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Development of a hydrologic and water quality model of Cedar Creek

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DEVELOPMENT OF A HYDROLOGIC AND WATER QUALITY MODEL OF CEDAR CREEK

by

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of the requirements for the Master of Science
degree in Civil and Environmental Engineering in the
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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Anthony Vecchi

has been approved by the Examining Committee for
the thesis requirement for the Master of Science degree
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ABSTRACT

The hypoxic zone in the Gulf of Mexico is a symptom of a greater problem of nutrient loss to streams across the American Midwest. The United States Environmental Protection Agency (EPA) has responded to the problem by requiring states along the Mississippi River to develop nutrient reduction strategies and implement practices that reduce nutrient loss. The state of Iowa developed their strategy and formed the Iowa Nutrient Research Center (INRC) to study the most effective conservation practices and policies. This thesis is conducted as part of the INRC and is focused on the development of a hydrologic and water quality model of the Cedar Creek watershed in southeastern Iowa.

The Cedar Creek hydrologic and water quality model was created using MIKE SHE, a coupled surface/subsurface modeling software. The model was calibrated using real-time streamflow and water quality measurements taken within the watershed. Several water quality scenarios were tested in order to determine the most effective ways to simulate nitrate concentration within the MIKE SHE framework. The results of this thesis will guide future hydrologic and water quality modeling in agricultural watersheds and serve as a demonstration of the ways to simulate nutrient transport within the landscape.

PUBLIC ABSTRACT

High amounts of nutrients in lakes and stream can be detrimental to aquatic life and to the communities that use them. The nutrients carried by the Mississippi River to the ocean has created a region of the Gulf of Mexico that is devoid of aquatic life. In an effort to reduce the size of this region, states in the American Midwest have developed plans to reduce the amount of nutrients entering the Mississippi River. This thesis investigates how computer models can be used to understand how water and nutrients move within a watershed with the objective of developing solutions to this complex problem.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Motivation and Overview

The water resources of the United States face threats ranging from drought in California to flooding in Texas (USDA, 2017; USGS, 2017). The uneven distribution of water across the country is not the only type of challenge. In the Gulf of Mexico, the introduction of water containing a large quantity of nutrients from the Mississippi River has created a hypoxic zone unable to support aquatic life, as shown in Figure 1.1 (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008). The nutrients, primarily nitrogen and phosphorus, are lost from Midwestern agricultural fields and delivered to small streams across that region (Malone, et al., 2014). These streams eventually empty into the Mississippi River, continuing the export of nitrogen and phosphorus to the Gulf of Mexico as depicted in Figure 1.2. A solution to this kind of geographically distributed water resource impairment requires efficient cooperation and planning (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008). In an effort to reach this kind of solution, the United States Environmental Protection Agency (EPA) established the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force in 2008. This group developed a plan shortly after its formation requiring the states along the Mississippi River to implement policies designed to reduce hypoxia in the Gulf of Mexico (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008). Under this plan, each of the 12 states would develop a nutrient reduction strategy with a different approach but a similar goal.

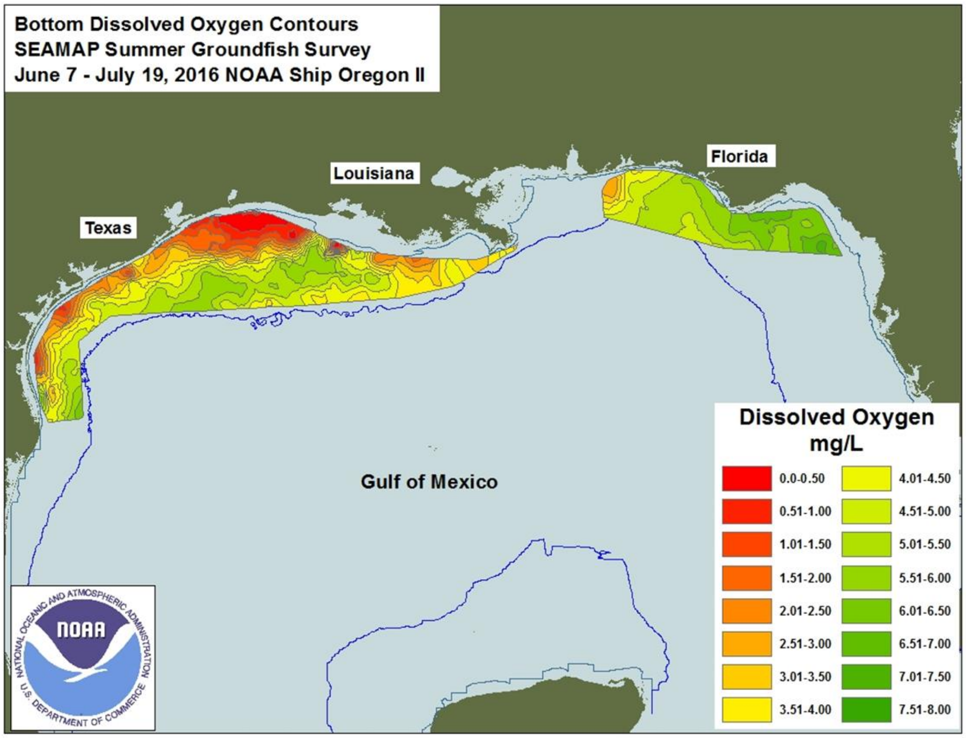

Figure 1.1: 2016 Hypoxic zone in the Gulf of Mexico (NOAA, 2017)

Figure 1.2: Map of the Mississippi River watershed (Louisiana Universities Marine Consortium, 2017)

1.2 Iowa Nutrient Research Center

In the state of Iowa, a group of state agencies and public universities responded to the EPA by developing the Iowa Nutrient Reduction Strategy. The document outlines the state's strategy for reducing nutrient loss from both non-point sources, such as agricultural fields, and point sources, such as a wastewater treatment facility (Iowa Department of Agriculture and Land Stewardship, 2012). In an average year, 20% of the total nitrogen load entering the Gulf of Mexico comes from the state of Iowa (Libra & Wolter, 2004). Of this total annual loss of nitrate from the state, 92% is estimated to have originated from non-point sources (Libra & Wolter, 2004).

The Iowa Nutrient Research Center (INRC) was created in 2013 to pursue research in support of the Iowa Nutrient Reduction strategy (Iowa Code § 466B.47, 2015). This collaborative research group is based at Iowa State University in Ames, Iowa but involves teams of researchers at the University of Northern Iowa in Cedar Falls, Iowa and the University of Iowa in Iowa City, Iowa. INRC researchers investigate issues including the effectiveness of nutrient reduction practices across the state of Iowa and how policy can be used to encourage the prioritization of water quality improvements within a community.

1.3 Goals and Objectives

Meeting the nutrient reduction goals laid out in the Iowa Nutrient Reduction Strategy requires the implementation of conservation practices across the state. Understanding the impact of each practice is important for state and local officials as they make decisions regarding the installation of new nutrient reduction projects. The research conducted by the INRC plays an important role in informing these policy decisions. Specifically, hydrologic watershed models can be used to evaluate how changes made to a watershed will affect flooding during high flow events and the export of nutrients out of the watershed. Developing these hydrologic models is the important first step for a watershed in planning an efficient strategy for reducing nitrate load. The goals of this thesis are:

1. To develop a hydrologic model of Cedar Creek which reproduces measured discharge at the watershed outlet

2. To develop a water quality model of Cedar Creek which reproduces average monthly nitrate concentration

The goals of this thesis are achieved by constructing the hydrologic and water quality model of Cedar Creek and designing scenarios that demonstrate the application of the model.

