</tr>
<tr>
<td>Binger et al. (1997)</td>
<td>Effect of watershed subdivision on runoff, fine sediment yield and nutrient predictions</td>
<td>Recommended a sensitivity analysis to determine an appropriate level of subdivision</td>
</tr>
<tr>
<td>Jha et al. (2004)</td>
<td>Effect of watershed subdivision on runoff, fine sediment yield and nutrient predictions</td>
<td>Streamflow was not significantly affected by subdivision</td>
</tr>
</tbody>
</table>

Table 2.1. Some hydrologic studies implementing watershed subdivision.

While Cho et al. (2010) utilized Soils and Water Assessment Tool (SWAT) to investigate the effect of watershed subdivision and filter width of a coastal plain watershed and suggested that streamflow was slightly affected by subdivision, Tripathi, Raghuwanshi, & Rao (2006) investigated the effect of subdivision on estimating water balance components and concluded that there was no variation in annual runoff values in the Nagwan watershed. Studies by Bingner, Garbrecht, Arnold, & Srinivasan (1997) and Jha, Gassman, Secchi, Gu, & Arnold (2004) utilized SWAT to study the effect of watershed subdivision on runoff, fine sediment yield and nutrient predictions. Bingner et
al. (1997) recommended a sensitivity analysis to determine an appropriate level of subdivision, while Jha et al. (2004) concluded that streamflow was not significantly affected by subdivision.

2.3. Regionalization and Modeling of Ungauged Watersheds

A major challenge associated with modeling ungauged watersheds is the scarcity or non-existence in some cases, of observed historical data for model calibration and validation. As a mitigation measure, most experts propose a practice known as regionalization, where observed data obtained from a gauged watershed with hydrologically similar characteristics is utilized for calibration of an ungauged watershed’s model (Beck et al., 2016; Chiang et al., 2002). This underscores the fact that understanding and analyzing how the land surface responds to rainfall and its consequent runoff is heavily reliant on river gauging. Since gauged data play an important role in hydrologic modeling, the question becomes how to analyze watersheds that have a paucity of data. In other words, how does an ungauged watershed’s model provide reliable runoff results for hydrologic analysis.

Despite several experts advocating the use of data from gauged watersheds for model calibration, Sivapalan (2003) has argued that even a quantifiable level of confidence that comes with extrapolation from a gauged watershed still does not provide an adequate level of understanding of hydrologic processes in an ungauged watershed. He concluded that “the root cause of our difficulties is the tremendous heterogeneity of land surface conditions, soils, vegetation, land use, etc., and the space-time variability of climate input, occurring over a wide range of space and time scales”. He then proposed
several criteria to satisfy a paradigm shift in hydrology including acceptance of heterogeneity as a course of nature and developing new balance equations to compute processes in nested river basins. Sivapalan et al., (2003) reported that the International Association of Hydrological Sciences have in the past emphasized the need for periodic examination and improvement of existing methods employed in model prediction of flows in ungauged basins to underscore the importance of reliable model outcomes.

Several studies have investigated or evaluated the challenges associated with modeling of ungauged watersheds. In their research, Blöschl, Sivapalan, Wagener, Savenije, & Viglione (2013) outlined the importance of runoff prediction in ungauged watersheds for practical purposes such as the design of drainage infrastructure, flood defenses and runoff forecasting, watershed management and impacts of climate change. To achieve a level of model reliability, they also proposed a regionalization approach, despite documented shortcomings associated with the practice (Buytaert & Beven, 2009; Sivapalan, 2003). While studies by Tasker (1982) suggested cluster analysis method for comparing homogeneous catchments, Beck et al. (2016) stated that despite the successful transfer of calibrated parameters from donor catchments to ungauged basins, precipitation was underestimated by their model.

It is important to emphasize that model calibration in these previous studies were done with data from a hydrologically similar gauged watershed. But there are other studies that have proposed a different approach to problem of lack of calibration data when modeling ungauged watersheds. For example, Andréassian, Rojas-Serna, Perrin, & Michel (2006) proposed a combination of a few flow measurements at an ungauged watershed location, prior knowledge of calibrated watershed characteristics, and
parameters from a hydrologically similar watershed. They justified their approach on the possibility of making a few flow measurements before the beginning of a modeling project. As novel as this approach is, it would no doubt impose additional cost on already lean budgets, particularly for less financially endowed entities and would also entail a long wait for say a 10-, 20- or 50-year storm to occur before collecting the required observed data.

In their study, Edwards & Haan (1989) were concerned about the uncertainty of peak flow estimation resulting from parameter uncertainty. They developed a method of estimating the means and variances of input parameters that explicitly accounted for this challenge in ungauged watersheds. Because only a small fraction of the overall watershed parameters (slope and time to peak) were analyzed, their method is inadequate and unreliable for broad application.

For their part, Thomas, Baker, Grimm, & McCuen (2015) recommended the use of regression analysis and deterministic rainfall-runoff models as two approaches for ungauged watershed modeling. They stated that even though regression equations may produce biased estimates when calibrated to data from gauged watersheds, discharges from simulated rainfall-runoff models of an ungaged watershed under study could still be compared to discharges from gauged watersheds with similar characteristics. It should be emphasized that this recommendation means comparing an ungauged watershed with a hydrologically similar watershed, despite documented shortcomings.

Bardossy (2007) made a similar proposal for estimating parameters of hydrologic models on the assumption that catchments with similar watershed characteristics exhibit similar hydrologic responses. Blazkova & Beven (2002) also compared simulation results
with regionalized historical results. Despite the attractions of regionalization, Buytaert & Beven (2009) have highlighted associated problems arguing the practice is replete with uncertainties because model parameters represent quantities that cannot be measured nor calculated. Issues related to model parameter estimation and the uncertainties associated with their outputs have been similarly discussed by Hughes (2010).

Another approach at modeling ungauged watersheds is the application of statistical methods. In their study, Cibin, Athira, Sudheer, & Chaubey (2014) engaged in extensive statistical analysis and proposed a method to quantify predictive uncertainty in hydrologic processes in ungauged watersheds. They conducted a Monte Carlo simulation of a hydrologic model by utilizing sampled parameter sets with assumed probability distributions of two groups of the Bayesian probability distributions. Their results showed that curve number (CN), soil evaporation coefficient, available water capacity and surface lag time were parameters with the most sensitivity and significant effect on generated runoff. It is noteworthy that sensitivity analysis was done using data from a neighboring gauged watershed for calibration, effectively employing the practice of regionalization.

2.4. Geographic information system (GIS) Datasets

The integration of computers and geographic information system (GIS) in recent years has become ubiquitous in hydrologic modeling and watershed analysis, providing the necessary information for policy and decision making in watershed management. GIS technology provides a method for creating and storing elevation, land cover and land use, soils, and impervious information in retrievable digital formats. When integrated with
computers in hydrologic modeling, these GIS capabilities have enabled large-scale analysis of watersheds in an easy-to-manipulate stepwise procedure.

A very important GIS dataset in watershed hydrologic modeling is the Digital Elevation Model (DEM). It is a digital dataset that contains topographic information about a watershed’s terrain from where topologic attributes such as drainage areas, land and channel slopes, flow length and surface roughness can be derived. However, studies have shown that despite the availability and ease of use, GIS datasets have a significant effect on watershed simulation outcomes and can lead to overestimation or underestimation of a watershed’s runoff response (Garbrecht & Martz, 2000).

2.4.1. Digital Elevation Model (DEM) Issues

Digital Elevation Models (DEMs) are produced in raster format, consisting of a square matrix structure of grid cells having mean cell elevation in a two-dimensional array (Garbrecht & Martz, 2000; Zhang & Montgomery, 1994), triangular irregular networks (TINs) or contour-based networks (Moore, Grayson, & Ladson, 1991). The utilization of DEMs in water resources and other watershed modeling applications underscores the importance of quality and resolution in DEM selection criteria. According to Garbrecht & Starks (1995) and Östman (1987), the 30m x 30m USGS level 1 & 2 DEM data have coarse resolutions but are largely accurate, with few limitations that include difficulty in identifying drainage networks and deriving topographic attributes in low relief landscapes.

Traditional methods of manual evaluation of topographic maps have been replaced in recent years by simpler and easily available methods of automated extraction
of digitized information from DEMs, making the extraction of topographic characteristics of complex landscapes intuitively appealing. For hydrologists and water resources engineers, characterization of landscapes depends primarily on drainage networks, drainage divides, flow paths, and slope and aspect. Automated extraction of landscape characteristics from DEMs is replete with challenges because of limitations in the production techniques of the datasets (Garbrecht & Starks, 1995). Despite Garbrecht & Martz (2000) and Tribe (1992) highlighting the issues associated with automated drainage extraction to include positioning of the ends of the drainage networks and the assignment of drainage direction, the practice has remained attractive to watershed modelers because of its critical role and relative accuracy of simulation outcomes (O'Callaghan & Mark, 1984).

The extraction of digitized information has been widely demonstrated using different algorithms (Jenson & Domingue, 1988; Martz & Garbrecht, 1992; Moore, Grayson, & Ladson, 1991; O'Callaghan & Mark, 1984), and attributes derived from DEMs have been largely reported to be affected by resolution or grid size (Hutchinson & Dowling, 1991; Jenson, 1991). In their study of DEM grid size effect on landscape representation and simulation results, Zhang & Montgomery (1994) utilized high resolution DEMs to generate a series of simulated landscapes of different grid sizes and concluded that a 10-m grid size DEM was a compromise for use in hydrologic modeling. Thieken, Lücke, Diekkrüger, & Richter (1999) further stated that topographic attributes are significantly different when extracted from DEMs of different resolutions, affecting topographic features, flow characteristics and runoff results significantly.
While Zhang & Montgomery (1994) recommended the use of DEMs with 10-m resolution for many watershed modeling applications, Garbrecht & Martz (2000) justified the use of high resolution DEMs for some hydrologic applications in agreement with conclusions reached by Seybert (1997), that data resolution affects runoff response estimates. Jenson & Domingue (1988) on the other hand, argued that in low relief landscapes, such as the location of the experimental study areas used in their research, DEM resolution was not considered significant because artifacts may still occur during production.

2.4.2. Resolution/Grid Cell Size/Resampling

DEM resolution limitations and their impacts on watershed modeling have been investigated in the past with interesting results. Chaubey, Cotter, Costello, & Soerens (2005) and Geza & McCray (2008) investigated the impacts of data resolution using the Soil and Water Assessment Tool (SWAT) model and concluded that simulation results in studies on stream flow and water quality are significantly affected. While Chaubey et al. (2005) investigated the overall uncertainty of model output for different data resolutions, Dixon & Earls (2009) utilized SWAT to study streamflow sensitivity to data resolution and concluded that an original 30-m DEM resampled to 90-m produced different streamflow results when compared to results from an original 90-m DEM.

In GIS data processing, resampling is the procedure where an original raster data is converted to a new raster cell or grid size, largely by extrapolation. Drawbacks of resampling were stated by Dixon & Earls (2009) to include the loss of information contained in an original raster dataset. This means that a DEM of finer resolution
becomes degraded at coarser resolution when resampled. Seybert (1997) studied the effect of data resolution on the output of an event-based model and concluded that runoff volume was less sensitive than peak discharge estimates. In generally, data resolution affects the level of detail required for high quality model simulations.

2.4.3. Creating a Soil Conservation Service Curve Number (CN) Grid

Soil Conservation Service (SCS) Curve Number (CN) methodology is a methodology that assigns a runoff factor called curve number (CN) based upon a combination of soil types, land use and antecedent moisture conditions. This dimensionless runoff index has values ranging from 1 to 100, with higher CN values indicative of higher potential for runoff (Shukur 2017). It can also be defined as a measure of a watershed’s runoff response to a rainstorm (Simanton et al. 1996).

While CN grids are not readily available for download, they can be generated using GIS technology and typically used to extract CNs for individual subbasins in a watershed. The advantages of soils and land use data integration using GIS technology have been explained by Cox (1977) in a process that involves an intricate set of steps, resulting in generating CN grids. To generate a CN grid, land use/land cover datasets are integrated with soil data from the individual study areas by adopting the procedure outlined by Merwade (2012). In the initial steps, land use classes, as defined by the USGS Land Cover Institute (LCI), are re-classified to represent four major classes (Anderson, 1976) and used to prepare the land use data for integration. The four major classes include water, medium residential, forest and agricultural (Table 2.2). The resultant grid is then converted to a polygon feature after re-classification.
<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
<th>Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Open water</td>
<td>1</td>
<td>Water</td>
</tr>
<tr>
<td>90</td>
<td>Woody wetlands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>Emergent herbaceous wetlands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Developed, open space</td>
<td>2</td>
<td>Medium Residential</td>
</tr>
<tr>
<td>22</td>
<td>Developed, low intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Developed, medium intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Developed, high intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Deciduous forest</td>
<td>3</td>
<td>Forest</td>
</tr>
<tr>
<td>42</td>
<td>Evergreen forest</td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>Mixed forest</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Barren land</td>
<td>4</td>
<td>Agricultural</td>
</tr>
<tr>
<td>52</td>
<td>Shrub/scrub</td>
<td></td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>Grassland/herbaceous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>Pasture/hay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>82</td>
<td>Cultivated crops</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Original NLCD classification and re-classification (USGS, 2013).

Similarly, the soil dataset is prepared for integration by creating a ‘SoilCode’ field name in its attribute table and populated with soil group information from the component table of the soil data geodatabase. Soil groups A, B, C and D are then allocated percentages and populated based on the ‘SoilCode’ for each polygon. The resultant land use and soil polygons are subsequently merged, using the ‘Union’ tool in Arc Hydro Tools to create a feature class containing both land use and soils information. A CN Look-Up table containing curve numbers corresponding to soil and land use combinations is then created. Finally, using the Utility menu in HEC-GeoHMS, the merged feature class and the CN Look-Up table are used to generate a CN grid (Merwade, 2012).
2.5. Conclusions

The importance of reliable watershed model results in hydrologic studies has been highlighted by the International Association of Hydrological Sciences’ emphasis on the need for the examination and improvement of existing methods employed in model prediction of flows. When modeling ungauged watersheds, experts in the field of water resources engineering and hydrology have recommended a practice known as regionalization as a mitigation measure, where observed historical data is utilized for model calibration and validation. But the temporal and spatial variability in climate, and heterogeneity in watershed characteristics make it difficult to utilize results from such models for any meaningful hydrologic analysis and application. Also, the type and use of input datasets affect watershed results.

Despite the attraction of automated extraction of digitized information from DEMs, studies have shown that their resolution affect landscape characteristics such as drainage networks, drainage divides, flow paths, and slope and aspect. These topographic attributes are significantly different when extracted from DEMs of different resolutions, affecting topographic features, flow characteristics and runoff results significantly. Similarly, studies show that an original DEM resampled to a new raster dataset produced different streamflow results when compared to results from the original DEM. Finally, there are advantages of integrating soils and land cover data using remote sensing technology to create a CN grid for use in assigning a runoff potential index to subbasins in a watershed. In general, better understanding of the impacts of the methods and materials used in watershed modeling further improves hydrologic analysis of ungauged watersheds.
Chapter Three: Evaluating Watershed Subdivision Effect on Runoff Characteristics for Improved Hydrologic Analysis of Ungauged Watersheds

Abstract

Watershed subdivision is a common practice that has innovated the hydrologic modeling process through the application of computers and geographic information system (GIS) technology in the study of watershed hydrology. Despite the advantages of subdividing a very large watershed into smaller subbasins, the practice of watershed subdivision impacts the results of watershed model simulations in a remarkable manner. Previous studies have suggested the use of observed data from a hydrologically similar watershed for calibration and validation but the impacts of subdivision on topographic, topologic and runoff characteristics in ungauged waterhseds has not been adequately evaluated. To better understand the underlying processes in ungauged watershed hydrology, this study further evaluates the effect of subdivision on runoff characteristics to obtain an improved hydrologic analysis of ungauged watersheds. The Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) was used to simulate runoff hydrographs at the outlet of watersheds of varying sizes, treated as ungauged and located in different hydrologic sub-regions. Specifically, results show that total channel slopes and total flow lengths increased with further subdivision, resulting in high peak discharges. Overall, these findings suggest that a better understanding of runoff processes provide a basis for improved hydrologic analysis of ungauged watersheds.
3.1. Introduction

The primary goal of watershed modeling is the determination and estimation of hydrologic impacts of changes to a watershed (Casey, Stagge, Moglen, & McCuen, 2015; Norris & Haan, 1993). Water resources engineers and watershed managers have the responsibility of making decisions on how to manage watershed resources in a sustainable manner. A critical and essential component to that decision making is simulation results from watershed models. For example, when planning flood mitigation projects, the design of hydraulic structures is based on a risk analysis that requires hydrological input datasets associated with runoff characteristics obtained from model simulations. Vital input datasets for this purpose include peak discharge, time to peak and runoff volume (Jha, Gassman, Secchi, Gu, & Arnold, 2004; Gül, Harmancioglu, & Gül, 2010; Plate, 2002; Tung & Mays, 1980; Volpi & Fiori, 2014). It is important to note that, the unreliability and lack of adequate understanding of input model datasets result in either over estimation or under estimation of project costs which may ultimately lead to loss of lives and properties.

However, the evolution of watershed modeling in recent years has seen the innovative integration of Geographic Information System (GIS) technology and computer software. This means that the modeling and simulation of very large watersheds hitherto impossible has become easier and ubiquitous. A common practice in watershed modeling is the subdivision of a large watershed into several subbasins. Several studies in the past have investigated this practice and have concluded that it has impact on simulation results of runoff responses (Norris & Haan, 1993; Casey et al., 2015; Tripathi et al., 2006; Cleveland & Thompson, 2009).
Specifically, Casey et al. (2015) used WinTR-20 to study the effect of subdivision on runoff and concluded that different subdivision scenarios produce different peak discharge values without a corresponding change in runoff volume. Chang (2009) in his investigation of the impact of watershed delineation on hydrology and water quality simulation stated that the practice was inefficient and irrational. Han, Huang, Zhang, Li, & Li (2014) and Momm et al. (2017) concluded that finer subdivisions were not helpful and suggested an integrated framework to define an optimal level of subdivision. Norris & Haan (1993) used HEC-1 to evaluate the impact of subdividing watersheds on estimated hydrographs and concluded that the determination of the number of subdivisions should be subjective and should depend on data resolution and area of interest within the watershed. Wang, Chen, Huang, Xiao, & Shen (2016) proposed the use of evolutionary algorithms in combination with watershed discretization while Momm et al. (2017) suggested characterization procedures in watershed subdivision, based on different reference data layers.

Studies in the past have utilized the Soil and Water Assessment Tool (SWAT) to investigate the impacts of watershed subdivision on modeling the effectiveness of best management practices and arrived at different conclusions. While some of these studies concluded that runoff volume at a watershed outlet was not significantly affected by subdivision (Chen & Mackay, 2004; FitzHugh & Mackay, 2001; Jha et al., 2004), others found that peak discharge increased with increased subdivision (Norris & Haan, 1993; Tripathi et al., 2006), but decreased with further subdivision for small urban watersheds (Cleveland & Thompson, 2009; Zaghloul, 1983). Similarly, because of its wide-ranging capability and applicability, several watershed modeling studies have also been
conducted in the past utilizing HEC-HMS. For example, HEC-HMS has been used for calibration, verification, and sensitivity analysis (Cunderlik & Simonovic, 2004), event and continuous modeling (Chu & Steinman, 2009), simulation of additive effect of multiple detention basins (Emerson, Welty, & Traver, 2003) and for regional scale flood modeling in the San Anthonio River basin (Knebl, Yang, Hutchison, & Maidment, 2005). Other examples utilizing HEC-HMS include studies on ungauged catchment runoff simulation by Gumindoga, Rwasoka, Nhapi, & Dube (2016), runoff simulation in a tropical catchment by Halwatura & Najim (2013), application of HEC-HMS and SCS CN in ungauged agricultural watersheds by Ibrahim-Bathis & Ahmed (2016), continuous rainfall-runoff modeling by Kaffas & Hrissanthou (2014), and flood forecasting by Oleyiblo & Li (2010), hydrologic risk management by Pistocchi & Mazzoli (2002).

Despite the numerous studies on the practice of watershed subdivision, there has been no consensus in the literature as to what number of subdivisions will produce reasonable, reliable and reproduceable results. Most importantly, there is no concise explanation of how the interaction between the different modeling parameters affect runoff characteristics beyond the fact that they are affected. This has led to questions of reliability and reproducibility of the watershed modeling process, especially in the hydrologic analysis of ungauged watersheds.

It is important to emphasize that even though most of the previous studies were carried out for gauged watersheds with available observed data for calibration and validation, there still has been no consensus in the literature on the practice of watershed subdivision. Therefore, it is important to further evaluate the effect of subdivision practice on runoff characteristics, particularly in ungauged watersheds for a better
understanding of watershed processes and to obtain an improved hydrologic analysis in ungauged watersheds. Even more important is the fact that proper management decisions depend largely on the reliability of model outcomes. The objective of this study, therefore, was to further evaluate the effect of watershed subdivision on runoff responses, using HEC-HMS to simulate runoff hydrographs for a design storm event at the outlet of watersheds of different sizes, located in different hydrologic regions and treated as ungauged watersheds. Specifically, the research aims to evaluate how watershed subdivision affects peak discharge values as a basis for improved hydrologic analysis of ungauged watersheds.

3.2. Methodology

3.2.1. Materials

3.2.1.1. Study Areas

The State of South Dakota is in the Mid-western region of the United States, having a boarder with North Dakota to the north, Minnesota, and Iowa to the east, Nebraska to the south and Wyoming and Montana to the west (Figure 3.1). It is the location of the study areas for this research (Figure 3.2). The state of South Dakota lies between longitude 97°28´3´´W to 104°3´W and latitude 42°29´32´´N to 45°56´N. It has a total area of 77,121 mi², consisting of 75,898 mi² and 1,224 mi² of land and water respectively, and is about 383 mi long and 237 mi wide. The state’s terrain has an elevation between 966 ft and 7,242 ft, with an average elevation of 2,200 ft. The major drainage systems are the Cheyenne, Missouri, James, and White Rivers. Annual average
temperature in South Dakota ranges between 86.5° high and 1.9° low, with an average annual precipitation ranging between 15 inches to 28 inches (Berg, 1998; Sando, 1998)

Figure 3.1. Showing the location of South Dakota on the US map
In this study, land use/land cover for the study areas were reclassified (Table 3.1) as agricultural, water, medium residential and forest, according to United States Geological Service (USGS) Land Cover Institute land class definitions (Anderson, 1976; Shukur, 2017).

This research initially evaluated the effect of subdivision on three different watersheds in Perkins county - Indian Creek (W1), Mud Creek (W2), and Wolf Butte (W3), located in the South Dakota hydrologic subregion C (Sando, 1998).

Figure 3. 2. Showing the study areas (Indian Creek and St. Paul’s Church watersheds) in Perkins and Brookings Counties in South Dakota, respectively.
However, because analysis of simulation results showed a similar trend for the selected watersheds, it was therefore decided that a fourth watershed from hydrologic subregion A, in Brookings county - St. Paul’s Church (W4), be modeled and its results compared to W1.

Perkins county is the second largest county by area in South Dakota state and lies on the north edge of the state, bordering North Dakota on the Missouri Plateau in the Great Plains region. The county is drained in the north by the Grand River, and in the south by the Moreau River and their respective tributaries. These two drainage systems

<table>
<thead>
<tr>
<th>Number</th>
<th>Original NLCD classification</th>
<th>Revised classification (re-classification)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Open water</td>
<td>1 Water</td>
</tr>
<tr>
<td>90</td>
<td>Woody wetlands</td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>Emergent herbaceous wetlands</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Developed, open space</td>
<td>2 Medium Residential</td>
</tr>
<tr>
<td>22</td>
<td>Developed, low intensity</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Developed, medium intensity</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Developed, high intensity</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Deciduous forest</td>
<td>3 Forest</td>
</tr>
<tr>
<td>42</td>
<td>Evergreen forest</td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>Mixed forest</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Barren land</td>
<td>4 Agricultural</td>
</tr>
<tr>
<td>52</td>
<td>Shrub/scub</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>Grassland/herbaceous</td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>Pasture/hay</td>
<td></td>
</tr>
<tr>
<td>82</td>
<td>Cultivated crops</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. 1. Original NLCD classification and re-classification (USGS, 2013)
flow eastward into the Missouri River. Perkins county has a total area of 2,980 mi² (7,500 km²) consisting of 2,870 mi² (7,400 km²) of land and 20 mi² (52 km²) of water. According to Wiesner (1980), Perkins county is “an upland plain that is moderately dissected by streams and entrenched drainageways. Relief is gently rolling-to-steep in much of the county and a few prominent buttes and ridges on the landscape. Slopes are mostly nearly sloping to moderately sloping”. The highest elevation in Perkins county is 829 meters (2,720 ft). Shown in Figure 3.3 are (a) HUC12 layer for Perkins County with three study areas, (b) W3, (c) W1, and (d) W2 all located in the county.

Figure 3.3. Showing (a) HUC12 layer for Perkins County with three study areas, (b) W3, (c) W1, and (d) W2 located in Perkins county.
Average annual precipitation in Perkins county is around 15 inches and out of this amount, 13 inches usually occurs in April, with an average seasonal snow fall of 30 inches. Three of the study areas, Indian Creek watershed (W1), Mud Creek watershed (W2) and Wolf Butte Creek watershed (W3) are in this county and belong to hydrologic subregion C (Sando, 1998). These waterheds were treated as unguaged, with sizes ranging from 6.487 mi² (W1), 14.331 mi² (W2) to 23.696 mi² (W3). Table 3.2 shows their different sizes, hydrologic unit code (HUC), land use, soil groups, and average curve numbers (CNs). Out of these three study areas in Perkins county, only W1 was selected for analysis because, while there was inadequate simulation data for W2, simulation results for W3 showed similar trends as W1. It is important to note that W1, W2 and W3 belong the South Dakota hydrologic subregion C. Therefore, simulation results for W1 were analyzed and compared to W4, which belongs to South Dakota hydrologic subregion A.

<table>
<thead>
<tr>
<th>Wshd</th>
<th>Size (mi²)</th>
<th>Land Use (%)</th>
<th>Soil Group (%)</th>
<th>Average CN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Agric.</td>
<td>Water</td>
<td>Med. Res</td>
</tr>
<tr>
<td>W1</td>
<td>6.487</td>
<td>98.6</td>
<td>1.2</td>
<td>0.0</td>
</tr>
<tr>
<td>W2</td>
<td>14.331</td>
<td>98.0</td>
<td>1.3</td>
<td>0.6</td>
</tr>
<tr>
<td>W3</td>
<td>23.696</td>
<td>96.8</td>
<td>0.3</td>
<td>2.8</td>
</tr>
<tr>
<td>W4</td>
<td>14.350</td>
<td>92.4</td>
<td>2.8</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Table 3.2. Showing sizes of study areas and their land use, soil groups and average curve numbers (CNs)

In Table 3.2, watershed characteristics for W1 and W4 are as follows: agriculture is the dominant land use with 99% and 92%, respectively; W1 has no medium residential development and is 1.2% covered by water and 0.2% by forest; Land use in W2 on the
other hand is about 3% water, 5% medium residential and 0.5% covered by forest; Soil type is dominated by Soil group D in both W1 and W4 watersheds with 39% and 70%, respectively, while average CNs are 82 and 85, respectively; Land use and soil types were extracted from land cover and soils datasets for all the study areas.

According to the U.S. Natural Resources Conservation Service criteria for defining soil infiltration characteristics (Table 3.3), W1 exhibits very low infiltration rates corresponding to high surface runoff potential, when thoroughly wetted and a high runoff potential because of soil group D dominance. W3 exhibits low infiltration rate when thoroughly wetted and had a dominance of soil group C. Infiltration rates are high or moderate for watersheds with a dominance of soil groups A and B, respectively, corresponding to low or low-to-moderate surface runoff potential.

<table>
<thead>
<tr>
<th>Soil Group</th>
<th>Description</th>
<th>Infiltration Rate</th>
<th>Surface Runoff Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Well drained soils, typically sands, loamy sands, or sandy loams</td>
<td>High even when thoroughly wetted</td>
<td>Low</td>
</tr>
<tr>
<td>B</td>
<td>Moderate fine to moderately coarse soils such as silt loams or loams</td>
<td>Moderate when thoroughly wetted</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>C</td>
<td>Fine-textured sandy clay loam soils and soils with underlying layer impeding drainage</td>
<td>Low when thoroughly wetted</td>
<td>High</td>
</tr>
<tr>
<td>D</td>
<td>Fine clay soils and soils with an underlying impermeable layer, soils in areas of permanently high-water table</td>
<td>Very low when thoroughly wetted</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 3.3. U.S. Natural Resources Conservation Service criteria for Hydrologic soil groups.
Brookings county is the location of St Paul’s Church watershed (W4), lying to the east of South Dakota and bordering Minnesota to the west. Its main drainage system is the Big Sioux River which flows through its east central part in a southeastward direction. The county has numerous lakes and ponds and consist of flatland surface terrains. Its total area is 805 mi² (2,080 km²), consisting of 782 mi² (2,030 km²) and 13 mi² (34 km²) of land and water respectively, and lies on the Prairie Coteau at elevations of between 1,600 ft to 1,800 ft. The county has a continental climate with extreme temperatures. Precipitation in Brookings is frontal precipitation, falling at slow rate and usually as thunderstorms (Westin, Buntley, Shubeck, & Puhr, 1959). The St. Paul’s watershed belongs to the South Dakota hydrologic subregion A (Sando, 1998), with an area of 14,350 mi² and treated as an ungauged watershed. Figure 3.4 shows (a) HUC12 layer for Brookings County and (b) shape and clipped DEM with streams while its size, land use, soil groups, and average curve number (CN) are shown in Table 3.2.

According to the U.S. Natural Resources Conservation Service criteria for defining soil infiltration characteristics, W4 exhibit very low infiltration rates corresponding to high surface runoff potential, when thoroughly wetted. High runoff potential is a function of soil group D dominance. Infiltration rates are high or moderate for watersheds with a dominance of soil groups A and B, respectively, corresponding to low or low-to-moderate surface runoff potential (Table 3.3). Shown in Figure 3.4 are (a) HUC12 layer for Perkins County and (b) shape and clipped DEM with streams for W4. Soil types for the study area were classified based on stipulated criteria by the US Department of Agricultural Natural Resources Conservation Service hydrologic soil classification (Stewart, Canfield, & Hawkins, 2011). These are hydrologic soil groups A
(sandy, loamy sand or sandy loamy), B (silt or loam), C (sandy clay loam) and D (clay loam, silt clay loam, sandy clay, silty clay, or clay) and shown in Table 3.3.

Figure 3.4. Showing (a) HUC12 layer for Brookings County and (b) shape and clipped DEM with streams for W4.

3.2.1.2. **Modeling Software: Description, Setup and Datasets Used**

Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) is a hydrologic modeling system designed by the US Army Corps of Engineers to simulate rainfall-runoff processes of watersheds (Scharffenberg & Fleming, 2006). The application of HEC-HMS in the field of water resources and hydrology is wide ranging. Examples of areas of application include urban flood frequency studies, flood-loss
reduction studies, flood warning system planning studies, reservoir spillway capacity studies, stream restoration studies, and surface erosion and sediment routing studies (Kaffas & Hrissanthou, 2014; Knebl, Yang, Hutchison, & Maidment, 2005; Oleyiblo & Li, 2010; Pistocchi & Mazzoli, 2002). Simulation results are either used directly or integrated with other software in different hydrologic-hydraulic applications such as flow forecasting, flood damage remediation, water availability, urban drainage, or for future urbanization impacts (Pistocchi & Mazzoli, 2002). Basic simulation steps are outlined in its User’s manual (USACE, 2016). Data preprocessing using HEC-GeoHMS and storm event simulation using HEC-HMS are shown in the flowchart in Figure 3.5.