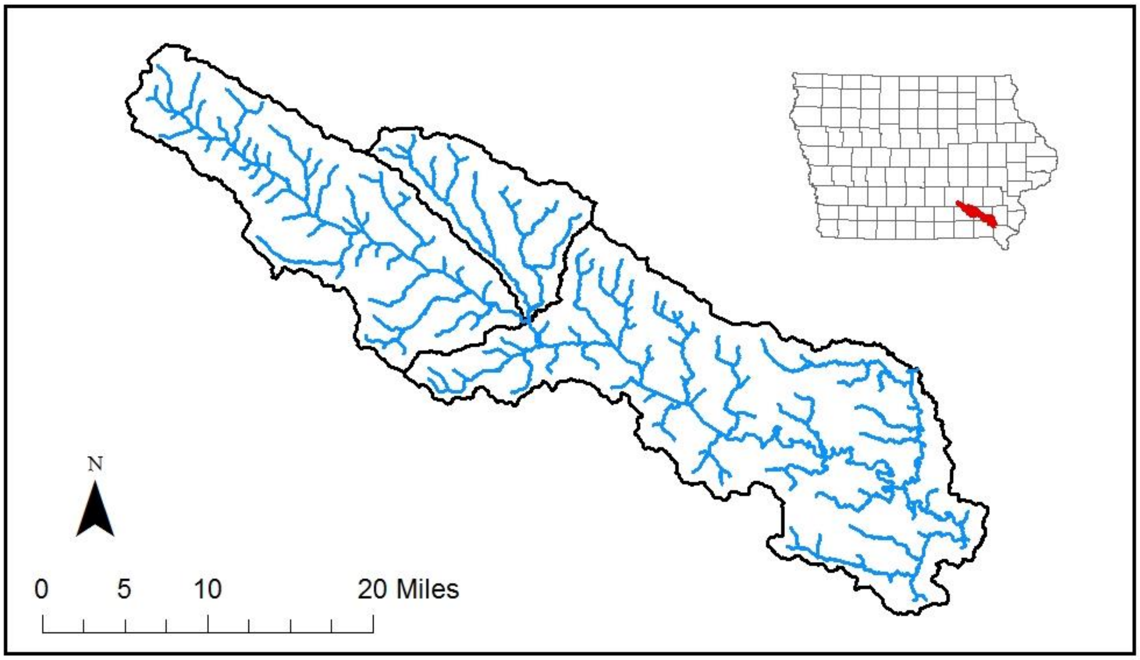

Figure 1.3: Cedar Creek watershed location and stream network

1.4 Contribution of Thesis

Typical coupled surface/subsurface hydrologic modeling studies, such as the one by Zhou et al. (2013), have focused on small catchments. This thesis investigates the use of this kind of hydrologic model on a watershed scale. The chosen watershed is equipped with stream flow and water quality sensors which allows for comparison between measurements and simulations. These comparisons can be used to investigate the skill of a complex hydrologic model in predicting streamflow and a simple water quality model in predicting in-stream nutrient concentrations. While the water quality model developed in this thesis is conceptually simple, it is formed within the framework of a complex, physically-based model. This is a new application for such a model and its results can guide the efforts to predict in-stream concentrations of water quality species in complex watershed models.

1.5 The Role of the Cedar Creek Model

The focus of this thesis is on the development of a hydrologic model for Cedar Creek and its application in predicting hydrologic and water quality responses to precipitation. The project was conducted at IIHR – Hydroscience and Engineering and funded by the INRC. The role of this project is to demonstrate the effectiveness of physically based models in simulating watershed hydrology and evaluate the skill of this type of model in simulating water quality. Understanding how water and nutrients move within a watershed is crucial to developing effective and efficient solutions to the problems of flooding and poor water quality. The Cedar Creek model is used to evaluate the different ways in which the movement of nitrate within a watershed can be simulated within a physically-based modeling framework. Cedar Creek model simulations inform similar hydrologic and water quality modeling efforts by illustrating the value of simplified conceptualizations regarding the sources of nitrate in the landscape and its transport into the stream network.

1.6 Chapter Summary

Poor water quality in the United States, highlighted by a hypoxic zone in the Gulf of Mexico, prompted the United States EPA to act. The motivation for this thesis originates from the 2008 EPA plan requiring the states along the Mississippi River to reduce their contributions of nitrogen and phosphorus to the Gulf of Mexico. As one of these states, Iowa organized a team of state agencies and universities to develop the INRS. This document outlines the science-based approach that will be used to reduce the amount of nitrogen and phosphorus leaving the state. The Iowa Nutrient Research Center was formed in order to evaluate the methods by which the nutrient reduction goals were to be met and improve understanding about the fate and transport of nutrients within a watershed.

The goal of this thesis is to develop a physically-based hydrologic and water quality model of Cedar Creek. The project was conducted at IIHR – Hydroscience and Engineering and funded through the Iowa Nutrient Research Center. The Cedar Creek model will improve the understanding of how water and nutrients move within the Cedar Creek watershed and demonstrate the value of using a simple approach to simulating in-stream nitrate concentration.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Flooding and poor water quality pose economic and environmental threats to communities all over the world. In the predominantly agricultural American Midwest, flooding and the loss of nutrients to both surface water and groundwater threaten drinking water sources, physical infrastructure, and the fishing industry in the Gulf of Mexico. While a single field of crop land contributes a relatively small nutrient loading, the compounded effect of the Midwest as a whole has created a hypoxic zone in the Gulf of Mexico near the outlet of the Mississippi River (Babcock & Kling, 2015). In a similar way, the relatively small impact of changes to the landscape that route rainfall to streams faster leads to floods impacting downstream communities.

While these small changes to a watershed can compound to cause significant problems, targeted, small-scale solutions can be used to achieve significant downstream benefits. The development of hydrologic models for watersheds, and smaller catchments, is a useful way to assess how small-scale changes to the landscape can improve water quality and reduce the severity of flooding downstream. These models can also help identify the regions where a best management practice (BMP) would have the greatest impact and which BMP would be the most effective.

2.2 Iowa Nutrient Reduction Strategy

Hypoxia describes the condition where dissolved oxygen levels in a body of water are too low to support life (Babcock & Kling, 2015). This occurs when nutrient-rich water stimulates the growth of algae at such a rate that their death and decomposition consumes more dissolved oxygen than the ocean water can supply. There are approximately 400 known hypoxic zones around the world (Babcock & Kling, 2015). In the United States Midwest, the hypoxic zone in the Gulf of Mexico is the most important. The nutrients lost from farmland in the Midwest directly feeds the growth of the algae, thereby causing hypoxia.

The size of the hypoxic zone in the Gulf of Mexico is estimated each year by the Louisiana Universities Marine Consortium. The hypoxic zone has been measured since 1985. In

2015, the hypoxic zone was the 11th largest recorded, representing an area approximately the size of Connecticut (Louisiana Universities Marine Consortium, 2015). Figure 2.1 shows the size of the hypoxic zone over the period of record. The goal shown in this figure was set by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force in 2008 in hopes of achieving it by 2015 (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008). The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force also set a goal that states within the upper Mississippi River Basin develop a plan to achieve a 45% reduction in riverine total nitrogen and total phosphorus loads.

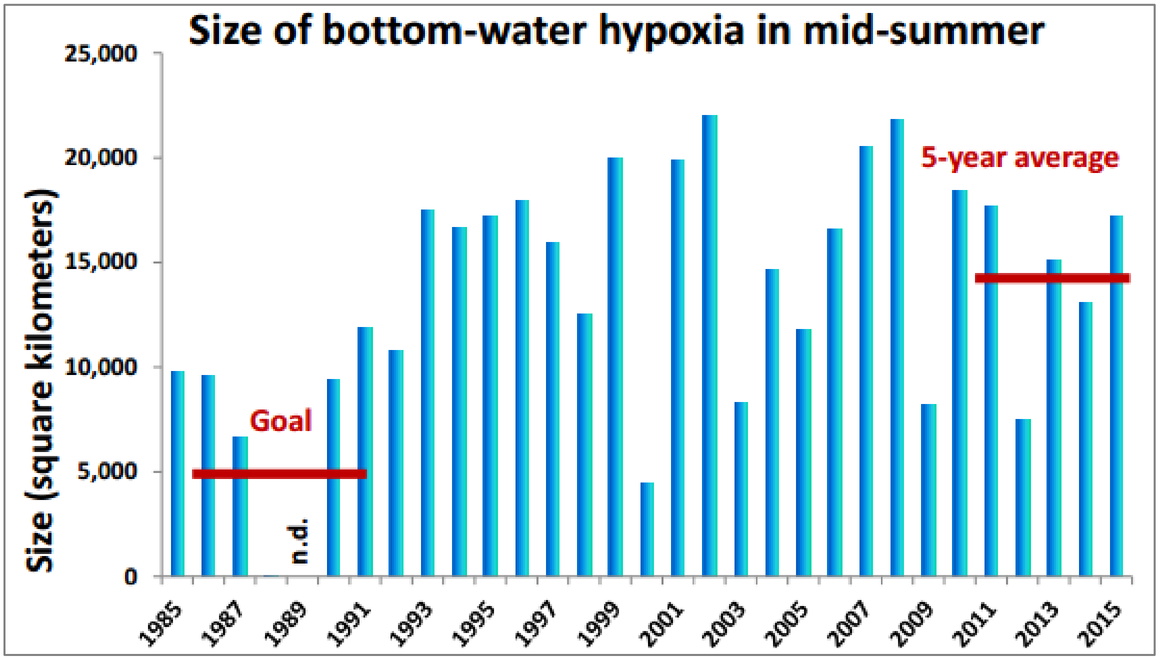

Figure 2.1: The area of the hypoxic zone in the Gulf of Mexico from 1985 to 2015 (Louisiana Universities Marine Consortium, 2015).

In 2012, the state of Iowa developed the Iowa Nutrient Reduction Strategy (INRS). This science and technology-based approach is aimed at assessing the problem of nutrient loss to streams in Iowa and reducing nutrient loads leaving the state (Iowa Department of Agriculture and Land Stewardship, 2012). The INRS lays out nutrient load reduction goals in line with those set by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. Specifically, the INRS calls on nonpoint sources to achieve 41% reduction in nitrogen load and 29% reduction in phosphorus load in order to achieve a total nitrogen and phosphorus load reduction of 45%. Specific BMPs, and their estimated removal efficiencies, are also included in the INRS.

2.3 Peak Discharge Reduction and Water Quality Improvements

Large flood events have impacted the Midwest several times in recent years. Floods in 1993, 2008, 2011, 2013, and 2014 each displaced communities, decreased crop production, and, in some cases, led to economic losses of billions of dollars (Mallakpour & Villarini, 2015). For decades, the natural hydrology of the Midwest has been altered by human activities such as the installation of agricultural drainage systems and urbanization (Babbar-Sebens, Barr, Tedesco, & Anderson, 2013). These changes have led to economic efficiency but have degraded the natural ability of the landscape to intercept, store, and slow the movement of surface runoff to streams. Coupled with the observed increase in frequency of extreme rainfall events (Min, Zhang, Zwiers, & Hegerl, 2011), surface runoff is expected to increase by 10-20% by 2041-2060 (Babbar-Sebens, Barr, Tedesco, & Anderson, 2013). As the threat of flooding becomes more serious, communities rely on hydrologic modeling to determine and test different solutions.

Three potential practices for reducing peak flow in watersheds include ponds, wetlands, and cover crops. Ponds and wetlands both serve to slow the movement of runoff to the stream. While most commonly employed for water quality improvement, wetlands have been shown to offer peak flow reduction on the watershed scale when they are sized and placed in an optimized way (Babbar-Sebens, Barr, Tedesco, & Anderson, 2013). By slowing the movement of water, wetlands have the potential to remove nutrients in the water via in-stream processing and plant uptake. Wetlands designed to directly intercept agricultural runoff can decrease the nitrogen load exported by 33 to 66% (Mitsch & Day Jr., 2006).

Conservation agricultural practices such as cover crops are also a useful practices for improving water quality and reducing peak discharge. Cover crops describe any crop that is planted over a field that would otherwise be barren, often during the winter (Dabney, Dalgado, & Reeves, 2001). These crops provide a wide range of ecological benefits including reduction of soil loss, better utilization of soil nutrients, increased infiltration, and increased soil organic matter content (Dabney, Dalgado, & Reeves, 2001). During winter months, the cover crop would take up a portion of the nitrogen left in the soil after the primary crop is harvested. After killing the cover crop, it begins to degrade and return the nutrients to the soil. The result of this practice is an estimated 42.5% reduction in nitrogen loss from fields that use artificial drainage in the Midwest (Malone, et al., 2014). On top of these benefits, it has been shown that by adopting cover crops as a practice can reduce peak discharge for a watershed by 7 to 10% (Drake, 2014).

2.4 Local Water Quality

Statewide, water quality has become a major focus in Iowa. The quality of Iowa's surface and groundwater resources has been the subject of political, journalistic, and academic scrutiny. While Cedar Creek has not been central to the discussion of water quality in Iowa, it is part of an INRS Water Quality Initiative project within the state.

Efforts within the state of Iowa have been focused on assessing the statewide export of nutrients to the Gulf of Mexico. In 2016, researchers at IIHR at the University of Iowa in Iowa City, Iowa deployed a network of water quality monitoring devices in an effort to measure this statewide load and to eventually develop the means to meeting the goals outlined in the INRS (Weber, Jones, & Davis, 2016). A recent estimate puts the contribution of nitrogen load from Iowa at 20% of the total load carried by the Mississippi River to the Gulf of Mexico (Libra & Wolter, 2004).

Within the Cedar Creek watershed, ambient water quality monitoring has been conducted since 1998 as part of the Iowa Department of Natural Resources (DNR) Ambient Stream monitoring program (Iowa Department of Natural Resources, 2017). This program monitors 75 streams and 1 spring across the state of Iowa, collecting samples at an approximately monthly frequency. The sampling location is co-located with a United States Geological Survey (USGS) stream gauge, and is shown in the map in Figure 2.2 below. A summary of the nitrate-nitrite as N measured data through 2015 is shown in the graph in Figure 2.3. Annual load, estimated using this data and measured streamflow at the co-located USGS stream gauge, is shown in Figure 2.4. In 2016, Cedar Creek, which accounts for 1% of the total area in Iowa, accounted for 0.3% of the total load from the state of Iowa. Yield estimates for Cedar Creek in 2016, along with yield estimates made by Dr. Chris Jones for other watersheds, are shown in Figure 2.5 (personal communication, March 2017). These estimates show that the nitrate-nitrate as N yield for Cedar Creek is lower than other watersheds in Iowa and the state of Iowa as a whole.