Figure 3.5. Flowchart showing data preprocessing using HEC-GeoHMS and storm event simulation using HEC-HMS.
To create HMS models for simulation, downloaded datasets (Table 3.4) were clipped to output extents of each study area’s boundary and projected to the X-, Y- and Z- coordinates of the Universal Transverse Mercator (UTM) coordinate system, according to steps outlined in Minami, Sakala, & Wrightsell (2000). Thereafter, Arc Hydro Tools and HEC-GeoHMS (10.1) extensions were utilized to extract and estimate watershed boundaries and drainage areas, flow path lengths and slopes, streams and reach lengths, and average watershed land slopes, according to procedures outlined by Fleming & Doan (2009). Using the ‘Utility’ menu in HEC-GeoHMS, land use/land cover classes and hydrologic soil groups were integrated to generate CN grids for all individual study areas and utilized in generating HMS models. The resultant HMS models were then imported to HEC-HMS for simulation (Figure 3.5).
<table>
<thead>
<tr>
<th>Data Type</th>
<th>Description</th>
<th>Data Sources</th>
<th>Spatial Reference Information</th>
<th>Geodetic Model</th>
<th>Format</th>
<th>Source Scale Denominator</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Elevation Data</td>
<td>The NED is a seamless mosaic of best-available elevation data. One of the effects of the NED processing steps is a much-improved base of elevation data for calculating slope and hydrologic derivatives.</td>
<td>USDA/NRCS - National Geospatial Center of Excellence (<a href="https://gdg.sc.egov.usda.gov/GDGOrder.aspx">https://gdg.sc.egov.usda.gov/GDGOrder.aspx</a>)</td>
<td>Grid Coordinate System: Universal Transverse Mercator</td>
<td>Horizontal Datum Name: North American Datum of 1983 (NAD83)</td>
<td>GeoTIFF</td>
<td>10 meter</td>
<td>Unknown</td>
</tr>
<tr>
<td>National Hydrography Dataset (NHD)</td>
<td>Vector dataset provides a network of rivers and streams, including intermittent streams, ditches, and canals. NHD integrates USGS hydrography line data with the EPA Reach File Version 3 data.</td>
<td>USDA/NRCS - National Geospatial Center of Excellence (<a href="https://gdg.sc.egov.usda.gov/GDGOrder.aspx">https://gdg.sc.egov.usda.gov/GDGOrder.aspx</a>)</td>
<td>Grid Coordinate System: Universal Transverse Mercator</td>
<td>Horizontal Datum Name: North American Datum of 1983 (NAD83)</td>
<td>ARC/INFO Shape</td>
<td>24,000</td>
<td>2016</td>
</tr>
<tr>
<td>Soil Survey Geographic (SSURGO II) Soil</td>
<td>These data provide information about soil features on or near the surface of the Earth. Data were collected as part of the National Cooperative Soil Survey. These data are intended for geographic display and analysis at the state, regional, and national levels. Soil Classification</td>
<td>USDA/NRCS - National Geospatial Center of Excellence (<a href="https://gdg.sc.egov.usda.gov/GDGOrder.aspx">https://gdg.sc.egov.usda.gov/GDGOrder.aspx</a>)</td>
<td>Horizontal Coordinate System Definition: Geographic</td>
<td>Horizontal Datum Name: World Geodetic System of 1984 (WGS84)</td>
<td>ESRI Shape file</td>
<td>250,000</td>
<td>2000 - Present</td>
</tr>
<tr>
<td>National Land Cover Dataset (NLCD)</td>
<td>The dataset is a generalized and nationally consistent land cover data layer for the United States based primarily on a decision-tree classification of circa 2011 Landsat satellite data and can be used for several purposes in a GIS. Land Use Classification</td>
<td>USDA/NRCS - National Geospatial Center of Excellence (<a href="https://gdg.sc.egov.usda.gov/GDGOrder.aspx">https://gdg.sc.egov.usda.gov/GDGOrder.aspx</a>)</td>
<td>Grid Coordinate System: Universal Transverse Mercator</td>
<td>Horizontal Datum Name: North American Datum of 1983 (NAD83)</td>
<td>Tag Image File Format (TIFF)</td>
<td>30 meter</td>
<td>2011</td>
</tr>
<tr>
<td>12 Digit Watershed Boundary Dataset in HUC8</td>
<td>This dataset is intended to be used as a tool for water resolution.</td>
<td>USDA/NRCS - National Geospatial Center of Excellence (<a href="https://gdg.sc.egov.usda.gov/GDGOrder.aspx">https://gdg.sc.egov.usda.gov/GDGOrder.aspx</a>)</td>
<td>Grid Coordinate System: Universal Transverse Mercator</td>
<td>Horizontal Datum Name: North American Datum of 1983 (NAD83)</td>
<td>ARC/INFO Shape</td>
<td>24,000</td>
<td>2013 - Present</td>
</tr>
</tbody>
</table>

Table 3.4. Showing dataset types, description, sources, special references, geodetic models, format, source scale denominator and year of processing.
In this study, HEC-HMS projects were created for each of the study areas and their respective subdivision scenarios added as basin models. Hydrologic parameter processes and methods selected for model simulations are shown in Table 3.5 as follows:

Soil Conservation Service curve number (SCS CN) model was selected for Subbasin Loss Method, SCS Unit Hydrograph for Subbasin Transform Method, CN Lag Method for subbasin lag times (for computing time of concentration), while Muskingum Routing was selected for River Routing (U.S.D.A., 1986).

<table>
<thead>
<tr>
<th>Subbasin process</th>
<th>Loss method</th>
<th>Transform method</th>
<th>Lag method</th>
<th>River routing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chosen Method</td>
<td>SCS curve number</td>
<td>SCS unit hydrograph</td>
<td>CN lag method</td>
<td>Muskingum</td>
</tr>
</tbody>
</table>

Table 3.5. Hydrologic parameter processes and methods.

Availability of data was the main justification for the selection of basin methods. In HEC-HMS, the SCS-CN loss model calculates runoff volume (excess precipitation) as a function of cumulative precipitation, land use and land cover, soils, and antecedent moisture, while SCS Unit Hydrograph transform method computes peak discharge, and Muskingum routing method computes a downstream hydrograph for a given upstream hydrograph as a boundary condition.

Included in HEC-HMS are equations that compute runoff volume or excess precipitation, peak discharge or excess runoff and time to peak. Runoff volume ($P_e$) was computed from cumulative precipitation, land use/land cover, soils, and antecedent moisture; peak discharge ($q_p$) was computed from watershed area, while time of
concentration (Tc) was computed as the sum of travel times for sheet, shallow and channel flows. The SCS CN loss model (Boughton, 1989) was selected in this study to calculate excess runoff from the equation:

\[ P_e = \frac{(P-I_a)^2}{P-I_a+S} \]  \hspace{1cm} (1)

where \( P_e \) is runoff volume at time \( t \), \( P \) is accumulated rainfall depth at time \( t \), \( I_a \) is the initial abstraction (initial loss) and \( S \) is potential maximum retention.

The empirical relationship between \( I_a \) and \( S \) is given by:

\[ I_a = 0.2S \]  \hspace{1cm} (2)

Therefore, excess runoff becomes:

\[ P_e = \frac{(P-0.2S)^2}{P+0.8S} \]  \hspace{1cm} (3)

The relationship between CN and maximum abstraction, \( S \) to watershed characteristics is given by:

\[ S = \frac{1000-10CN}{CN} \]  \hspace{1cm} (4)

CN varies from 100 (for water bodies) to 30 (for permeable soils with high infiltration).

The SCS unit hydrograph model was selected to simulate peak discharge using the equation:

\[ q_p = C \frac{A}{T_p} \]  \hspace{1cm} (5)

where \( q_p \) is peak discharge, \( A \) is area of watershed, \( T_p \) is time to peak and \( C \) is a conversion factor.

Time to peak, \( T_p \) is related to Lag Time, \( t_{lag} \) (average time of flow for all locations on a watershed) by:

\[ T_p = \frac{\Delta t}{2} + t_{lag} \], where \( \Delta t \) is excess precipitation duration  \hspace{1cm} (6)
\[ t_{lag} = 0.6t_c \text{ (ungaged watersheds)} \]  

(7)

Time of concentration, \( t_c \) was estimated as follows:

\[ t_c = t_{\text{sheet}} + t_{\text{shallow}} + t_{\text{channel}} \]  

(8)

where \( t_{\text{sheet}} \) is travel time through sheet segments, \( t_{\text{shallow}} \) is travel time through shallow segments and \( t_{\text{channel}} \) is the sum of travel time in channel segments of the watershed.

Time of concentration was calculated for surface flow using the TR-55 methodology for watersheds. In HECGeo-HMS, TR-55 worksheet was generated for flow path segments and flow path parameters automatically during watershed parameter processing. Surface flows consisted of sheet flow, shallow flow, and channel flow.

The characteristics for calculating time of travel for Sheet flow included Manning’s n, flow length, storm duration (2-year 24-hour rainfall) and land slope; characteristics for calculating time of travel for Shallow flow were surface description (1 – unpaved, 2 – paved), flow length, watercourse slope, and average velocity. Average velocity was computed based on watercourse slope, and time of travel was calculated by dividing travel length by average velocity as follows:

\[ T_t = \frac{L}{3600V} \]  

(9)

where \( T_t \) is time of travel for shallow concentrated flow (hr), \( L \) is length of travel (ft) of water from watershed to the outlet, \( V \) is average velocity of flow (ft/s) and 3600 is a conversion factor. The characteristics for calculating time of travel for Channel flow are cross sectional area (ft2), wetted perimeter (ft), hydraulic radius (ft), channel slope (ft/ft), Manning’s roughness coefficient, average velocity (ft/s) and flow length, (ft). Average velocity was computed using Manning’s equation as follows:

\[ V = \frac{1}{n} R^{2/3} S^{1/2} \]  

(10)
where $V$ is average velocity (ft/s), $n$ is Manning’s roughness coefficient, $R$ is hydraulic radius (ft) and $S$ is channel slope (ft/ft).

The Muskingum routing method was selected to model channel flow. It computes a downstream hydrograph for a given upstream hydrograph by solving the continuity equation using the finite difference method as follows:

$$\left(\frac{I_t + I_{t-1}}{2}\right) - \left(\frac{O_t + O_{t-1}}{2}\right) = \left(\frac{S_t - S_{t-1}}{\Delta t}\right)$$

(11)

where $I_t$ is inflow, $O_t$ is outflow, volume of storage, $S_t$ is the weighted difference between inflow and outflow during the same time. Muskingum storage is defined as:

$$S_t = KO_t + KX(I_t - O_t) = K[XI_t + (X)O_t]$$

(12)

where $K$ is time of travel of flood through a reach and $X$ is a dimensionless weight ($0 \leq X \leq 0.5$). In this study, $K$ was calculated based on the TR-55 methodology (Cronshey, 1986; McCuen & Okunola, 2002) while $X$ was set to 0.01 with the assumption that the channels had mild slopes with over-bank flows (Tewolde & Smithers, 2006).

Availability of data was the main justification for the selection of basin methods. HEC-HMS uses hydrologic models as follows (Table 3.4): SCS CN loss model concept to calculate runoff volume (excess precipitation) as a function of cumulative precipitation, land use and land cover, soils, and antecedent moisture; SCS Unit Hydrograph transform method to compute peak discharge; and Muskingum routing method to compute a downstream hydrograph for a given upstream hydrograph as a boundary condition. Meteorologic Model and Control Specifications components were specified to run the simulation.
3.2.2. Methods

3.2.2.1. Generating Subdivision Models

Each of the study watersheds was subdivided into multiple model scenarios or levels. Study area W1 was subdivided into 6 subdivision levels, using a threshold area for stream definition tool in HEC-GeoHMS preprocessing menu. Any further subdivisions beyond level 6, including those generated by a default stream definition area, produced a cascade of channel travel time errors, resulting from negative or zero slope values, in the TR-55 worksheet. On the other hand, study area W4 was subdivided into 7 levels, with level 7 generated using the software’s default area for stream definition. Any further subdivision beyond this level resulted in a cascade of channel travel time errors.
Figure 3. 6. Depicting six (6) WI subdivision scenarios or levels: (a) level 1 (entire watershed), (b) level 2 (3 subdivisions), (c) level 3 (5 subdivisions), (d) level 4 (11 subdivisions), (e) level 5 (25 subdivisions) and (f) level 6 (53 subdivisions).
Subdivision levels are illustrated in Figure 3.6 (a-f) for W1. The first scenario or level depicts the entire watershed as one subbasin. In level 2, the watershed was subdivided into 3 subbasins, and then 5, 11, 25, and 53 subdivisions, levels 3, 4, 5, and 6, respectively. These subbasins were determined by a threshold area for stream definition which the software uses to automatically subdivide the watershed. For W1, a threshold area of 10 km² was used to delineate the entire watershed as 1 subdivision, representing level 1. Using trial and error, no threshold area produced less than 3 subdivisions. This method was repeated between subsequent levels until a maximum number of 53 subdivisions, representing level 6, were attained. It is important to emphasize that for each watershed in this study, the maximum number of subdivision levels was determined by the attainment of a certain subdivision level beyond which further subdivision will result in channel slope errors. To implement the watershed subdivision, a stepwise process outlined by Fleming & Doan (2013) was followed, using HEC-GeoHMS and Arc Hydro Tools extensions in the ArcMap 10.4.1 environment.

Grid layers produced during data preprocessing were utilized as input datasets in successive steps to build HMS basin models. In the HEC-GeoHMS Project Setup menu, new projects were started and generated, then watershed slope (WshSlope) grids used in computing Basin Slopes in the Characteristics menu were created using Arc Hydro Tools. In the Parameters menu, percent impervious data and curve number grids were added as subbasin parameters from raster, while a design storm of 1.0 inch was manually entered into a generated TR-55 Excel worksheet and used in calculating time of travel (Tt) for overland flows, according to TR-55 methodology (Cronshey, 1986). This was repeated for each watershed subdivision model scenarios or levels.
In the HMS processes submenu of the Parameters menu, Soil Conservation Service Curve Number (SCS CN) and SCS Unit Hydrograph were selected as the Loss and Transform methods respectively, while the CN Lag Method was selected for the subbasin lag times and automatically computed. CN grids used for computing the CNs for the study watersheds were generated from integrating land use classes and soil group datasets of the watersheds according to a combination of steps outlined by Merwade (2012), Shukur (2017) and Stewart et al. (2011).

3.2.2.2. Model Simulation

To simulate the watershed models, projects were created for each study area and their respective subdivision model scenarios or levels added as basin models, using HEC-HMS 4.2. The Meteorologic Models components in HEC-HMS which computes the precipitation input for all subbasins, were parameterized for a hypothetical one-inch (1.0 in) two (2) year, 24-hour design storm. In this precipitation model, Frequency and SCS storms were utilized as precipitation methods but evapotranspiration and snowmelt were not processed.

Two sets of simulation results are presented in Section 3.3 for each study area. The first set of results is for simulation runs utilizing the frequency storm precipitation method in the Meteorologic Module of the HEC-HMS, while the second set is for a set of results utilizing the SCS type 2 storm precipitation method. Both precipitation methods are suitable as design storms, and as results show, do not produce remarkably different results. However, the SCS storm type 2 was preferred for detailed analysis in this research because the storm patterns of the study areas match the SCS type 2 storm
patterns. In South Dakota where the study areas are located, the storm patterns are characterized by thunderstorms with warm, moderately humid summers and dry, cold winters. The other reason for prioritizing the SCS storm is that model parameterization does not exhibit the complexities associated with the frequency storm. For instance, in the Meteorologic Module component in HEC-HMS, parameterization of the frequency storm involves model calibration to fit observed or historical data such as storm duration, intensity duration and intensity position. On the other hand, the SCS storm which implements design storm patterns developed for use in small agricultural watersheds, required only the parameterization of the storm’s depth. And because the goal of the experiment was to further evaluate runoff characteristics for a better and improved understanding of runoff processes in ungauged watersheds, a calibrated model was not prioritized. The study areas in this study are in hydrologic regions A and region C, respectively, in South Dakota State (Sando, 1998) that exhibit the SCS type 2 storm patterns.

Control Specifications components, which set the time span for a simulation run, was parameterized for simulation to start at 00:00 hours on 16th August and end at 00:05 hours on 18th August 2017 for W1 project, and to start at 00:00 hours on 16th August and end at 00:00 hours on 19th August 2017 for W4. The same HEC-HMS input parameters (Meteorologic and Control Specifications) were used for each of the experimental watersheds and their respective subdivision model scenarios or levels. The models were simulated for a time-step of five (5) minutes intervals, according to procedures outlined by Scharffenberg & Fleming (2006). The flowchart of Figure 3.5 shows data preprocessing using HE-GeoHMS and storm event simulation using HEC-HMS.
3.3. Results

The experiments in this study were set up to further evaluate the effect of watershed subdivision on runoff responses in four watersheds (W1, W2, W3 and W4) and simulation results analyzed. Also, simulation results were normalized and plotted. In this section, simulation results are presented for Frequency storm and SCS type 2 storm precipitation methods as follows:

i. Simulation results for W1

ii. Simulation results for W2

iii. Simulation results for W3

iv. Simulation results for W4 and

v. Comparison of peak discharge values for W1 and W4 for SCS storm

3.3.1. Simulation Results for W1

3.3.1.1. Frequency Storm Precipitation Method

Simulation results for study area W1 are shown in Table 3.6 when frequency storm precipitation method was selected as the Meteorologic model. Subdivision level 1 depicted the entire watershed, level 2 had 3 subdivisions and subsequent levels had 5, 11, 25 and 53 subdivisions, respectively. Further subdivision beyond 53 resulted in channel travel time errors as recorded in the TR-55 methodology worksheet (Cronshey, 1986).

Peak discharge was highest for level 6 (31.2 cfs) with 53 subdivisions and lowest for level 3 (28.3 cfs) with 5 subdivisions. Level 1 had a peak discharge of 30.7 cfs, 29 cfs for level 2, 30.5 and 30.4 cfs for levels 4 and 5, respectively. As shown in Figure 3.7, peak discharge fluctuated for lower levels of subdivisions. This result agrees with conclusions
of previous studies (Norris & Haan, 1993; Tripathi, Raghuwanshi, & Rao, 2006), but thereafter, the peak discharge increased steadily as subdivision further increased (Cleveland & Thompson, 2009; Zaghloul, 1983). This later result tends to contradict the results reported by Norris & Haan (1993) that peak discharge values plateau with further subdivision. While total channel slopes and total flow lengths increased with further subdivision, and while time to peak did not fluctuate in a remarkable manner, drainage area and runoff volume remained approximately the same. Total channel slopes and total flow lengths also increased with further subdivision. Peak discharge occurred after 16 hours for the storm for levels 2, 3, and 4, respectively, and after 17 hours for levels 1, 5, and 6, respectively (Figure 3.7).

<table>
<thead>
<tr>
<th>Subdivision Levels</th>
<th>Number of Subdivisions</th>
<th>Drainage Area (mi²)</th>
<th>Peak Discharge, Qp (cfs)</th>
<th>Time to Peak, Tp (hr)</th>
<th>Runoff Volume, Q (in)</th>
<th>Total Channel Slope (ft/ft)</th>
<th>Total Flow Length (ft.)</th>
<th>Total Channel Slope/Total Flow Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>6.487000</td>
<td>30.70</td>
<td>17.25</td>
<td>0.07</td>
<td>0.0035</td>
<td>52142</td>
<td>6.71E-08</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>6.486900</td>
<td>29.00</td>
<td>16.05</td>
<td>0.07</td>
<td>0.0043</td>
<td>55177</td>
<td>7.74E-08</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>6.487000</td>
<td>28.30</td>
<td>16.20</td>
<td>0.07</td>
<td>0.0226</td>
<td>55409</td>
<td>4.08E-07</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>6.486973</td>
<td>30.50</td>
<td>16.15</td>
<td>0.07</td>
<td>0.0684</td>
<td>74016</td>
<td>9.24E-07</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>6.486867</td>
<td>30.40</td>
<td>17.20</td>
<td>0.07</td>
<td>0.1983</td>
<td>98383</td>
<td>2.02E-06</td>
</tr>
<tr>
<td>6</td>
<td>53</td>
<td>6.486979</td>
<td>31.20</td>
<td>17.10</td>
<td>0.07</td>
<td>0.5874</td>
<td>139897</td>
<td>4.20E-06</td>
</tr>
</tbody>
</table>

Table 3.6. Frequency storm simulation results for W1 showing 6 levels of subdivisions.
3.3.1.2. **Soil Conservation Service (SCS) Storm Precipitation Method**

Simulation results for study area W1 are shown in Table 3.7 when SCS type 2 storm precipitation method was modeled. The highest peak discharge (51.3 cfs) occurred for subdivision level 6, followed by level 5 (50.2 cfs). Levels 2 and 3 had the same amounts of peak flows (47.7 cfs), while levels 1 and 4 had 50.0 cfs and 48.9 cfs, respectively. In Figure 3.8, peak discharge fluctuated for the lower subdivisions and then steadily increased for higher levels of subdivisions. Time to peak fluctuated within one hour of each other in a non-remarkable manner, while runoff volume remained unchanged for all subdivision levels. Total channel slopes and total flow lengths increased with further subdivision (Figure 3.9). These results follow the same pattern.
shown in the frequency storm analysis and agree with conclusions from published literature (Casey et al., 2015). Hydrographs at the outlet of W1 depicting different subdivision levels when using SCS storm model for simulation are shown in Figure 3.10.

<table>
<thead>
<tr>
<th>Subdivision Levels</th>
<th>Number of Subdivisions</th>
<th>Drainage Area (mi²)</th>
<th>Peak Discharge, Qp (cfs)</th>
<th>Time to Peak, Tp (hr)</th>
<th>Runoff Volume, Q (in)</th>
<th>Total Channel Slope (ft/ft)</th>
<th>Total Flow Length (ft)</th>
<th>Total Channel Slope /Total Flow Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>6.487000</td>
<td>50.00</td>
<td>16.55</td>
<td>0.11</td>
<td>0.0035</td>
<td>52142</td>
<td>6.71E-08</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>6.486900</td>
<td>47.70</td>
<td>15.15</td>
<td>0.11</td>
<td>0.0043</td>
<td>55177</td>
<td>7.74E-08</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>6.486900</td>
<td>47.70</td>
<td>15.15</td>
<td>0.11</td>
<td>0.0226</td>
<td>55409</td>
<td>4.08E-07</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>6.486973</td>
<td>48.90</td>
<td>15.50</td>
<td>0.11</td>
<td>0.0684</td>
<td>74016</td>
<td>9.24E-07</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>6.486867</td>
<td>50.20</td>
<td>16.50</td>
<td>0.11</td>
<td>0.1983</td>
<td>98383</td>
<td>2.02E-06</td>
</tr>
<tr>
<td>6</td>
<td>53</td>
<td>6.486979</td>
<td>51.30</td>
<td>16.45</td>
<td>0.11</td>
<td>0.5874</td>
<td>139897</td>
<td>4.20E-06</td>
</tr>
</tbody>
</table>

Table 3.7. SCS type 2 storm simulation results for W1 showing 6 levels of subdivisions.
Figure 3.8. Showing subdivision effect on runoff when simulated with an SCS type 2 storm precipitation method for W1.

Figure 3.9. Showing total channel slopes and total flow lengths trends for W1.
3.3.2. Simulation results for W2

3.3.2.1. SCS Storm Precipitation Method

Simulation results for W2, using the SCS storm precipitation method are presented in Table 3.8, showing three levels of subdivision. Level 1 represents the entire watershed while levels 2 and 3 consist of 3 and 5 subdivisions. Level 3 was the highest level of subdivision for W2 because beyond this level, channel travel times errors were reported in the TR-55 worksheet resulting from negative or zero channel slope values. The highest peak discharge value here occurred for level 2 (117 cfs), followed by levels 1 (115.5 cfs) and 3 (107.7 cfs).
Table 3.8. NSC type 2 storm simulation results for W2 showing 3 levels of subdivisions.

<table>
<thead>
<tr>
<th>Subdivision Levels</th>
<th>Number of Subdivisions</th>
<th>Drainage Area (mi²)</th>
<th>Peak Discharge, Qp (cfs)</th>
<th>Time to Peak, Tp (hr)</th>
<th>Runoff Volume, Q (in)</th>
<th>Total Channel Slope (ft/ft)</th>
<th>Total Flow length (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>14.114000</td>
<td>115.50</td>
<td>16.40</td>
<td>0.17</td>
<td>0.0007</td>
<td>61358.00</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>14.113700</td>
<td>117.00</td>
<td>15.50</td>
<td>0.17</td>
<td>0.0073</td>
<td>69065.69</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>14.114300</td>
<td>107.70</td>
<td>15.40</td>
<td>0.18</td>
<td>0.0123</td>
<td>101063.27</td>
</tr>
</tbody>
</table>

Also, time to peak was observed to be longer for level 1 (16.4 hrs) than level 2 (15.5 hrs) and 3 (15.4 hrs), respectively. However, drainage area and runoff volume remained relatively unchanged for all levels of subdivision, while total channel slopes and total channel lengths increased with further increase in the number subdivision.

Figure 3.11 shows the impact of subdivision of runoff characteristics when simulated using SCS storm method, while Figure 3.12 depicts how total channel slopes and total channel lengths increase with further subdivision.
Figure 3. 11. Showing subdivision effect on runoff when simulated with SCS type 2 storm for W2.

Figure 3. 12. Showing total channel slopes and total flow lengths trends for W2.
3.3.3. Simulation results for W3

3.3.3.1. SCS Storm Precipitation Method

Simulation results for 6 subdivision levels of W3 are shown in Table 3.9 when modeled with the SCS storm method. Peak discharge is highest for level 1 (51.9 cfs) and lowest for level 2 (50.2 cfs). Level 1 is the entire watershed modeled as one subdivision while level 2 consisted of 3 subdivisions. Other peak discharge values are 51.7 cfs for level 3 (5 subdivisions), 50.9 cfs for level 4 (11 subdivisions), 51.1 and 51.6 cfs for level 5 and 6, respectively. Subdividing the watershed beyond 27 subdivisions (level 6) resulted in channel travel time errors cascading throughout the system and reported in the TR-55 worksheet. Again, the K-value in the Muskingum routing equation is the channel travel time, and this value was obtained from the TR-worksheet.

<table>
<thead>
<tr>
<th>Subdivision Levels</th>
<th>Number of Subdivisions</th>
<th>Drainage Area (mi2)</th>
<th>Peak Discharge, Qp (cfs)</th>
<th>Time to Peak, Tp (hr)</th>
<th>Runoff Volume, Q (in)</th>
<th>Total Channel Slope (ft/ft)</th>
<th>Total Flow length (ft)</th>
<th>Total Channel Slope/Total Flow length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>9.168600</td>
<td>51.90</td>
<td>16.40</td>
<td>0.12</td>
<td>0.0028</td>
<td>24723.00</td>
<td>1.13E-07</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>9.168600</td>
<td>50.20</td>
<td>18.15</td>
<td>0.12</td>
<td>0.0104</td>
<td>61486.47</td>
<td>1.69E-07</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>9.168505</td>
<td>51.70</td>
<td>17.40</td>
<td>0.12</td>
<td>0.0221</td>
<td>87070.24</td>
<td>2.54E-07</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>9.168545</td>
<td>50.90</td>
<td>18.05</td>
<td>0.12</td>
<td>0.0549</td>
<td>139691.11</td>
<td>3.93E-07</td>
</tr>
<tr>
<td>5</td>
<td>21</td>
<td>9.168661</td>
<td>51.10</td>
<td>17.55</td>
<td>0.12</td>
<td>0.1324</td>
<td>152229.20</td>
<td>8.70E-07</td>
</tr>
<tr>
<td>6</td>
<td>27</td>
<td>9.168600</td>
<td>51.60</td>
<td>17.25</td>
<td>0.12</td>
<td>0.2011</td>
<td>170690.70</td>
<td>1.18E-06</td>
</tr>
</tbody>
</table>

Table 3.9. SCS type 2 storm simulation results for W3 showing 6 levels of subdivisions.

Time to peak was longer for level 2 (18.15 hrs), followed by level 4 (18.05hrs), level 5 (17.55 hrs), level 3 (17.4 hrs), level 6 (17.25hrs) and level 1 (16.4hrs). While drainage
area and runoff volume remained relatively unchanged for all subdivision levels, total
channel slopes and total channel flow lengths increased with increasing subdivision
levels as shown in Figure 3.13 and Figure 3.14.

Figure 3. 13. Showing subdivision effect on runoff when simulated with an
SCS type 2 storm for W3.
3.3.4. Simulation results for W4

3.3.4.1. Frequency Storm Precipitation Method

Simulation results for study area W4 are shown in Table 3.10 when frequency storm precipitation method was modeled. Here, the experiment consisted of 7 subdivision levels, with the entire watershed as level 1. Level 2 had 3 subdivisions while subsequent levels had 5, 9, 21, 50 and 54 subdivisions, respectively. Level 7, corresponding to 54 subdivisions was produced from a default threshold area set by the software for delineation. Further subdivision beyond 54 resulted in a cascade of channel travel time errors, resulting from negative or zero channel slope values, in the TR-55 worksheet. It is important to note that time to peak and peak discharge values cannot be correctly computed when channel travel times and slope errors occur. As in the procedure for W1, to determine subsequent subdivision levels, a threshold area for stream definition
(delineation) was selected and the software automatically implemented the watershed subdivision process.

<table>
<thead>
<tr>
<th>Subdivision Levels</th>
<th>Number of Subdivisions</th>
<th>Drainage Area (m²)</th>
<th>Peak Discharge, Qp (cfs)</th>
<th>Time to Peak, Tp (hr)</th>
<th>Runoff Volume, Q (in)</th>
<th>Total Channel Slope (ft/ft)</th>
<th>Total Flow Length (ft)</th>
<th>Total Flow Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>14.329000</td>
<td>65.50</td>
<td>24.00</td>
<td>0.11</td>
<td>0.0012</td>
<td>80441</td>
<td>1.49E-08</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>14.328100</td>
<td>65.40</td>
<td>21.00</td>
<td>0.11</td>
<td>0.0050</td>
<td>83605</td>
<td>5.98E-08</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>14.328200</td>
<td>57.40</td>
<td>23.00</td>
<td>0.12</td>
<td>0.0079</td>
<td>95108</td>
<td>8.31E-08</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>14.328500</td>
<td>62.40</td>
<td>20.15</td>
<td>0.12</td>
<td>0.0209</td>
<td>141516</td>
<td>1.48E-07</td>
</tr>
<tr>
<td>5</td>
<td>21</td>
<td>14.3288570</td>
<td>65.30</td>
<td>23.00</td>
<td>0.12</td>
<td>0.0421</td>
<td>177077</td>
<td>2.38E-07</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>14.328409</td>
<td>74.90</td>
<td>23.30</td>
<td>0.12</td>
<td>0.1442</td>
<td>287466</td>
<td>5.02E-07</td>
</tr>
<tr>
<td>7</td>
<td>54</td>
<td>14.328397</td>
<td>75.60</td>
<td>23.25</td>
<td>0.12</td>
<td>0.1648</td>
<td>291794</td>
<td>5.65E-07</td>
</tr>
</tbody>
</table>

Table 3. 10. Frequency storm simulation results for W4 showing seven levels of subdivisions.