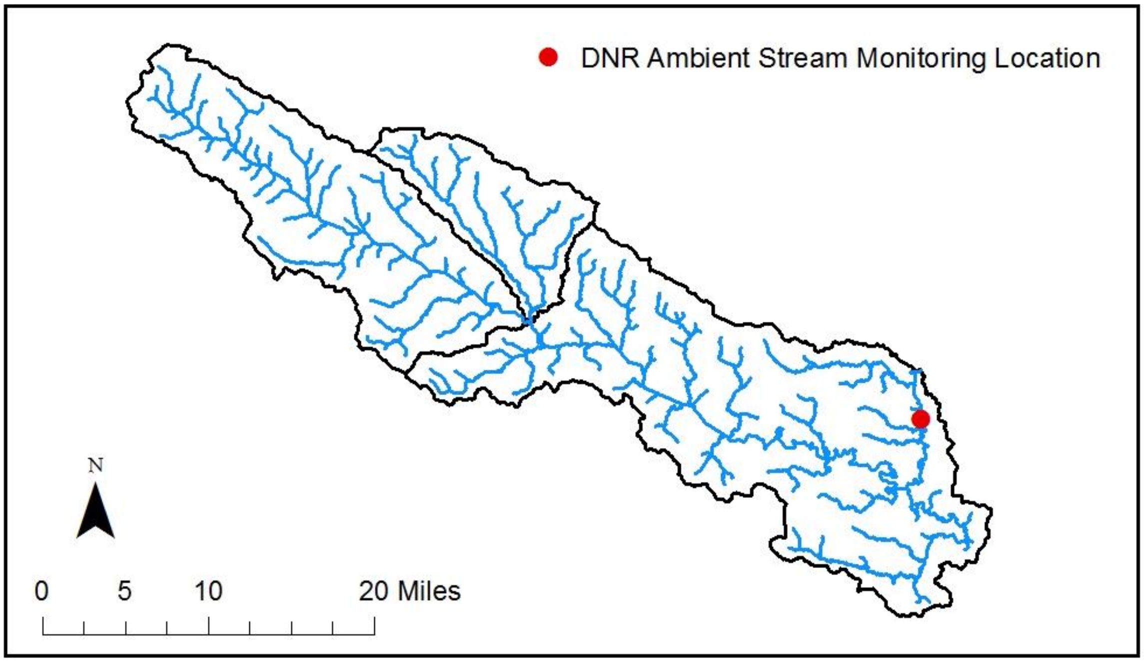

Figure 2.2: Location of DNR Ambient Stream Monitoring

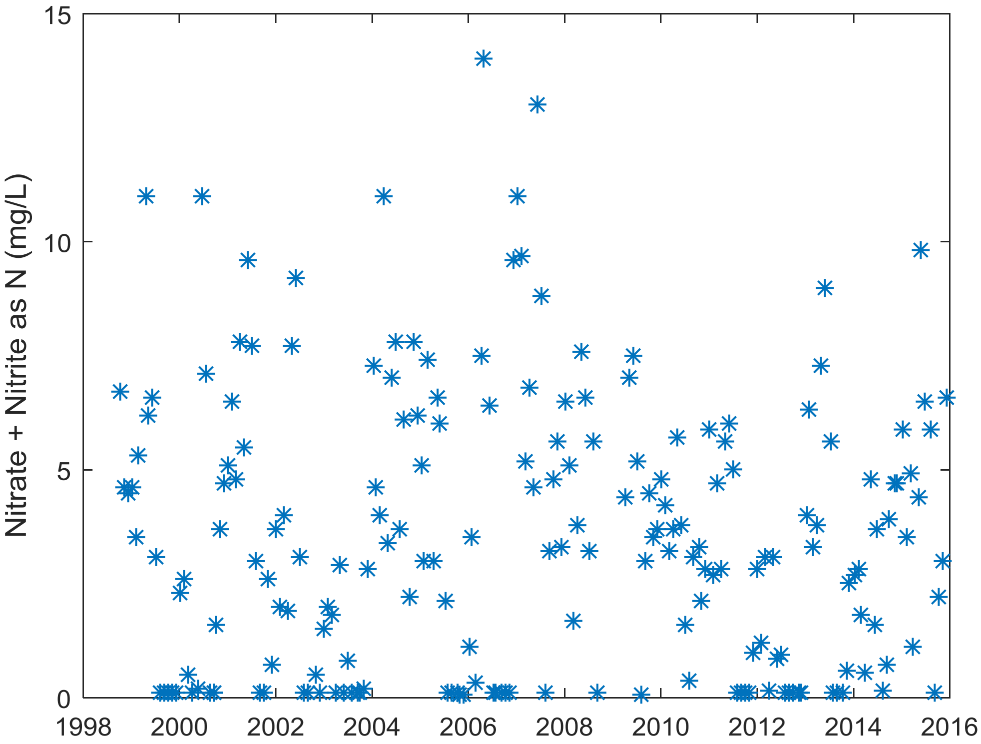

Figure 2.3: Historical DNR Ambient Stream Monitoring data at Cedar Creek

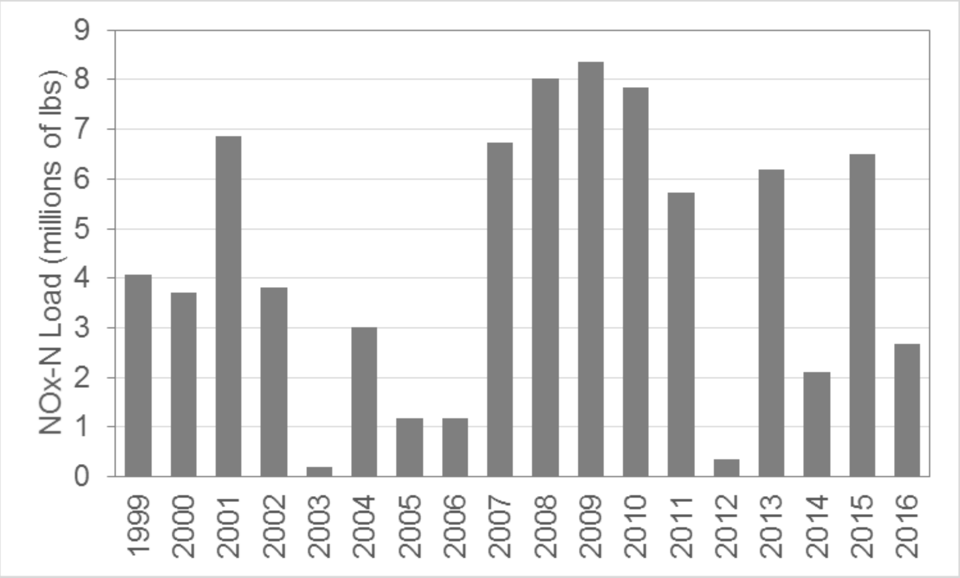

Figure 2.4: Annual nitrate-nitrite as N load estimates for Cedar Creek

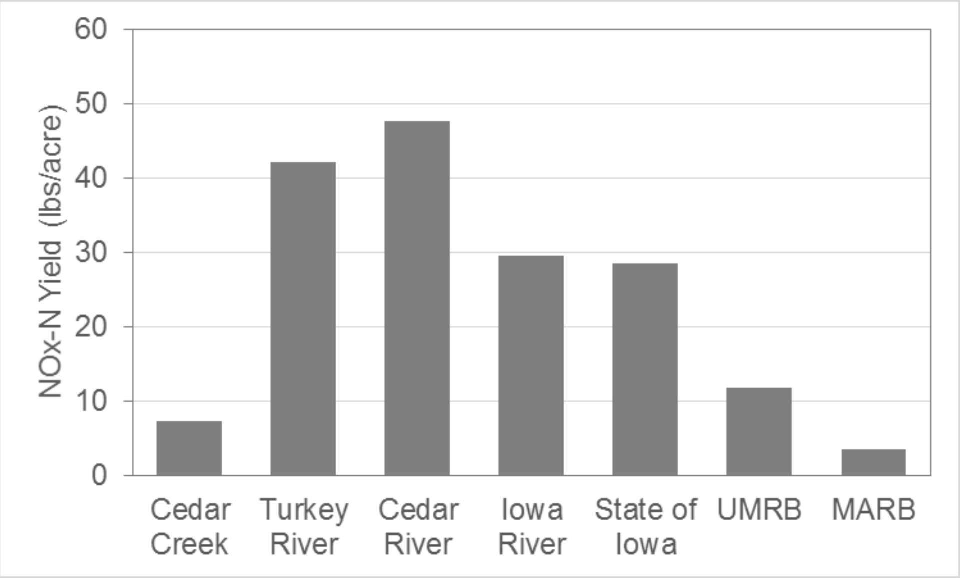

Figure 2.5: 2016 yield estimates for Cedar Creek, the Turkey River at Garber, Iowa, the Cedar River at Palo, Iowa, Iowa River at Wapello, Iowa, the state of Iowa, the Upper Mississippi River Basin (UMRB) and the Mississippi/Atchafalaya River Basin (MARB) (C. Jones, personal communication, March 2017)

Beginning in March 2016, real-time monitoring of nitrogen was conducted in the Cedar Creek watershed as part of research conducted by the INRC (Weber, Jones, & Davis, 2016). The water quality sensor in Cedar Creek measured nitrate and nitrite as nitrogen at a frequency of 5 minutes, uploading the collected data to the Iowa Water Quality Information System (IWQIS) in real time (IIHR-Hydroscience and Engineering, 2017). A summary of the water quality data collected at this water quality sensor is shown in Figure 2.6 below. The location of the water quality sensor in the Cedar Creek is approximately midway through the watershed, below the confluence of Cedar Creek and Competine Creek. Figure 2.7 below shows the location of this real-time monitoring device.