The highest peak discharge was 75.6 cfs was recorded for level 7 and 65.5 cfs for level 1, while the lowest peak discharge of 28.3 cfs occurred for level 3, corresponding to 5 subdivisions. Level 4 (9 subdivisions) had the earliest time to peak with flows peaking after 20 hours, followed by level 2 (21 hours) and 23 hours for levels 3 and 21, respectively (Figure 3.11). The fluctuation in peak discharge for lower levels of subdivisions agrees with results reported by Casey et al. (2015), but the continuous increase in peak discharge with further subdivision is contrary to conclusions reported by Cleveland & Thompson (2009) and Zaghloul (1983).

Runoff volume fluctuated for subdivision levels 1 and 2 but remained unchanged for all other subdivision levels. The fluctuations associated with time to peak and runoff volume were not remarkably different with findings reported by Casey et al. (2015), suggesting that time to peak and runoff volume were not sensitive to the practice of
subdivision. The results also show that total channel slopes and total flow lengths increased with increasing number of subdivisions (Figure 3.13). Hydrographs at the outlet of W4 depicting different subdivision levels when using SCS storm model for simulation are shown in Figure 3.15.

![Figure 3.15. Showing subdivision effect on runoff when simulated with a frequency storm for W4.](image)

3.3.4.2. **Soil Conservation Service (SCS) Storm Precipitation Method**

Simulation results for W4 are shown in Table 3.11 when SCS type 2 storm precipitation method was modeled. The highest peak discharge (107 cfs) occurred for subdivision level 7 and followed by level 6 (106.10 cfs). Subdivision level 3, corresponding to 5 subdivisions had the lowest amounts of peak discharge (83.5 cfs),
while levels 1, 2, 4 and 5 levels had 99.0, 95.1, 89.8 and 93.2 cfs, respectively (Figure 3.12).

Similarly, as shown in Figure 3.16, simulation results show that time to peak fluctuated within a few hours of each other but not in a remarkable manner, while runoff volume remained approximately the same for all subdivision levels. This result also agrees with conclusions from published literature (Casey et al., 2015). However, total channel slopes and total flow lengths increased with further subdivision levels (Figure 3.17).

<table>
<thead>
<tr>
<th>Subdivision Levels</th>
<th>Number of Subdivisions</th>
<th>Drainage Area (mi²)</th>
<th>Peak Discharge, Qp (cfs)</th>
<th>Time to Peak, Tp (hr)</th>
<th>Runoff Volume, Q (in)</th>
<th>Total Channel Slope (ft/ft)</th>
<th>Total Flow Length (ft)</th>
<th>Total Channel Slope Total Flow Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>14.329000</td>
<td>99.00</td>
<td>23.40</td>
<td>0.17</td>
<td>0.0012</td>
<td>80441</td>
<td>1.49E-08</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>14.328100</td>
<td>95.10</td>
<td>20.50</td>
<td>0.16</td>
<td>0.0050</td>
<td>83605</td>
<td>5.98E-08</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>14.328200</td>
<td>83.50</td>
<td>22.25</td>
<td>0.17</td>
<td>0.0079</td>
<td>95108</td>
<td>8.31E-08</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>14.328500</td>
<td>89.80</td>
<td>21.00</td>
<td>0.17</td>
<td>0.0209</td>
<td>141516</td>
<td>1.48E-07</td>
</tr>
<tr>
<td>5</td>
<td>21</td>
<td>14.328570</td>
<td>93.20</td>
<td>22.45</td>
<td>0.17</td>
<td>0.0421</td>
<td>177077</td>
<td>2.38E-07</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>14.328409</td>
<td>106.10</td>
<td>23.20</td>
<td>0.17</td>
<td>0.1442</td>
<td>287466</td>
<td>5.02E-07</td>
</tr>
<tr>
<td>7</td>
<td>54</td>
<td>14.328397</td>
<td>107.10</td>
<td>23.15</td>
<td>0.17</td>
<td>0.1648</td>
<td>291794</td>
<td>5.65E-07</td>
</tr>
</tbody>
</table>

Table 3.11. NSC type 2 storm simulation results for W4 showing 7 levels of subdivisions.
Figure 3.16. Showing subdivision effect on runoff when simulated with an SCS type 2 storm.

Figure 3.17. Showing total channel slopes and total flow lengths trends for W4.
Figure 3.18. Showing hydrographs at the outlet of W4 for the respective subdivision levels.

Slight fluctuations for lower levels of subdivision for time to peak and runoff volume were not extensively evaluated because overall simulation results in this study reasonably agree with reported conclusions in the literature. These conclusions suggest that time to peak and runoff volume are not significantly impacted by further watershed subdivisions and therefore less sensitive to subdivision practice for simulations at the outlet of a watershed (Chen & Mackay, 2004; FitzHugh & Mackay, 2000; Jha et al., 2004; Casey et al., 2015). Figure 3.18 shows hydrographs at the outlet of W4 for 7 subdivision levels.
In this research, it is important to note that the study areas were treated as ungauged watersheds and in the criteria for ranking subdivision levels, level 1 was the entire watershed for each study area. The number of subdivisions in subsequent levels was determined by a stipulated threshold area for stream definition (drainage network delineation) while the software algorithm automatically implemented the subdivision procedure. It is also important to note that between any two subdivision levels, any incremental change in the threshold area did not produce a different number of subdivisions.

3.3.5. Comparison of peak discharge values for W1 and W4

This section compares simulation results for W1 to simulation results for W4 when SCS storm was modeled. For W1, the highest peak discharge (51.3 cfs) occurred for subdivision level 6, and the lowest amounts of peak flows (47.7 cfs) occurred for levels 2 and 3, while for W4 the highest peak discharge (107 cfs) for W4 was recorded for level 7 and the lowest peak discharge (83.5 cfs) occurred for level 3 (Tables 3.6 and 3.8; Figures 3.8 and 3.12).

3.4. Discussions

This study utilized HEC-HMS to simulate runoff responses in four watersheds treated and analyzed as ungauged. The experiments were set up to further evaluate the sensitivity of runoff characteristics to the practice of watershed subdivision for a better understanding of runoff processes as a basis for improved hydrologic analysis in ungauged watersheds. The notion of ungauged watersheds in this study refers to
watersheds where scarcity of observed data for model calibration and validation is endemic.

3.4.1. W1 Discussion

Simulation results for W1 were compared side by side for both the frequency storm precipitation method and SCS storm method (Table 3.5 and Table 3.6) showed that peak discharge values initially fluctuated for lower subdivision levels and did not stabilize with further subdivisions (Figure 3.7 and Figure 3.8), instead there was steady increase in peak discharge as subdivision levels increased. It should be noted that during watershed delineation, any further subdivision beyond a certain level resulted in a cascade of channel travel time errors because of negative or zero channel slope values. This meant that time to peak and peak discharge could not be reliably computed in the TR-55 worksheet. In this study, peak discharge initially fluctuated and then increased steadily with further subdivision. This result tends to contradict reports by Bingner et al., (1997), Norris & Haan (1993) and Tripathi et al. (2006) that peak discharge plateau for higher subdivision levels.

Observed increase in peak discharge values suggest that runoff is a function of time of concentration. In the SCS unit hydrograph transform model, direct runoff or peak discharge is related to time to peak (Equation 5), which in turn is related to Lag time (Equation 6). The Lag time is an estimate of the average time of flow for all locations on a watershed and was computed during HEC-GeoHMS processing. Its value was then used by the HEC-HMS transform model for SCS unit hydrograph to solve Equation 6 for time to peak. Lag time is 60% of time concentration (Equation 7) for ungauged watershed
and from information obtained from the TR-55 methodology worksheet (McCuen & Okunola, 2002) and applied in this study, time of concentration was calculated as the sum of travel times for sheet flow, shallow flow, and channel flow (Equation 8). This information was utilized in the computation of lag time. Therefore, despite observed initial fluctuations, increasing peak discharge indicate that as geometric properties such as drainage densities change due to further subdivision or delineation of the drainage network, overland flow elements are being replaced by defined channels and their contributing areas, resulting in alterations in time of concentration (Goodrich, 1992).

Analysis of simulation results for W1 using the SCS storm method show that time for the discharge to peak occurred several hours after the storm started (Table 3.7 and Figure 3.8), with the earliest peak flow occurring 15 hours for subdivision levels 2 and 3, consisting of 3 and 5 subdivisions, respectively. This long duration for peak discharge is attributable to the shape and orientation of the watershed. For long and narrow (elongated) watersheds such as W1, tributaries flow into the main channel along its length in which downstream flows reach the outlet before flows from upstream tributaries (Singh, 1997), indicating that a watershed’s shape and orientation significantly influence the duration of peak flows (Ayalew & Krajewski, 2017). In this study, simulation results show that runoff volume was not affected by subdivision practice, a result that agrees with the conclusions reported by Jha et al. (2004), while drainage area remained approximately the same for all subdivision levels (Table 3.7). Peak discharge value was the same for level 5 (25 subdivisions) compared to level 1, increasing by 2% and 3%, for levels 4 (11 subdivisions) and 7 (53 subdivisions), respectively, and by 5% for levels 2 (3 subdivisions) and 3 (5 subdivisions), respectively. Also, time to peak was the same for
levels 1 and 5, 1% different for level 6, 7% for level 4, and 9% each for levels 2 and 3, respectively, compared to subdivision level 1. However, runoff volume remained unchanged for all subdivision levels (Table 3.7).

3.4.2. W2 Discussion

The W2 study area was subdivided into only three subdivision levels because beyond level 3, consisting of 5 subdivisions, channel travel time errors were reported in the TR-55 worksheet. It is important to note that information from the TR-55 worksheet is utilized in model parameterization. For instance, channel time of travel obtained from TR-55 worksheet is used as the K-value component of the Muskingum routing method adopted in this study. The Muskingum routing was selected because all the channels in the study areas were assumed to be natural reaches and so exhibit banks with gentle slopes. This assumption allowed for adjustment in the X-component of the Muskingum equation between 0.0 and 0.5. In this study, 0.01 was chosen for X-value.

To resolve channel travel time issues, a subbasin exhibiting channel travel time errors due to a reported negative or zero channel slope value in the TR-55 worksheet can be merged with a neighboring subbasin whose channel travel time was calculated without error. Figure 3.19 illustrates how subdivision level 4 consisting of 11 subdivisions but exhibiting channel travel time errors for subbasin W480, was merged with W440 to generate W1070. A new subdivision level with 10 subbasins was produced with error free calculated channel time of travels for all subdivisions. However, despite resolving channel slope issues by merging subdivisions, there is a tendency to introduce more artifacts into the automated process of watershed delineation. This gives rise to the need
to quantify its overall impact on simulation results, particularly in ungauged watersheds where observed data is scarce or non-existent. Therefore, only a small number of subdivision levels were generated for W2 and therefore its simulation results were not compared to simulation results from the other study areas. However, the limited W2 results show that while drainage area, time to peak and runoff volume tend to stabilize with further subdivision (Figure 3.11), the fluctuation observed in peak discharge values are like reported results for lower levels of subdivision (Norris & Haan, 1993), suggesting that subdivision affects peak discharge but has negligible impact on drainage area, time to peak and runoff volume.

Figure 3. 19. Showing subdivision in W2 to illustrate how subbasins are merged to resolve the cascading of channel slope errors during subdivision.
3.4.3. W3 Discussion

Study area W3 was subdivided into 6 subdivision levels, with level 6 being the highest attainable level before channel travel time errors begin to occur due to negative or zero slope values as reported in the TR-55 worksheet. The negative or zero slope values are issues associated with DEM smoothness or the presence of pits and sinks during production. As in W1, simulation results for W3 shows that peak discharge fluctuated initially for lower subdivisions and then steadily increase for levels 4 through levels 5 and 6. Time to peak and runoff volume did not exhibit any remarkable change with further increase in subdivision levels, while total channel slopes and total channel flow lengths increased steadily with further increase in subdivision. This trend is like results observed for W1.

It is important to note that W1, W2 and W3 are in the same hydrologic subregion C, in Perkins County. In the same manner that W2 simulation results were not considered for detailed analysis, W3 simulation results too were not considered for detailed analysis because its results showed similar trends as W1. A fourth study area (W4) from hydrological subregion A (Brookings County) was therefore modeled and its results compared to simulation results for W1.

3.4.4. W4 Discussion

Study area W4 was subdivided into 7 subdivision levels. Simulation results for W4 using the SCS storm method show that peak discharge increased by 4% for level 2 compared to level 1, 6% for level 5, 7% for level 6, and 8%, 10% and 17% for levels 7, 4 and 3, respectively. Time to peak was 1% different for levels 6 and 7, 4% for level 5, 5%
for level 3 and 13% for level 2, respectively, when compared to level 1. Runoff was 6% for level two relative to level one but remained unchanged for all other levels.

Comparing simulation results for W1 and W4 when SCS storm was modeled showed that, the highest peak discharge (51.3 cfs) for W1 occurred for subdivision level 6, and the lowest amounts of peak flows (47.7 cfs) occurred for levels 2 and 3, while for W4 the highest peak discharge (107 cfs) was recorded for level 7 and the lowest peak discharge (83.5 cfs) occurred for level 3. These results show that the highest values of peak discharge occur for the highest number of subdivision levels while the lowest values occur for intermediate subdivision levels. In real life situation, comparing extreme peak discharge values from simulation results gives a watershed manager the ability to avoid making decisions that result in either overestimating or underestimating of project costs.

Generally, simulation results for both the frequency storm and SCS storm methods indicate that total channel slopes and total flow lengths tend to increase with further subdivision (Figures 3.9 and 3.12), resulting in increased peak discharges. Peak discharge increased with increasing subdivision levels because, according the SCS unit hydrograph model, channel travel time is a function of channel length (Equation 9) and average flow velocity (Equation 10). Average velocity computed from Manning’s equation requires channel slope and hydraulic radius values. These values are reported in the TR-55 worksheet. Therefore, as channel slopes and flow lengths increase with further subdivision, so does peak discharge. It is important to note that the slope variable in Manning’s equation is a square root, meaning that flow velocities are slower for longer flow lengths. However, in this study, there was no determination of whether peak
discharge values were closer to real conditions because the model was not calibrated using observed data.

3.5. Conclusions

In this study, HEC-HMS was utilized to run simulations on subdivision model scenarios/levels for watersheds belonging to different hydrologic subregions. Simulation results were analyzed based on Meteorologic models calibrated for frequency and SCS storms precipitation methods. Models with SCS storm method were prioritized for analysis because the method was better suited for the study.

Simulation results for W1 for both the frequency and SCS storm methods indicate that peak discharge values initially fluctuated for lower subdivision levels and did not stabilize with further subdivisions, instead there was an increase in peak discharge values as subdivision levels increased. The initial fluctuation in peak discharge agrees with reported results but the subsequent increase in peak discharge with further subdivision tend to contradict other reported conclusions in the literature.

Simulation results for W1 when modeling SCS storm showed that peak discharge occurred several hours after the storm started, with the earliest peak flow occurring 15 hours for subdivision levels 2 and 3, consisting of 3 and 5 subdivisions, respectively. The long duration is attributable to the shape and orientation of the watershed. The slight variation in time to peak between subdivision levels was not remarkable and agrees with other studies. Simulation results were satisfactory for runoff volume, also agreeing with findings from the literature. Relative to subdivision level 1, peak discharge was the same for level 5 (25 subdivisions), increasing by 2% and 3%, for levels 4 (11 subdivisions) and
7 (53 subdivisions), respectively, and by 5% for levels 2 (3 subdivisions) and (3 subdivisions), respectively.