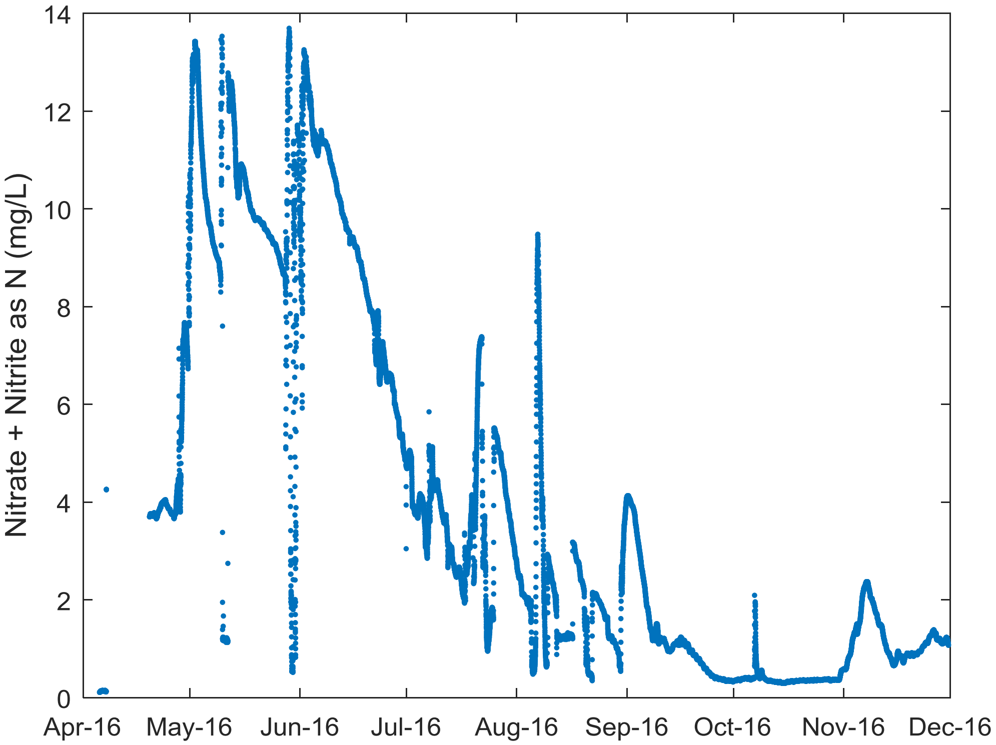

Figure 2.6: Water quality data at IIHR water quality sensor at Cedar Creek

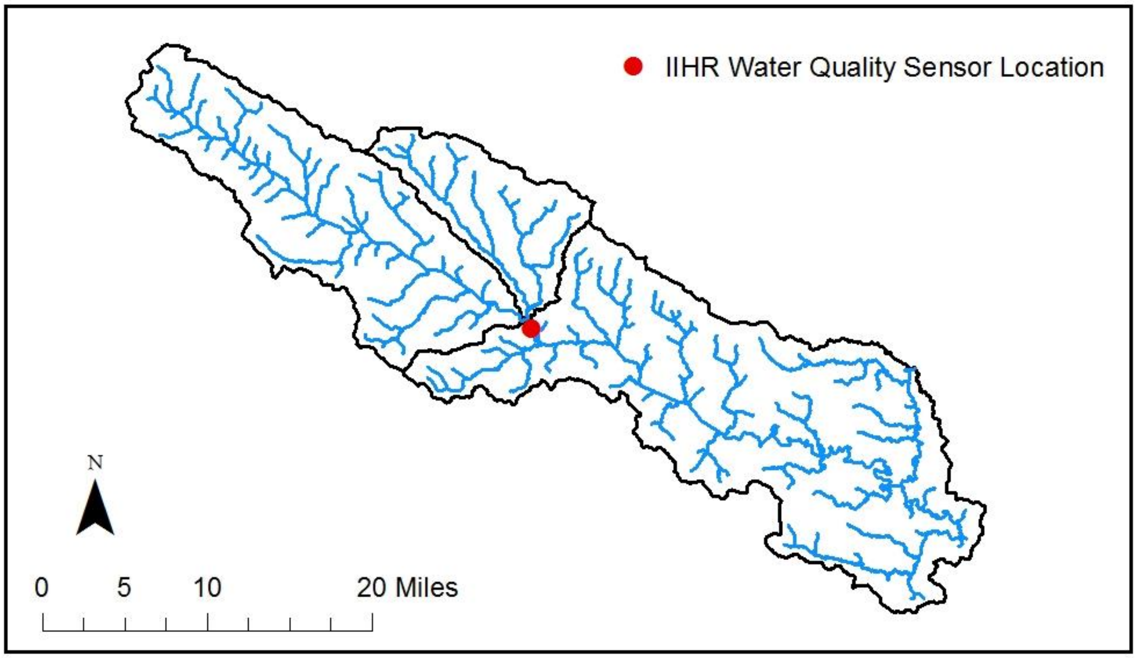

Figure 2.7: Location of IIHR Water Quality Monitoring device

2.5 History of Hydrologic Modeling

Hydrological modeling aims to improve understanding and predict the ways in which rainfall becomes runoff and travels through the subsurface, eventually evaporating, transpiring, or becoming streamflow. In a retrospective, summary paper, Singh and Woolhiser (2002) reflect on the beginnings of hydrologic modeling with the rational method in 1850 and the unit hydrograph concept in the 1930s. These kinds of early modeling efforts were focused on developing conceptual and theoretical models for components of the hydrologic cycle. While these mathematical models become more physically based over the years, it was not until the 1960s that advances in technology and computing allowed for the component models to be joined into a single cumulative one (Singh & Woolhiser, 2002). This model, now called HSPF, led the way to what would become a growing field of computational watershed models. Continued advances in computational power has led to these models becoming increasingly complex and exhaustive in their inclusion of physical hydrologic processes. Some hydrologic models have been proposed that use physical parameters that evolve through time according to signals in hydrologic observations (Pathiraja, Marshall, Sharma, & Moradkhani, 2016).

The challenges facing developers of hydrologic models now relate to the growing wealth of data obtained through remote sensing (Singh & Woolhiser, 2002). Future hydrologic models could use real-time data and remotely sensed measurements as inputs and could include a broader range of environmental processes (Laniak, et al., 2013).

2.6 Comparison of Modeling Approaches

Hydrologic models can generally be classified as either lumped conceptual model or physically based. Conceptual models often lump components of the hydrologic cycle into a single unit (Karvonen, Koivusalo, Jauhiainen, Palko, & Weppling, 1999). Under these models, the surface catchment and aquifer may be an independent unit governed by mathematical models of physical processes. These units use a single set of physical properties for potentially large areas, meaning that these models often are unable to handle watersheds with a high diversity of hydrological processes due to land use or geological differences (Carpenter & Georgakakos, 2006). The decision to use this kind of modeling approach is often due to availability of, or lack thereof, sufficient data regarding the physical properties of the area to be modeled. The ability for lumped, conceptual models to simulate hydrologic processes for a large area in a relatively short amount of time is also a primary consideration when selecting an appropriate modeling approach (Karvonen, Koivusalo, Jauhiainen, Palko, & Weppling, 1999).

Distributed, physically based modeling is better suited to capture the heterogeneity of the natural world (Beven, 1989). Physical properties are assigned on a model grid, allowing for variability in a range of physical parameters on small scales. These types of models are limited in resolution by the resolution of the physical data available for the modeled region (Carpenter & Georgakakos, 2006). Distributed, physically based models require less calibration than other model types and have been found to better match stream discharge measurements without calibration than lumped, conceptual models (El-Nasr, Arnold, Feyen, & Berlamont, 2005). Advances in computational power and hydrologic data collection will lead to increases in the feasible resolution for distributed, physically based models.

2.7 Similar Studies

MIKE SHE is a distributed, physically based, coupled surface/subsurface hydrological and water quality modeling system produced by DHI (Graham & Butts, 2005). Since 1995, MIKE SHE has been used widely in the hydrologic modeling community as it was one of the first commercially available distributed, physically based hydrologic models (El-Nasr, Arnold, Feyen, & Berlamont, 2005). In MIKE SHE, overland flow is routed using a 2D finite difference solution of the diffusive wave approximation of the Saint Venant equation, flow in the unsaturated flow is solved using a 1D finite difference solution of the Richards equation, and flow in the saturated zone is solved using a 3D finite difference solution for Darcy's law. MIKE SHE can be coupled with MIKE 11, a 1D hydraulic model based on the 1D solution for the Saint Venant equations (DHI, 2014). Similarly, a water quality module called ECOLAB can be coupled to a MIKE SHE hydrologic model to allow for the estimate of the fate and transport of different species across all hydrologic and hydraulic model components (DHI, 2014).

MIKE SHE is not alone in its widespread adoption and use for hydrologic watershed modeling. Hydrogeosphere, a coupled surface/subsurface, distributed, physically based hydraulic model has similar capabilities and has been used to develop hydrologic watershed models in the state of Iowa (Brauer, 2015). While Hydrogeosphere has been used to model hydrologically similar watersheds to the Cedar Creek watershed, no known model for the Cedar Creek watershed is available for comparison to the results of this study. MIKE SHE has also been used to model watersheds with similarities to the Cedar Creek watershed, but never with the same objectives as the one laid out in this study. The model developed for this project can therefore not be directly compared to an existing model.

Brauer (2015) used Hydrogeosphere to develop a surface/subsurface, distributed, physically based model of the Upper Roberts Creek watershed in northeast Iowa. The relatively small watershed is approximately 35 mi^2 and lies in the Paleozoic Plateau landform, as shown in Figure 3.6. This study demonstrates the use of Hydrogeosphere, and similar models, in evaluating the effectiveness of different BMPs in reducing nutrient load and peak discharges.