Simulations results for W4 when modeled with SCS storm method showed that highest peak discharge (107 cfs) occurred for level 7, followed by level 6. Subdivision level 3, consisting of 5 subdivisions had the lowest amounts of peak discharge (83.5 cfs), while levels 1, 2, 4 and 5 had 99.0, 95.1, 89.8 and 93.2 cfs, respectively. Comparatively, peak discharge increased by 4% for level 2 compared to level 1, 6% for 5, 7% for levels 6, and 8%, 10% and 17% for levels 7, 4 and 3, respectively. Time to peak fluctuated within a few hours of each other but not in a remarkable manner, while runoff volume remained approximately the same for all subdivision levels. These results that agree with conclusions from published literature. Comparing extreme peak discharge values from simulation results gives the watershed manager or water resources engineer the ability to avoid making decisions that result in overestimation or underestimation of project costs.

HEC-HMS simulation results also utilizing both the frequency and SCS storm precipitations showed that total channel slopes and total flow lengths increased with further subdivision for both study areas, indicating that as the watersheds were further subdivided, there was a corresponding change in flow from sheet flow to shallow flow and from shallow flow to channel flow, resulting in increased channel slopes and channel lengths, and ultimately resulting in high peak flows.

Overall, these results show that a better understanding of runoff processes provide the basis for improved hydrologic analysis of ungauged watersheds and provide information for proper management decisions.
4. Chapter Four: Evaluating Input Data Resolution Effect on Runoff Characteristics for Improved Hydrologic Analysis of Ungauged Watersheds

Abstract

Data resolution is important in watershed studies requiring the use of geographic information system (GIS) datasets for modeling and simulation. However, the use of datasets from different sources and at different resolutions have impacts on simulation results. While several studies have proposed the use of observed data for model calibration, they have failed to address the inter-relationship between data resolution and runoff characteristics and how this interaction affect simulation results. The objective of this study was to further evaluate the impact of data resolution on runoff characteristics in ungauged watersheds. Runoff hydrographs at the outlets of different resolution models were evaluated and analyzed, using the US Army Corps of Engineering Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). Simulation results indicate that peak discharge values increased as finer resolution datasets were resampled to coarser resolutions with a corresponding reduction in the sizes of drainage areas. Therefore, a better understanding of the impacts of data resolution on runoff is a basis for improved hydrologic analysis in ungauged watersheds.
4.1. Introduction

Topographic and topologic attributes such as drainage networks, slopes and aspects are important components of hydrologic and water resources engineering studies. These watershed characteristics are derived from Geographic Information System (GIS) datasets such Digital elevation Models (DEMs).

The increasing use of computers and GIS technology in watershed modeling has become ubiquitous because of availability, accessibility wholesale download and use of GIS datasets. However, studies have shown that there are issues associated with the scale and methods involved in the production and collection of such datasets. For instance, GIS datasets are generated using a multi-resolution structure to cast raster data model in a geographic coordinate system and processed with a consistent resolution, coordinate system, elevation units, and vertical and horizontal datum (Gesch et al., 2002). These resolutions include grid spacings of 1-arc-second (approx. 30 meters), 1/3-arc-second (approx. 10 meters) and 1/9-arc-second (approx. 3 meters). Researchers and engineers in the water resources sector have questioned the accuracy of such data. In Smith & Sandwell (2003), the accuracy of Shuttle Radar Topography Mission (SRTM) data was compared to the National Elevation Dataset (NED) and Hector Mine ALSM datasets. They concluded that the SRTM data was considerably more accurate than the NED data when each of them was compared the the higher quality Hector Mine ALSM.

Other studies have also investigated the issues associated with GIS datasets. In their research, Gesch, Oimoen, & Evans (2014) assessed the accuracy of NED in comparison to SRTM and found that corresponding aspect values can vary substantially between NED and SRTM datasets but that the NED exhibited a lower overall slope errors
than SRTM across a range of slopes categories. Similarly, Jenson & Domingue (1988) stated that despite the advantage of deriving a huge amount of topographic information from GIS datasets such as a DEM, there are problems associated with the traditional methods employed in calculating slope, aspect and shaded relief, needed to accurately determine flow direction in flat terrain. They concluded that the accuracy of topographic attributes from DEMs depends on its quality and resolution. Also, Stephens, Bates, Freer, & Mason (2012) evaluated widely available spaceborne DEMs and concluded that they were replete with errors that impacted river channel flow connectivity to adjoining floodplains. For reliable flood plain hydrodynamic modeling, they stated that accurate DEMs are required and proposed a DEM adjustment method that utilizes drainage network information to remove all pits in spaceborne DEMs.

In recent years, traditional methods of manual evaluation of topographic maps have been replaced by simpler and easily available methods of automated extraction of digitized information from DEMs. This ability makes it relatively easy to extract topographic characteristics of complex landscapes. For hydrologists and water resources engineers, characterization of landscapes depends primarily on drainage networks, drainage divides, flow paths, and slope and aspect. Despite the relative ease of automation, the process of extracting landscape characteristics from DEMs is affected by a combination of systematic errors such as human and algorithmic errors (Garbrecht & Starks, 1995). Some of these limitations were report by Garbrecht & Martz (2000) to include quality and resolution of the datasets. Other reported issues are positioning of the ends of the drainage networks and the assignment of the drainage direction (Garbrecht & Martz, 2000; Tribe, 1992). In their own assessment, O'Callaghan & Mark (1984) stated
that automated extraction of attributes from DEMs has remained attractive to watershed modelers because of its critical role and relative accuracy of model simulation outcomes.

The automated extraction of digitized information using different algorithms has been widely demonstrated (Jenson & Domingue, 1988; Martz & Garbrecht, 1992; Moore, Grayson, & Ladson, 1991; O'Callaghan & Mark, 1984), and attributes derived from DEMs have been reported to be affected by their resolutions or grid sizes (Hutchinson & Dowling, 1991; Jenson, 1991). In their study of DEM grid size effect on landscape representation and simulation results, Zhang & Montgomery (1994) utilized high resolution DEMs to generate a series of simulated landscapes of different grid sizes and concluded that a 10-m grid size DEM was a compromise for use in hydrologic modeling.

Evaluating scaling issues in GIS, Thieken, Lücke, Diekkrüger, & Richter (1999) reported that topographic attributes are significantly different (5% for basin size and 20% for flow lengths).

For many watershed applications, 10m DEMs have been recommended for use by Zhang & Montgomery (1994). Similarly, Garbrecht & Martz (2000) and Seybert (1997) have justified the use of high resolution DEMs for some hydrologic applications while emphasizing that runoff response estimates are impacted by data resolution. However, for low relief terrains, Jenson & Domingue (1988) argued that DEM resolution was not a significant factor because during production artifacts such as pits and sinks may still occur.
4.2. Methodology

4.2.1. Materials

4.2.1.1. Study Areas

South Dakota State is in the Mid-western region of the United States, having a boarder with North Dakota to the north, Minnesota, and Iowa to the east, Nebraska to the south and Wyoming and Montana to the west (Figure 4.1). It is the location of the study areas for this research (Figure 4.1). The state of South Dakota lies between longitude 97°28´3´´W to 104°3´W and latitude 42°29´32´´N to 45°56´N. Its total area is 77,121 mi², consisting of 75,898 mi² and 1,224 mi² of land and water respectively, and is about 383 mi long and 237 mi wide. The state’s terrain has an elevation between 966 ft and 7,242 ft, with an average elevation of 2,200 ft. The major drainage systems are the Cheyenne, Missouri, James, and White Rivers. Average temperature in South Dakota ranges between 86.5°F high and 1.9°F low, with an average annual precipitation ranging between 15 inches to 28 inches (Berg, 1998; Sando, 1998)
The study area is Indian Creek watershed in Perkins county, and it is the second largest county by area in South Dakota state. Perkins county lies on the north edge of the state, bordering North Dakota, on the Missouri Plateau in the Great Plains region. The county is drained in the north by the Grand River, in the south by the Moreau River and their respective tributaries. These two drainage systems flow eastward into the Missouri River. Perkins county has a total area of 2980 mi² (7500 Km²) consisting of 2870 mi² (7400 Km²) of land and 20 mi² (52 Km²) of water. According to Wiesner (1980), “It is an upland plain that is moderately dissected by streams and entrenched drainageways. Relief is gently rolling-to-steep in much of the county and a few prominent buttes and
ridges on the landscape. Slopes are mostly nearly to moderately sloping”. The highest elevation in Perkins county is 829 meters (2720 ft).

Land use/land cover for the study area was reclassified (Table 4.1) as agricultural, water, medium residential and forest, according to United States Geological Service (USGS) Land Cover Institute land class definitions (Anderson, 1976; Shukur, 2017). Its Soil types (Table 4.2) are classified based on stipulated criteria by the US Department of Agricultural Natural Resources Conservation Service hydrologic soil classification (Stewart, Canfield, & Hawkins, 2011). These hydrologic soil classes are A (sandy, loamy sand or sandy loamy); B (silt or loam); C (sandy clay loam) and D (clay loam, silt clay loam, sandy clay, silty clay, or clay) soil groups.

<table>
<thead>
<tr>
<th>Original NLCD classification</th>
<th>Revised classification (re-classification)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NumberDescription</td>
<td>NumberDescription</td>
</tr>
<tr>
<td>11</td>
<td>Open water</td>
</tr>
<tr>
<td>90</td>
<td>Woody wetlands</td>
</tr>
<tr>
<td>95</td>
<td>Emergent herbaceous wetlands</td>
</tr>
<tr>
<td>21</td>
<td>Developed, open space</td>
</tr>
<tr>
<td>22</td>
<td>Developed, low intensity</td>
</tr>
<tr>
<td>23</td>
<td>Developed, medium intensity</td>
</tr>
<tr>
<td>24</td>
<td>Developed, high intensity</td>
</tr>
<tr>
<td>41</td>
<td>Deciduous forest</td>
</tr>
<tr>
<td>42</td>
<td>Evergreen forest</td>
</tr>
<tr>
<td>43</td>
<td>Mixed forest</td>
</tr>
<tr>
<td>31</td>
<td>Barren land</td>
</tr>
<tr>
<td>52</td>
<td>Shrub/scub</td>
</tr>
<tr>
<td>71</td>
<td>Grassland/herbaceous</td>
</tr>
<tr>
<td>81</td>
<td>Pasture/hay</td>
</tr>
<tr>
<td>82</td>
<td>Cultivated crops</td>
</tr>
</tbody>
</table>

Table 4. 1. Original NLCD classification and re-classification (USGS, 2013)
Table 4.2. U.S. Natural Resources Conservation Service criteria for Hydrologic soil groups.

<table>
<thead>
<tr>
<th>Soil Group</th>
<th>Description</th>
<th>Infiltration Rate</th>
<th>Surface Runoff Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Well drained soils, typically sands, loamy sands, or sandy loams</td>
<td>High even when thoroughly wetted</td>
<td>Low</td>
</tr>
<tr>
<td>B</td>
<td>Moderate fine to moderately coarse soils such as silt loams or loams</td>
<td>Moderate when thoroughly wetted</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>C</td>
<td>Fine-textured sandy clay loam soils and soils with underlying layer impeding drainage</td>
<td>Low when thoroughly wetted</td>
<td>High</td>
</tr>
<tr>
<td>D</td>
<td>Fine clay soils and soils with an underlying impermeable layer, soils in areas of permanently high-water table</td>
<td>Very low when thoroughly wetted</td>
<td>High</td>
</tr>
</tbody>
</table>

Average annual precipitation in Perkins county is around 15 inches and out of this amount, 13 inches usually occurs in April, with an average seasonal snow fall of 30 inches. W1 belongs to the South Dakota hydrologic subregion C (Sando, 1998), with an area of 6.487 mi² and treated as unungaged for experimetal purposes only. Figure 4.2 shows its location in Perkins County, South Dakota while Table 4.3 shows its size, land use, soil groups, and average curve numbers (CNs).

Watershed characteristics for the study area indicate that agriculture is the dominant land use with 99%, 1.2% covered by water, 0.2% by forest and very minimal medium residential development. Soil type is dominated by Soil group D (39%) and an average CN of 82.
Table 4. Showing size of study area and its land use, soil groups and average curve numbers (CNs).

<table>
<thead>
<tr>
<th>Wshd</th>
<th>Size (mi²)</th>
<th>Land Use (%)</th>
<th>Soil Group (%)</th>
<th>Average CN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Agric</td>
<td>Water</td>
<td>Med.</td>
</tr>
<tr>
<td>W1</td>
<td>6.487</td>
<td>98.6</td>
<td>1.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 4. 2. Showing (a) HUC12 layer for Perkins County and (b) shape and clipped boundary extent for W1
4.2.1.1. **Modeling Software: Description/Setup**

Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) is a hydrologic modeling system designed by the US Army Corps of Engineers to simulate rainfall-runoff processes of watersheds (Scharffenberg & Fleming, 2006). The application of HEC-HMS in the field of water resources and hydrology is wide ranging.

Examples of areas of application include urban flood frequency studies, flood-loss reduction studies, flood warning system planning studies, reservoir spillway capacity studies, stream restoration studies, and surface erosion and sediment routing studies. Simulation results are either used directly or integrated with other software in different hydrologic-hydraulic applications such as flow forecasting, flood damage remediation, water availability, urban drainage, or for future urbanization impacts. Basic simulation steps are outlined in its User’s manual (USACE, 2016).

To create HMS models for simulation, downloaded datasets (Table 4.4) were clipped to output extents of the study area’s boundary and projected to the X-, Y- and Z-coordinates of the Universal Transverse Mercator (UTM) coordinate system, according to steps outlined in Minami, Sakala, & Wrightsell (2000). Then, Arc Hydro Tools and HEC-GeoHMS (10.1) extensions were utilized to extract and estimate watershed boundaries and drainage areas, flow path lengths and slopes, streams and reach lengths, and average watershed land slopes, according to procedures outlined by Fleming & Doan (2009). The ‘Utility’ menu in HEC-GeoHMS was utilized to integrate land use/land cover classes and hydrologic soil groups to a generate CN grid for the study area and utilized in generating HMS models each resolution scenario. The resultant HMS models were then imported to
HEC-HMS for simulation. Figure 4.3 is a flowchart showing a storm event simulation using HEC-HMS.

Figure 4.3. Flowchart showing data preprocessing using HEC-GeoHMS and storm event simulation using HEC-HMS.
<table>
<thead>
<tr>
<th>Data Type</th>
<th>Description</th>
<th>Data Sources</th>
<th>Spatial Reference Information</th>
<th>Geodetic Model</th>
<th>Format</th>
<th>Source Scale Denominator</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Elevation Data</td>
<td>The NED is a seamless mosaic of best-available elevation data. One of the effects of the NED processing steps is a much-improved base of elevation data for calculating slope and hydrologic derivatives.</td>
<td>USDA/NRCS - National Geospatial Center of Excellence</td>
<td>Grid Coordinate System: Universal Transverse Mercator</td>
<td>Horizontal Datum Name: North American Datum of 1983 (NAD83)</td>
<td>GeoTIFF</td>
<td>10 meter</td>
<td>Unknown</td>
</tr>
<tr>
<td>National Hydrography Dataset (NHD)</td>
<td>Vector dataset provides a network of rivers and streams, including intermittent streams, ditches, and canals. NHD integrates USGS hydrography line data with the EPA Reach File Version 3 data.</td>
<td>USDA/NRCS - National Geospatial Center of Excellence</td>
<td>Grid Coordinate System: Universal Transverse Mercator</td>
<td>Horizontal Datum Name: North American Datum of 1983 (NAD83)</td>
<td>ARC/INFO Shape File</td>
<td>24,000</td>
<td>2016</td>
</tr>
<tr>
<td>Soil Survey Geographic (SSURGO II) Soil</td>
<td>These data provide information about soil features on or near the surface of the Earth. Data were collected as part of the National Cooperative Soil Survey. These data are intended for geographic display and analysis at the state, regional, and national levels. Soil Classification</td>
<td>USDA/NRCS - National Geospatial Center of Excellence</td>
<td>Horizontal Coordinate System Definition: Geographic</td>
<td>Horizontal Datum Name: World Geodetic System of 1984 (WGS84)</td>
<td>ESRI Shape file</td>
<td>250,000</td>
<td>2000 - Present</td>
</tr>
<tr>
<td>National Land Cover Dataset (NLCD)</td>
<td>The dataset is a generalized and nationally consistent land cover data layer for the United States based primarily on a decision-tree classification of circa 2011 Landsat satellite data and can be used for several purposes in a GIS. Land Use Classification</td>
<td>USDA/NRCS - National Geospatial Center of Excellence</td>
<td>Grid Coordinate System: Universal Transverse Mercator</td>
<td>Horizontal Datum Name: North American Datum of 1983 (NAD83)</td>
<td>Tag Image File Format (TIFF)</td>
<td>30 meter</td>
<td>2011</td>
</tr>
<tr>
<td>12 Digit Watershed Boundary Dataset in HUC8</td>
<td>This dataset is intended to be used as a tool for water resolution.</td>
<td>USDA/NRCS - National Geospatial Center of Excellence</td>
<td>Grid Coordinate System: Universal Transverse Mercator</td>
<td>Horizontal Datum Name: North American Datum of 1983 (NAD83)</td>
<td>ARC/INFO Shape File</td>
<td>24,000</td>
<td>2013 - Present</td>
</tr>
</tbody>
</table>

Table 4.4. Showing dataset types, description, sources, special references, geodetic models, format, source scale denominator and year of processing.
For its wide-ranging capability and applicability, several watershed modeling studies have been conducted in the past utilizing HEC-HMS. For example, the software has been used for calibration, verification, and sensitivity analysis (Cunderlik & Simonovic, 2004), event and continuous modeling (Chu & Steinman, 2009), simulation of additive effect of multiple detention basins (Emerson, Welty, & Traver, 2003) and for regional scale flood modeling in the San Anthonio River basin (Knebl, Yang, Hutchison, & Maidment, 2005). Other examples include studies by Gumindoga, Rwasoka, Nhapi, & Dube (2016), Halwatura & Najim (2013), Ibrahim-Bathis & Ahmed (2016), Kaffas & Hrissanthou (2014), Oleyiblo & Li (2010), Pistocchi & Mazzoli (2002), Chu & Steinman (2009) and Scharffenberg & Fleming (2006).

In this study, HEC-HMS projects were created for the study area and their respective resolution scenarios added as basin models. Hydrologic parameter processes and methods selected for model simulations are shown in Table 4.5 as follows: Soil Conservation Service curve number (SCS CN) model was selected for Subbasin Loss Method, SCS Unit Hydrograph for Subbasin Transform Method; CN Lag Method for subbasin lag times (for computing time of concentration), and Muskingum Routing methods were selected for River Routing (U.S.D.A., 1986)

<table>
<thead>
<tr>
<th>Subbasin process</th>
<th>Loss method</th>
<th>Transform method</th>
<th>Lag method</th>
<th>River routing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chosen Method</td>
<td>SCS curve number</td>
<td>SCS unit hydrograph</td>
<td>CN lag method</td>
<td>Muskingum</td>
</tr>
</tbody>
</table>

Table 4.5. Hydrologic parameter processes and methods
Availability of data was the main justification for the selection of basin methods. In HEC-HMS, the SCS-CN loss model calculates runoff volume (excess precipitation) as a function of cumulative precipitation, land use and land cover, soils, and antecedent moisture, while SCS Unit Hydrograph transform method computes peak discharge, and Muskingum routing method computes a downstream hydrograph for a given upstream hydrograph as a boundary condition.

Included in HEC-HMS are equations that compute runoff volume or excess precipitation, peak discharge or excess runoff and time to peak. Runoff volume was computed from cumulative precipitation, land use/land cover, soils, and antecedent moisture; peak discharge was computed from watershed area and time of concentration and time of concentration, Tc was computed as the sum of travel times for sheet, shallow and channel flows.

The SCS CN loss model (Boughton, 1989) was selected in this study to calculate excess runoff from the equation:

\[ P_e = \frac{(P-I_a)^2}{P-I_a+S} \]  

(1)

where \( P_e \) is runoff volume at time t, \( P \) is accumulated rainfall depth at time t, \( I_a \) is the initial abstraction (initial loss) and \( S \) is potential maximum retention.

The empirical relationship between \( I_a \) and \( S \) is given by:

\[ I_a = 0.2S \]  

(2)

Therefore, excess runoff becomes:

\[ P_e = \frac{(P-0.2S)^2}{P+0.8S} \]  

(3)

The relationship between CN and maximum abstraction, \( S \) to watershed characteristics is given by:
\[ S = \frac{1000 - 10CN}{CN} \quad (4) \]

CN varies from 100 (for water bodies) to 30 (for permeable soils with high infiltration).

The SCS unit hydrograph model was selected to simulate peak discharge using the equation:

\[ q_p = C \frac{A}{T_p} \quad (5) \]

where \( q_p \) is peak discharge, \( A \) is area of watershed, \( T_p \) is time to peak and \( C \) is a conversion factor.

Time to peak, \( T_p \) is related to Lag Time, \( t_{lag} \) (average time of flow for all locations on a watershed) by:

\[ T_p = \frac{\Delta t}{2} + t_{lag}, \text{ where } \Delta t \text{ is excess precipitation duration} \quad (6) \]

\[ t_{lag} = 0.6t_c \text{ (ungaged watersheds)} \quad (7) \]

Time of concentration, \( t_c \) was estimated as follows:

\[ t_c = t_{\text{sheet}} + t_{\text{shallow}} + t_{\text{channel}} \quad (8) \]

where \( t_{\text{sheet}} \) is travel time through sheet segments, \( t_{\text{shallow}} \) is travel time through shallow segments and \( t_{\text{channel}} \) is the sum of travel time in channel segments of the watershed.

Time of concentration was calculated for surface flow using the TR-55 methodology for watersheds. In HEC-Geo-HMS, TR-55 worksheet was generated for flow path segments and flow path parameters. Surface flows consisted of sheet flow, shallow flow, and channel flow.

The characteristics for calculating time of travel for Sheet flow included manning’s \( n \), flow length, storm duration (2-year 24-hour rainfall) and land slope; characteristics for calculating time of travel for Shallow flow were surface description (1
- unpaved, 2 – paved), flow length, watercourse slope, and average velocity. Average velocity was computed based on watercourse slope and time of travel was calculated by dividing travel length by average velocity as follows:

\[ T_t = \frac{L}{3600V} \]  \hspace{1cm} (9)

where \( T_t \) is time of travel for shallow concentrated flow (hr), \( L \) is length of travel (ft) of water from watershed to the outlet, and \( V \) is average velocity of flow (ft/s) and 3600 is a conversion factor; and characteristics for calculating time of travel for Channel flow are cross sectional area (ft²), wetted perimeter (ft), hydraulic radius (ft), channel slope (ft/ft), manning’s roughness coefficient, average velocity (ft/s) and flow length, (ft.). Average velocity was computed using manning’s equation.

\[ V = \frac{1}{n} \frac{R^2}{S^{1/2}} \]  \hspace{1cm} (10)

where \( V \) is average velocity (ft/s), \( n \) is manning’s roughness coefficient, \( R \) is hydraulic radius (Gan et al.) and \( S \) is channel slope (ft/ft).

The Muskingum routing method was selected to model channel flow. It computes a downstream hydrograph for a given upstream hydrograph by solving the continuity equation using the finite difference method as follows:

\[ \left( I_t - \frac{1}{2} I_{t-1} + I_t \right) - \left( O_t - \frac{1}{2} O_{t-1} + O_t \right) = \left( S_t - S_{t-1} \right) \]  \hspace{1cm} (11)

where \( I_t \) is inflow, \( O_t \) is outflow, volume of storage, \( S_t \) is the weighted difference between inflow and outflow during the same time. Muskingum storage is defined as:

\[ S_t = KO_t + KX(I_t - O_t) = K[XI_t + (X)O_t] \]  \hspace{1cm} (12)

where \( K \) is time of travel of flood through a reach and \( X \) is a dimensionless weight \((0 \leq X \leq 0.5)\). In this study, \( K \) was calculated based on the TR-55 methodology (Cronshey, 1986; McCuen & Okunola, 2002) while \( X \) was set to between 0.01 and 0.5 with the
assumption that the reaches were of mild slopes with over-bank flows (Tewolde & Smithers, 2006)

HEC-HMS uses the SCS CN loss model concept to calculate runoff volume (excess precipitation) as a function of cumulative precipitation, land use and land cover, soils, and antecedent moisture; SCS Unit Hydrograph transform method computes peak discharge; and Muskingum routing method computes a downstream hydrograph for a given upstream hydrograph as a boundary condition. SCS storm precipitation method was selected as the Meteorologic Model while Control Specifications components were specified to run the simulations.

4.2.2. Methods

4.2.2.1. Resampling

DEM s are datasets containing topographic information about a landscape and according to Garbrecht & Starks (1995), drainage networks and topographic attributes are easily identified and derived in DEMs with finer resolutions. This means that DEMs with coarser resolutions are especially not suitable for low relief surface terrains because of difficulty in identifying drainage networks and other topographic attributes. However, simulation results have been reported to be impacted when different input datasets are combined. To resolve this issue, datasets are resampled to a common resolution before use. Dixon & Earls (2009) described data resampling as a GIS operation of converting a raster dataset into new raster cells or grid sizes by extrapolation and stated that there was a loss of information as a finer resolution data was degraded to a coarse one.
In this study, the ArcMap 10.4.1 ArcToolbox was utilized in the resampling procedure. Studies show that input datasets at different resolutions affect simulation results (Dixon & Earls, 2009). Therefore, in this study, all datasets used were resampled to the same resolution for any one resolution model. Using the resampling tool in ArcGIS, the nearest neighbor resampling technique was selected for this study because it minimizes changes in pixel values and is the most suitable for discrete datasets such as land use data. The original DEM and CN grid used in this research are at 10m resolutions while the impervious percent dataset was at a 30m resolution. All datasets were resampled to 10-, 20-, 30-, 40-, 50-, 60-, 70-, 80-, 90-, and 100-m grid sizes, respectively, representing the different experimental scenarios.

Resampling or resizing a dataset from finer resolutions to coarser, larger grid sizes results in distortions to the datasets. Figure 4.4 shows the difference in shape between catchments delineated from an original 10-m DEM (DEM10) and its resampled 50-m (DEM50) and 100-m (DEM100) variants, respectively. In Figure 4.5, the difference between flow accumulation grids extracted from a reconditioned original 10-m DEM (DEM10) and its 50-m (DEM50) and 100-m (DEM100) resampled variants are illustrated. While Figure 4.6 shows the difference between variants of 10- (%Imp10), 50- (%Imp50), and 100-m (%Imp110) resampled from an original 30-m impervious percent dataset, Figure 4.7 shows the difference between an original 10-m CN grid (CN50) and its corresponding resampled 50-m (CN50) and 100-m (CN100) versions. These differences are all illustrated by either rectangular, ellipsoid, or curved graphics.
Figure 4.4. Showing an original 10m DEM (DEM_{10}), resampled to 50m (DEM_{50}) and resampled to 100m (DEM_{100})
Figure 4.5. Depicting catchment grids for an original 10m DEM (DEM10), resampled to 50m (DEM50) and 100m (DEM100)
Figure 4.6. Depicting impervious % grids for a 10m (IMP_{10}), 50m (IMP_{50}) and 100m (IMP_{100}) resampled from an original 30m data.
Figure 4.7. Depicting an original 10m (CN\text{10}) CN grid, resampled to 50m (CN\text{50}) and 100m (CN\text{100}).
4.2.2.2. GIS Data Preprocessing

To build the different resolution model scenarios, datasets are subjected to preprocessing. For example, to process the 10-m resolution model scenario, a stepwise process outlined by Fleming & Doan (2013) was adopted, using ArcMap 10.4.1 and HEC-GeoHMS extensions. The initial steps involved using the HEC-GeoHMS Preprocessing menu where a DEM Reconditioning tool was used to modify an original 10m DEM (DEM10) by overlaying it with stream data layer to generate an AGREEDEM grid layer. The AGREE method was developed by Ferdi Hellweger at the University of Texas. Pits and sinks that occur in the DEM during production were filled using a Fill Sink tool to fill the depressions and pits on the AGREEDEM grid layer and to generate a Fill (Fil) grid layer. The Fill grid layer was then used by the Flow Direction tool to define the direction of steepest ascent for each terrain cell, using the eight-point pour algorithm to generate a flow direction (Fdr) grid layer. Further, the Flow Accumulation tool was used to determine the number of upstream cells draining to any given cell, compute flow accumulation, and to generate a flow accumulation (Fac) grid layer.

Watershed delineation follows a standards procedure in HEC-GeoHMS where the “Area SqKm to define stream” option in the Stream Definition tool was used to define a drainage network and subdividing the watershed into five subbasins. In this study, delineation was achieved by using a predetermined threshold area of five-kilometer square (5.0 Km2) to generate a stream (Str) grid layer. This threshold area is inversely proportional to the number of subdivisions. The HEC-GeoHMS stepwise procedure was completed by implementing Stream Segmentation, Catchment Grid Delineation (5 catchments), Catchment Polygon Processing and Drainage Line Processing processes.
The same stepwise procedure was followed to process data for 20-, 30-, 40-, 50-, 60-, 70-, 80-, 90-, and 100-m grid scenarios.

Figure 4. 8. Showing preprocessed data used for building HMS models.
4.2.2.3. **Generating Resolution Models**

In this study, procedural steps outlined by Fleming & Doan (2013) for HEC-GeoHMS, were adopted to develop a total of eleven resolution scenarios/grid size models. For the first or base-line model, datasets in their native or original resolutions were used as input data in successive steps to build an HMS basin model. This involved starting and generating a new project in the Project Setup menu, using preprocessed datasets. Arc Hydro tools were used to generate a watershed slope (WshSlope) grid used in computing Basin Slopes in the watershed characteristics menu. In the watershed parameters menu, percent impervious dataset and CN grid were added and processed. A design storm of 1.0 inch was manually entered into an Excel TR-55 worksheet and used to calculate time of travel (Tt) for channel flows, according to TR-55 methodology (Cronshey, 1986). The channel travel time was used as the Mukiingum routing K-value.

In the basin processes submenu of the HMS menu, Soil Conservation Service Curve Number (SCS CN) and SCS Unit Hydrograph were selected as the loss and transform methods respectively, while the CN Lag Method was selected for the subbasin lag times. All hydrologic parameters were automatically computed during the procedure.

Next, the 2nd model scenario was generated by following the same procedure. Here, 10-m grid layers produced during preprocessing were utilized as input data. A 10-m grid percent impervious data (IMP10) and 10-m curve number grid (CN10) were added in the watershed parameters menu. A design storm of 1.0 inch was again manually entered into an Excel TR-55 worksheet. Using the 20-, 30-, 40-, 50-, 60-, 70-, 80-, 90-, and 100-m grid sized datasets, these steps were repeated for all model scenarios to generate the 3rd, 4th, 5th, 6th, 7th, 8th, 9th, 10th, and 11th resolution scenarios.
It is important to note that the CN grid used for computing CNs in this study was generated by integrating land use classes and soil group datasets by following a combination of steps outlined by Merwade (2012), Shukur (2017), and Stewart et al., (2011).

4.2.2.4. Model Simulation

To simulate the model, a project was created, and respective grid size scenarios added as basin models, using HEC-HMS 4.2. Meteorologic Models component, which computes the precipitation input for all subbasins, was parameterized for a hypothetical one-inch (1.0 in) two (2) year, 24-hour design storm. SCS type 2 storm precipitation method was selected while evapotranspiration and snowmelt were not modeled. Control Specifications component, which sets the time span for a simulation run, was parameterized for the simulation to start at 00:00 hours on 16th August and end at 00:05 hours on 18th August 2017. The same HEC-HMS input parameters (Meteorologic and Control Specifications) were used for each grid size scenario to simulate a hydrograph at the respective outlets.