Thomas (2015) used Hydrogeosphere to develop a similar model of Beaver Creek, a 17 mi^2 watershed in northeast Iowa. The objective of the study was to use the hydrologic model to evaluate the impact of distributed flood mitigation practices, tile drainage, and terraces in an agricultural catchment. The results of the project demonstrated that Hydrogeosphere, and therefore similar hydrologic modeling tools, were useful in showing that distributed flood mitigation practices may reduce peak discharges, estimating the contribution of drainage tile on an annual scale, and demonstrating that terraces can be used to reduce and delay peak flows for small catchments within a watershed.

Zhou, Helmers and Qi (2013) developed a hydrologic model of 4.5 ha agricultural research field using MIKE SHE. While this project models a single field, the results show that MIKE SHE is useful in modeling agricultural areas in Iowa that contain subsurface tile drainage systems. The Zhou, Helmers and Qi (2013) study is relevant to this project due to the fact that tile drainage is present below agricultural land in the Cedar Creek watershed. This kind of small scale, targeted model is important when considering developing a similar model for a much larger catchment.

Refsgaard et al. (2014) explore how models of two catchments in Denmark developed using MIKE SHE can be used to better understand how nitrate reductions can be achieved. This study is important in that it demonstrates that MIKE SHE is useful in gaining an understanding of, and making predictions about, nitrate fate and transport within a watershed. While the model does not focus on catchments similar to the Cedar Creek watershed, it shares the goal of computing nutrient transport within a surface/subsurface, distributed, physically based hydrologic model.

2.8 Chapter Summary

Flooding and degrading water quality are global problems that pose economic and ecological problems to communities each year. In the United States Midwest, this problem is realized most notably in the hypoxic zone in the Gulf of Mexico and the recent flood events in the upper Midwest. Agricultural practices in the last century have changed the landscape in ways that leave communities more susceptible to large flood events and the loss of nutrients to streams and rivers. National policy and initiatives aim to reduce the size of the hypoxic zone in the Gulf of Mexico by reducing the loss of nutrients upstream in the Mississippi watershed. States such as Iowa have adopted plans to reduce the loss of both nitrogen and phosphorus by 45%. These goals have brought the issue of nutrient loss to the center of political and academic discussions within the state of Iowa.

There is interest within Iowa to develop a deeper understanding of how BMPs such as ponds, wetlands, and the use of cover crops could be employed to reduce nutrient loss and peak flows resulting from large rainfall events. This interest has led to the identification of several watersheds most in need of these type of improvements. The Cedar Creek watershed was chosen as one of these initial Water Quality Initiative watersheds. Hydrologic modeling tools are being used to assess the impact of different distributed improvements to these watersheds. In a more general sense, hydrologic models of all kinds have been used for over 100 years to make predictions and to better understand how water moves throughout the natural and man-made environment.

Lumped, conceptual models simplify the physical world into units with homogenous parameters. These models are often useful for catchments with limited knowledge of its physical properties. Distributed, physically based models offer a more heterogeneous description of a watershed based on its known, or estimated, physical properties and the governing equations for each individual hydrologic process.

MIKE SHE, a surface/subsurface, distributed, physically based modeling software has been used to successfully model watersheds around the world. Its applications have included predicting the impact of agricultural practices on drainage tile flow and estimating the nitrogen processing that occurs in the subsurface region of catchments. These studies, and others using similar models and techniques, are similar in nature and scope to this study and helped motivate this work.

CHAPTER 3: DESCRIPTION OF THE WATERSHED

3.1 Introduction

Understanding the physical characteristics of a watershed is the first step in accurately developing a hydrologic model for that watershed. With a deeper knowledge of the physical properties and history of a watershed, the results of a model can become more meaningful and the user will become better equipped to identify when a result is not a physically realistic one. In this chapter, the physical description of the Cedar Creek watershed will be presented in terms that relate to how they help inform and guide the development of the hydrologic model.

3.2 Hydrology

Cedar Creek is located in southeastern Iowa, as shown in Figure 3.1 below. The Cedar Creek watershed drains 567 mi^2 and consists of three sub-watersheds. The sub-watersheds are each defined by a 10 digit hydrologic unit code (HUC 10). They are named Headwaters Cedar Creek (0708010706), Competine Creek (0708010705) and Cedar Creek (0708010707). For the remainder of this report, Cedar Creek will be used to refer to the entire Cedar Creek watershed, not just the similarly named HUC 10 watershed. Cedar Creek drains to the Skunk River, which then drains into the Mississippi River.

3.2.1 Annual Water Cycle

On an annual time scale, the Cedar Creek watershed water cycle represents the balance of precipitation inputs with evapotranspiration and streamflow outputs. The assumption that the long term water balance is simply the balance between precipitation and evapotranspiration and streamflow is well established, and it has been shown that this assumption is still valid for annual time scales (Milly, 1994). The two outputs in this balance can further be broken down. Evapotranspiration is comprised of evaporation and transpiration, while streamflow is comprised of surface runoff and baseflow.

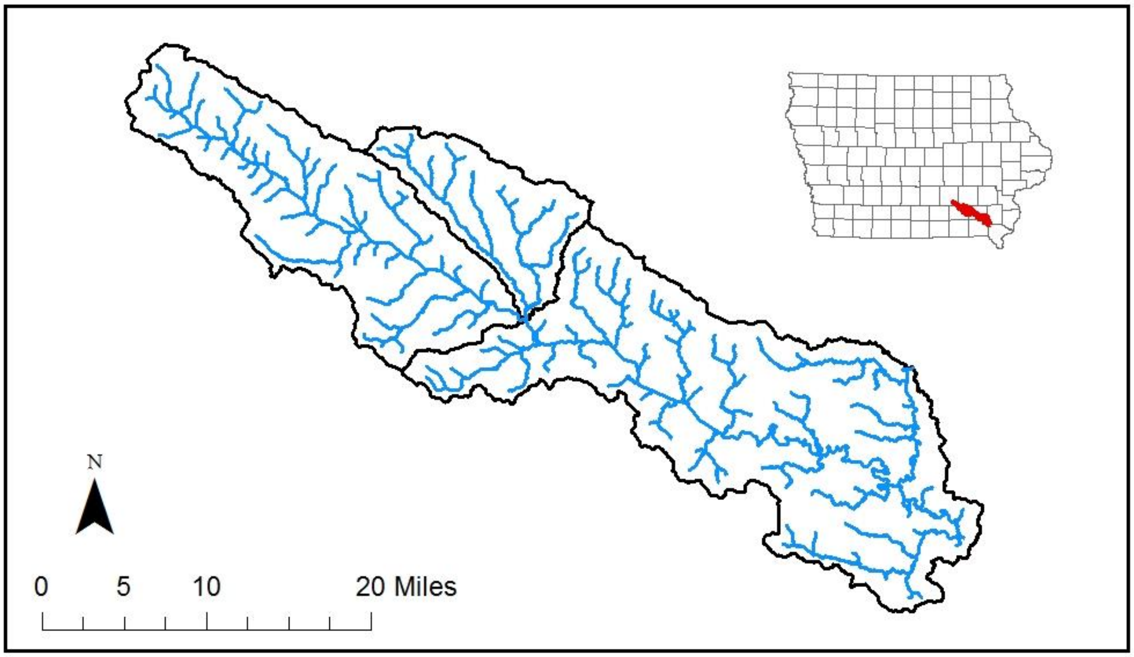

Figure 3.1: Cedar Creek watershed and its location in Iowa

Measurements within the Cedar Creek Watershed can be used to develop estimates for the annual volumes of the precipitation input and each output. The approximate mean annual precipitation total for Cedar Creek between 1981 and 2010 is 38 inches (PRISM Climate Group, Oregon State University, 2017). Obtaining an estimate for the mean annual evapotranspiration is more difficult, as this cannot be directly measured. However, a method has been developed to estimate the fraction of precipitation that becomes evapotranspiration for the continental United States (Sanford & Selnick, 2013). Using this method, it is possible to determine that the fraction of mean annual precipitation that becomes evapotranspiration in Cedar Creek is 0.65.