4.3. Results

The experiment in this study was set up to further evaluate the effect of data resolution on runoff responses at the outlet of an ungauged watershed. The study area was treated as ungauged, and eleven grid size model scenarios were simulated using HEC-HMS and their results analyzed. The first (baseline) model consisted of input datasets at their native or original resolutions while the rest consisted of resampled or
resized datasets. In this analysis, simulation results for different grid size models were compared to baseline results. Table 4.6 shows simulation results for drainage area, peak discharge, time to peak, runoff volume, total channel slopes and total flow length obtained from simulating runoff hydrographs at the outlet of each resolution model.

Figure 4.9 shows runoff hydrographs at the outlet of resolution models 1, 6 and 11.

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Grid Size/Resolution (m)</th>
<th>Drainage Area (mi²)</th>
<th>Peak Discharge (cfs)</th>
<th>Time to peak (hr)</th>
<th>Runoff Volume (in)</th>
<th>Total Slope (ft/ft)</th>
<th>Total flow length (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baseline</td>
<td>6.4868</td>
<td>45.20</td>
<td>16.20</td>
<td>0.11</td>
<td>0.0217</td>
<td>59802</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>6.4870</td>
<td>45.50</td>
<td>16.10</td>
<td>0.11</td>
<td>0.0226</td>
<td>55409</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>6.4994</td>
<td>47.40</td>
<td>15.55</td>
<td>0.11</td>
<td>0.0240</td>
<td>52129</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>6.4539</td>
<td>51.70</td>
<td>15.40</td>
<td>0.11</td>
<td>0.0226</td>
<td>45132</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>6.4584</td>
<td>54.80</td>
<td>15.25</td>
<td>0.11</td>
<td>0.0259</td>
<td>40341</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>6.4613</td>
<td>54.10</td>
<td>15.30</td>
<td>0.11</td>
<td>0.0226</td>
<td>40870</td>
</tr>
<tr>
<td>7</td>
<td>60</td>
<td>6.4605</td>
<td>55.80</td>
<td>15.25</td>
<td>0.11</td>
<td>0.0320</td>
<td>39527</td>
</tr>
<tr>
<td>8</td>
<td>70</td>
<td>6.4603</td>
<td>55.60</td>
<td>15.25</td>
<td>0.11</td>
<td>0.0281</td>
<td>38785</td>
</tr>
<tr>
<td>9</td>
<td>80</td>
<td>6.4621</td>
<td>54.40</td>
<td>15.25</td>
<td>0.11</td>
<td>0.0224</td>
<td>39377</td>
</tr>
<tr>
<td>10</td>
<td>90</td>
<td>6.4288</td>
<td>56.00</td>
<td>15.25</td>
<td>0.11</td>
<td>0.0314</td>
<td>37130</td>
</tr>
<tr>
<td>11</td>
<td>100</td>
<td>6.4288</td>
<td>56.00</td>
<td>15.25</td>
<td>0.11</td>
<td>0.0382</td>
<td>35247</td>
</tr>
</tbody>
</table>

Table 4.6. Showing simulation results for different grid size models
Simulation results for the model 1 (Table 4.6) indicate that drainage area was 6.4868 mi², and then increased slightly to 6.4870 mi² for model 2, and 6.4994 mi² for model 3. However, the drainage area started to decrease as grid sizes became larger in model 4 through model 11, corresponding to 6.4539 mi², 6.4584 mi², 6.4613 mi², 6.4605 mi², 6.4603 mi² and 6.4621 mi², 6.4288 mi², respectively. Peak discharge value for model 1 (45.2 cfs) was the lowest compared to other models. Models 10 and 11 had the highest peak discharge value of 56 cfs, corresponding to the smallest drainage areas.
It is important to note that models 10 and 11 had the highest peak discharges because both models had the highest channel slope and flow length values. However, there was a steady increase in peak discharge values compared to model 1 as grid cell sizes increased (Figure 4.11).

![Figure 4. 10. Showing the impact of data re-sizing on peak discharge relative to drainage area.](image)

Simulation results also show that peaking time for discharge decreased from 16.20 hrs for model 1 (baseline) to 16.10 hrs, 15.55 hrs, 15.40 hrs, 15.25 hrs and 15.30 hrs for models 2, 3, 4, 5 and 6, respectively, before flattening at 15.25 hrs between models 7 and 11 (Figure 4.12). The decrease in time to peak corresponds to a decrease in drainage sizes and increase in grid cell sizes. There was no corresponding change in runoff volume as drainage area became smaller and grid size increased, respectively (Figure 4.13).
Figure 4. 11. Showing the impact of data re-sizing on time to peak relative to drainage area.

Figure 4. 12. Showing the impact of data re-sizing on runoff volume relative to drainage area.
4.4. Discussions

The study utilized HEC-HMS to further evaluate the impacts of data resolution on runoff characteristics by simulating runoff hydrographs at the outlets of multiple watershed models utilizing datasets at different resolutions. The study area was considered as ungauged and simulation results analyzed to obtain a better understanding of runoff response to the interaction between input datasets and model parameters. A better understanding of watershed processes is a basis for improved hydrologic analysis of ungauged watersheds.

In this study, simulation results show that peak discharge values increased as finer datasets were resampled to coarser resolutions with corresponding reduction in the size of drainage areas (Figure 4.11). The highest amount of discharge (56 cfs) occurred for coarser datasets (models 10 and 11) and decreased for finer dataset models. Also, while longer peak times were observed to occur for finer datasets, there was a decrease for coarser datasets. The model 1 (baseline) had the lowest peak discharge value (45.2 cfs), and longest time to peak (16 hours) (Table 4.6 and Figure 4.10).

When compared to model 1, the difference in drainage size was 0% for model 2, 0.19% for model 3, 0.51% for model 4, 0.44% for model 5, 0.39% for model 6, 0.41% for models 7 and 8, 0.38% for model 9 and 0.9% for models 10 and 11, respectively. This result show that there is less than 1% change in drainage size across all resolution models, suggesting that resampling datasets from finer resolutions to coarser ones does not have a remarkable impact of drainage size.

Peak discharge for model 2 was 1% more than peak discharge for model 1. However, Peak discharge values fluctuated significantly for other models. When
compared to model 1, the difference by 5%, 13%, and 19%, for models 3, 4, and 5, respectively. Also, when compared to model 1, peak discharge was different by 18% for models 6 and 9, respectively, and 21% for models 7, 8, 10 and 11, respectively. Similarly, there was a difference in time to peak for the various grid size model scenarios when compared to baseline values. For instance, there was an initial fluctuation by 1%, 4%, and 5% difference for models 2, 3, and 4, respectively, before stabilizing at 6% for all other models, respectively (Figure 4.11). These results indicate that simulations results are affected by data resolution, especially peak discharge, and time to peak, and compare favorably with results reported by Garbrecht & Martz (2000) and Tribe (1992).

The observed fluctuations in simulated peak discharge values in this study suggest that peak discharge is most affected by resolution when compared to time to peak and runoff volume. This is because derived attributes from DEMs such as flow lengths and channel slopes constitute important variable in peak discharge computation. This is supported by the SCS Unit hydrograph method (Equation 5) adopted in this study to compute peak discharge. In this method, time of concentration is calculated as the sum of travel times for sheet, shallow and channel flows (Equation 8). The characteristics for calculating each of these flows are extracted from the DEM including land slope, surface description (1 – unpaved, 2 – paved), watercourse slope, channel cross sectional area, wetted perimeter, hydraulic radius, channel slope and channel flow length, and Manning’s roughness coefficient. Average velocity is computed from Manning’s equation (Equations 9, 10, 11 and 12). Therefore, as the DEM was resampled to coarser resolutions of larger grid cell sizes, detailed information such as flow paths and slopes and aspects in the original 10-m DEM required for calculating peak discharge was lost.
during automated extraction. A depiction of degraded catchment and flow accumulation grids shown in Figure 4.13 and results in Table 4.6 suggest that as channel slopes and flow lengths increase due to data resampling, peak discharge values are impacted. These result compares favorably with conclusions from studies by Hutchinson & Dowling (1991), Jenson (1991) and Dixon & Earls (2009).
As shown in Figure 4.13, runoff volume remained unchanged for all grid size models. This result agrees with conclusions from Seybert (1997) but however contradicts the study by Dixon & Earls (2009), which stated that DEM resolution affected all modeled-predicted flow volumes. In this study, while peak flow was significantly affected, runoff volume remained unaffected by data resolution. The unchanged runoff volume indicates that the factors that determine the magnitude of excess precipitation remained unchanged. These factors are the precipitation depth, initial abstraction, land
use and antecedent soil moisture. The CN grid utilized in the study was generated by integrating land use and soil data for the study area and applied to all grid size models.

Adopting the SCS loss method (Equation 3 and 4) for computing runoff volume in this study, a precipitation depth of 1.0 inch was applied and assumed to be uniform for the entire study area. Despite the resampled CN grid appearing degraded, Figure 4.7 shows that the CN value range remained unchanged, indicating that resizing did not degrade the information contained in the dataset. Similarly, resizing and use of percent impervious data did not have an impact on runoff volume, suggesting that the dataset only served to provide more detailed runoff information in combination with the CN grid (Fan, Deng, Hu, & Weng, 2013).

4.5. Conclusions

The study utilized HEC-HMS to further evaluate the effect of data resolution on runoff response by simulating runoff hydrographs at the outlet of an experimental watershed. A total of eleven grid size models were developed, with the first (baseline) model consisting of input datasets in their native or original resolutions and simulation results for different grid size scenarios compared to baseline results. Simulation results show that peak discharge values increased as finer datasets were resampled to coarser resolutions with corresponding reduction in the size of drainage areas. There was less than 1% change in drainage size across all resolution models, suggesting that resampling datasets from finer resolutions to coarser ones did not have a remarkable impact of drainage size. Comparing the impact of data resolution, results indicate that peak discharge was more impacted. While peak flow was significantly affected, runoff volume
was not impacted by data resolution. Despite the resampled CN grid appearing degraded, results shows that CN value range remained unchanged, indicating that resizing did not degrade the information contained in the dataset. Similarly, resizing percent impervious data did not have an impact on runoff volume, suggesting that the dataset only served to provide more detailed runoff information in combination with the CN grid.
5. Chapter Five: Overall Conclusions

This study reviewed the role of computers and GIS integration in watershed modeling by highlighting the procedures involved in the automated extraction of topographic attributes from GIS datasets, limitations of their resolutions, and associated impacts on simulation results. It also reviewed the practice of regionalization as a mitigating approach to the lack of observed data when modeling ungauged watersheds. The study further evaluated the effects of watershed subdivision and data resolution on runoff characteristics by utilizing HEC-HMS to simulate runoff hydrographs at the outlet watersheds treated as ungauged. Below are the overall conclusions from the study:

5.1. Chapter Two

The importance of reliable watershed model results in hydrologic studies has been highlighted by the International Association of Hydrological Sciences’ emphasis on the need for the examination and improvement of existing methods employed in model prediction of flows. Experts in the field of water resources engineering and hydrology have recommended a practice known as regionalization as a mitigate the problem of lack of observed data when modeling ungauged watersheds, but the temporal and spatial variability in climate, and heterogeneity in watershed characteristics make the use of results from such models for any meaningful hydrologic analysis and application unreliable. The type and use of input datasets affect model simulation results. Despite the appeal of automated extraction of digitized information from DEMs, studies have shown that their resolution affect terrain characteristics such as drainage networks, drainage divides, flow paths, and slope and aspect. These topographic attributes are significantly
different when extracted from DEMs of different resolutions, affecting topologic features, flow characteristics and runoff simulation results. Studies also show that an original DEM resampled to a new raster dataset produces different streamflow results when compared to results from the original DEM. There are advantages of integrating soils and land cover data using remote sensing technology to generate a CN grid for use in assigning a runoff potential index to subbasins in a watershed. In general, a better understanding of the impacts of the methods, materials, and limitations of GIS input datasets used in watershed modeling further improves hydrologic analysis of ungauged watersheds.

5.2. Chapter Three

Simulation results for W1 for both the frequency and SCS storm methods indicate that peak discharge values initially fluctuated for lower subdivision levels and did not stabilize with further sub-divisions, instead there was an increase in peak discharge values as subdivision levels increased. Simulation results for W1 when modeling SCS storm showed that peak discharge occurred several hours after the storm started because of the shape and orientation of the watershed. The slight variation in time to peak between subdivision levels was not remarkable and agrees with other studies. Simulation results show that runoff volume was not impacted by watershed subdivision. Simulations results for W4 modeled with SCS storm method showed that the highest peak discharge (107 cfs) occurred for level 7, followed by level 6. Subdivision level 3. Time to peak fluctuated within a few hours of each other but not in a remarkable manner, while runoff volume remained approximately the same for all subdivision levels. HEC-HMS
simulation results utilizing both the frequency and SCS storm precipitations show that total channel slopes and total flow lengths increased with further subdivision.

5.3. Chapter Four

The study utilized HEC-HMS to further evaluate the effect of data resolution on runoff response by simulating runoff hydrographs at the outlets of multiple watershed models utilizing datasets at different resolutions. A total of eleven grid size models were developed, with the first (baseline) model consisting of input datasets in their native or original resolutions and simulation results for different grid size scenarios compared to baseline results. Simulation results show that peak discharge values increased as finer datasets were resampled to coarser resolutions with corresponding reduction in the size of drainage areas. There was less than 1% change in drainage size across all resolution models, suggesting that resampling datasets from finer resolutions to coarser ones did not have a remarkable impact of drainage size. Comparing the impact of data resolution, results indicate that peak discharge was more impacted. While peak flow was significantly affected, runoff volume was not impacted by data resolution. Despite the resampled CN grid appearing degraded, results shows that CN value range remained unchanged, indicating that resizing did not degrade the information contained in the dataset. Similarly, resizing percent impervious data did not have an impact on runoff volume, suggesting that the dataset only served to provide more detailed runoff information in combination with the CN grid.
Chapter Six: Suggestions for Future Research

During this research, there are several important questions that were worth investigating but are outside the scope of my study. Below are suggestions that present good opportunities for future research.

- Generally, factors that affect runoff are precipitation amounts, watershed area, watershed shape, land use and land cover, and topography. In hydrology, stochastic models utilize these factors to predict the amount runoff at a watershed’s outlet. Future research should focus on utilizing Principal Component Analysis (PCA) to investigate which variables most affect peak discharge at the outlet of an ungauged watershed as a framework for flow prediction.

- In chapter three of this research, simulation results of ungauged watersheds included peak discharge, time to peak, runoff volume, channel slope and channel length. With watershed subdivision and data resolution as categorical factors, future research should focus on using the variables in these results to build a Generalized Additive Model (GAM) for flood prediction in ungauged watersheds.

- The runoff volume in this study remained unchanged for all model scenarios evaluated in this study. Given that runoff volume is a function of precipitation depths, initial abstraction, land use and antecedent moisture, future study should investigate which of these factors have more impact on runoff volume.
7. References


Cleveland, T. G., & Thompson, D. B. (2009). Subdivision of Texas Watersheds for Hydrologic Modeling. 0-5822, Texas Dept. of Transportation Research and Technology, Texas Tech Univ., Lubbock, TX.


digital elevation models: a review and a new method. Journal of Hydrology,
139(1-4), 263-293.

subdivision on simulation of water balance components. Hydrological Processes,

simulation of water balance components. Hydrological Processes: An

at the ASCE J Hydraul Div.

Washington, DC.

Hydrologic Engineering Center Davis, CA.

Volpi, E., & Fiori, A. (2014). Hydraulic structures subject to bivariate hydrological loads:
Return period, design, and risk assessment. Water Resources Research, 50(2),
885-897.

subdivision level on model assessment and identification of non-point source
priority management areas. Ecological Engineering, 87, 110-119.
doi:10.1016/j.ecoleng.2015.11.041