The remaining fraction of precipitation leaves that watershed as streamflow. A USGS stream gauge located 4.4 miles upstream of the outlet of the Cedar Creek watershed can be used to estimate the mean annual streamflow volume. The location of the USGS stream gauge within the watershed is shown in Figure 3.2. Based on the USGS streamflow data collected by this gauge from 1978 through 2016, the mean annual streamflow volume is 10.3 inches (USGS, 2017). This estimate implies that the fraction of mean annual streamflow to mean annual precipitation is 0.27, different from the estimate of 0.35 based on the evapotranspiration fraction of 0.65 for this region of Iowa. The difference between 0.35 and 0.27 for the fraction of precipitation becoming streamflow could be due to the uncertainty involved in the estimate for the mean annual evapotranspiration. To further breakdown the mean annual streamflow, the baseflow fraction can be estimated using a simple baseflow separation tool from researchers at Purdue University and assuming that the Cedar Creek watershed can be characterized by perennial streams with a porous aquifer (Engel, 2004). The results of this analysis show that the fraction of streamflow volume due to baseflow is 0.46 for Cedar Creek. Therefore, it can be seen that of the 10.3 inches of precipitation that become streamflow in an average year, 4.6 inches reach the stream as baseflow. This assumes that in a given year there will be no net change in the subsurface storage of water.

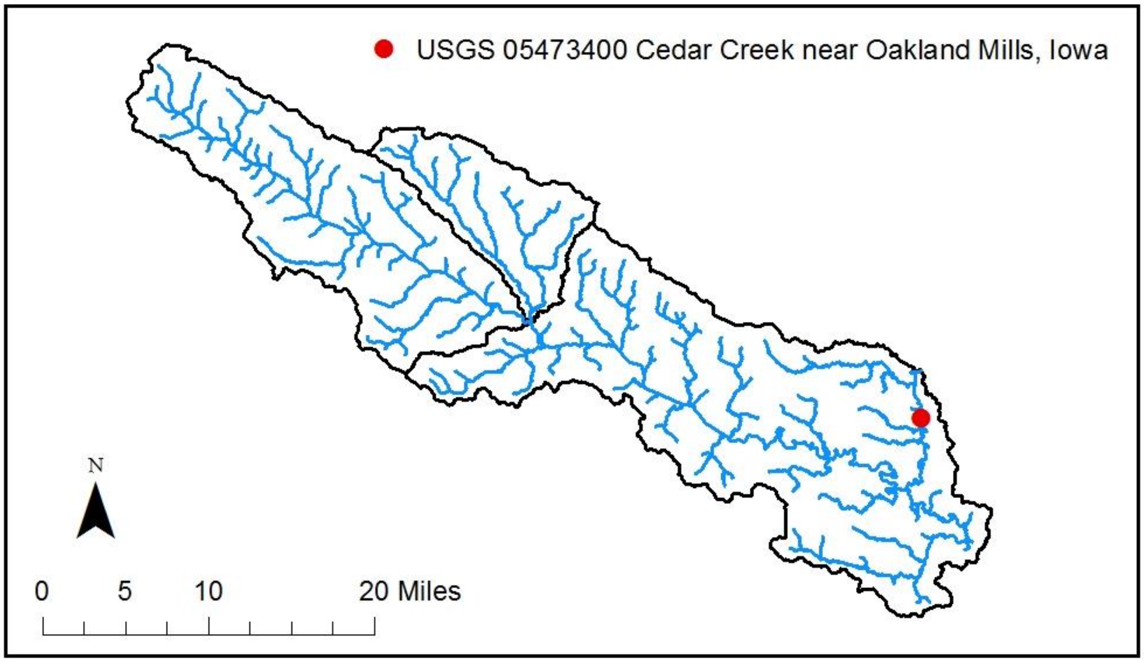

Figure 3.2: Location of USGS stream gauge 05473400 within Cedar Creek watershed

3.2.2 Monthly Trends in Water Cycle

On a sub-annual scale, it is important to understand how hydrologic processes change. The variation in precipitation over the year in Cedar Creek is shown below in Figure 3.3. The data used to obtain the monthly average precipitation estimates were collected over the span of 30 years, from 1981 to 2010 (PRISM Climate Group, Oregon State University, 2017). The average monthly precipitation for Cedar Creek ranges from 5.0 inches in May to 1.4 inches in January. The data also show that, on average, 57% of annual precipitation falls on the Cedar Creek Watershed between May and September and that 25% of the annual precipitation falls in May and June.

The monthly variation in discharge for the Cedar Creek watershed can be observed using the streamflow data collected by the USGS at their stream gauge within the Cedar Creek watershed (USGS, 2017). This monthly variation in discharge is shown below in Figure 3.4. The distribution of average monthly streamflow shows that 66% of all streamflow volume leaves the watershed during the months of March through July, and that 31% leaves the watershed during May and June. While there is some overlap with the monthly trends in precipitation, the high average streamflow observed in March and April are not directly explained by precipitation trends. The streamflow in these months is likely driven by the melting of snowfall accumulated in the winter months of January and February. The relatively low average streamflow resulting from precipitation in the late summer months of July through September are likely a result of the large impact of evapotranspiration during these months due to climate and agricultural activity.

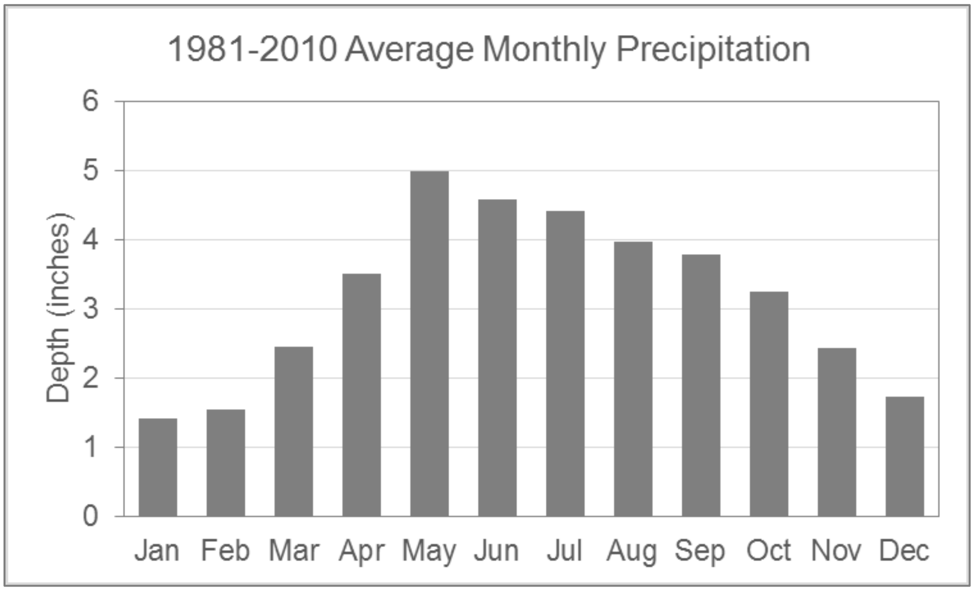

Figure 3.3: Average monthly precipitation for Cedar Creek watershed (PRISM Climate Group, Oregon State University, 2017)

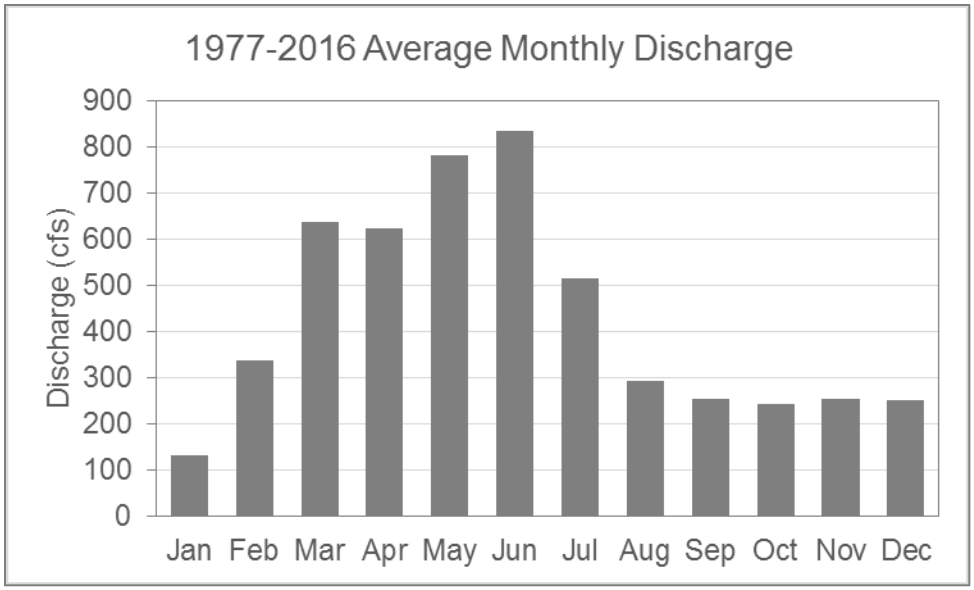

Figure 3.4: Average monthly discharge for Cedar Creek near Oakland Mills, Iowa (USGS, 2017)

3.2.3 Time of Year for the Occurrence of Peak Discharge

In order to better understand the hydrologic processes that shape the Cedar Creek watershed, it is important to know when peak discharge events happen during the year. Peak discharge events for the Cedar Creek watershed are determined from streamflow monitoring at the USGS streamflow gauge within the watershed (USGS, 2017). These events, shown in Figure 3.5, illustrate the fact that the highest concentration of annual peak discharge events occur in the months of May and June. The historical peak discharge measured in Cedar Creek of 20,000 cfs occurred in 1976, but the month and day of occurrence for this event is unknown and is therefore not included when considering the time of the year for the occurrence of the peak discharge (USGS, 2017). It is important to note that the next 4 highest peak discharge events do not occur in the months of May and June. The second highest discharge event occurred in April, and several other peak discharge events occur in the late summer months of August and September. Generally speaking, peak discharge events that occur from the month of April and beyond are due to extreme rainfall events, while those occurring before April and due, at least in part, to snow melt.

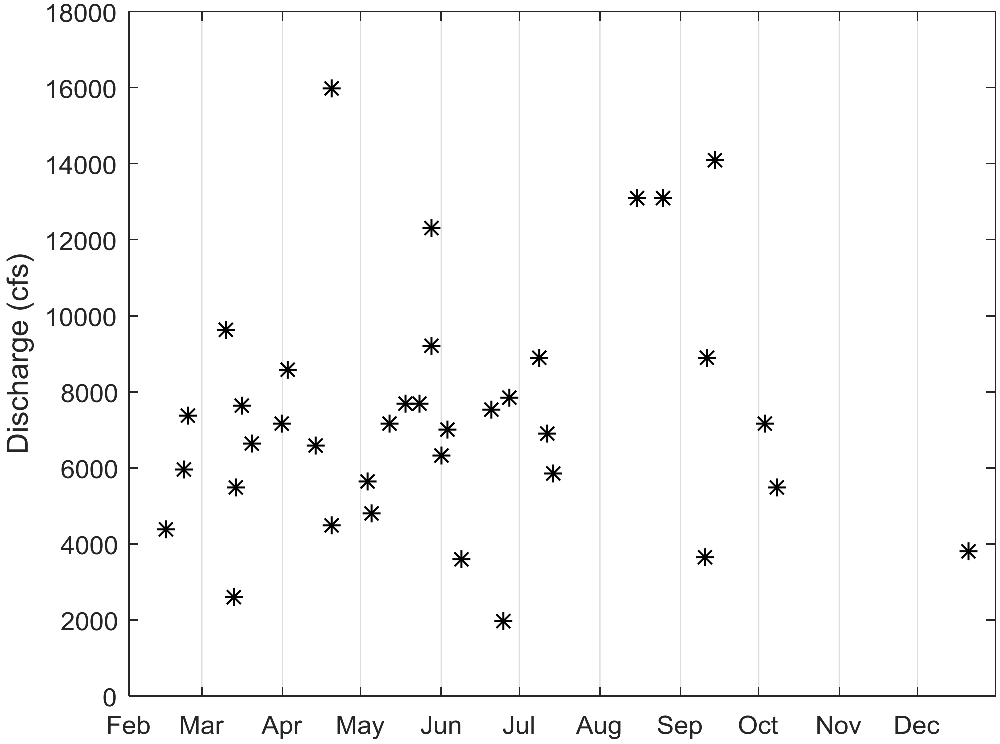

Figure 3.5: Annual peak discharge for Cedar Creek near Oakland Mills, Iowa (USGS, 2017)

3.3 Physical Properties of the Watershed

The hydrologic output of a watershed, its discharge and evapotranspiration volumes, are not solely a product of the climatological forcings of that watershed. The physical properties of the watershed landscape shape how the catchment will transform precipitation into baseflow, surface runoff, and evapotranspiration. In this section, the geology, soil types, topography, and land use types within the Cedar Creek watershed will be examined in the context of how they shape the hydrologic response. These properties, and their relative resolution and accuracy, are important components to consider when developing the hydrologic model for Cedar Creek.

3.3.1 Geology

The Cedar Creek watershed lies completely within the Southern Iowa Drift Plain. This landform region of Iowa extends to the state's southern border and to the Mississippi River in the east, as shown in Figure 3.6. The Southern Iowa Drift Plain is the largest landform in Iowa and is characterized by variable terrain and a landscape with well-defined drainage systems due to the fact that streams have had time to erode the land surface longer than in other regions of Iowa due to its relatively older glacial history (Iowa Department of Natural Resources, 2006).

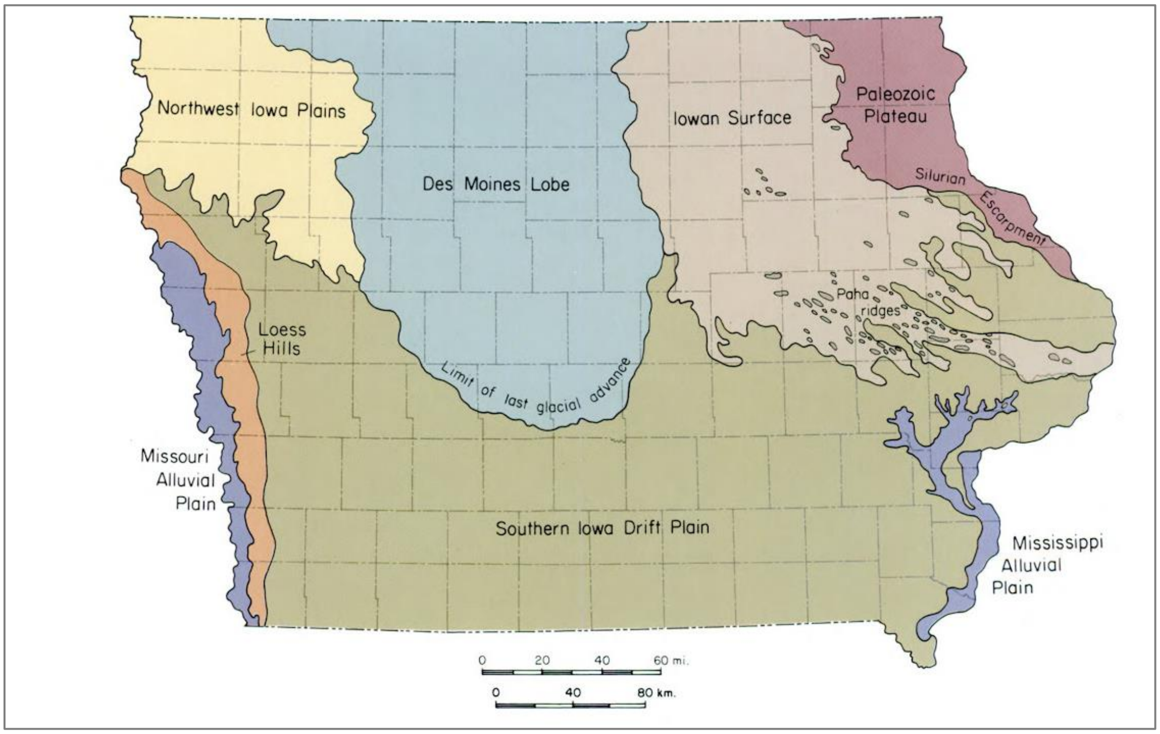

Figure 3.6: Landforms of Iowa (Prior, 1991)

In Figure 3.7, the bedrock depth across the Cedar Creek watershed is shown. Similar to other watersheds in the Southern Iowa Drift Plain, the bedrock is exposed to the surface in several portions of the watershed (Iowa Department of Natural Resources, 2006). The deepest bedrock sections are found along the northeastern boundary of the watershed and near the southern portion of the watershed. In each of these areas, the bedrock is approximately 200 feet below the land surface. The bedrock is mostly Pennsylvanian, an impermeable shale geologic rock, with some areas near the outlet of the watershed classified as Mississippian, a limestone rock marked by sporadic fractures (Iowa Geological Survey, 2015). These geological details will be useful in understanding the baseflow contributions from different regions of the Cedar Creek watershed, based on the presence of impermeable shale and fractured limestone bedrock.

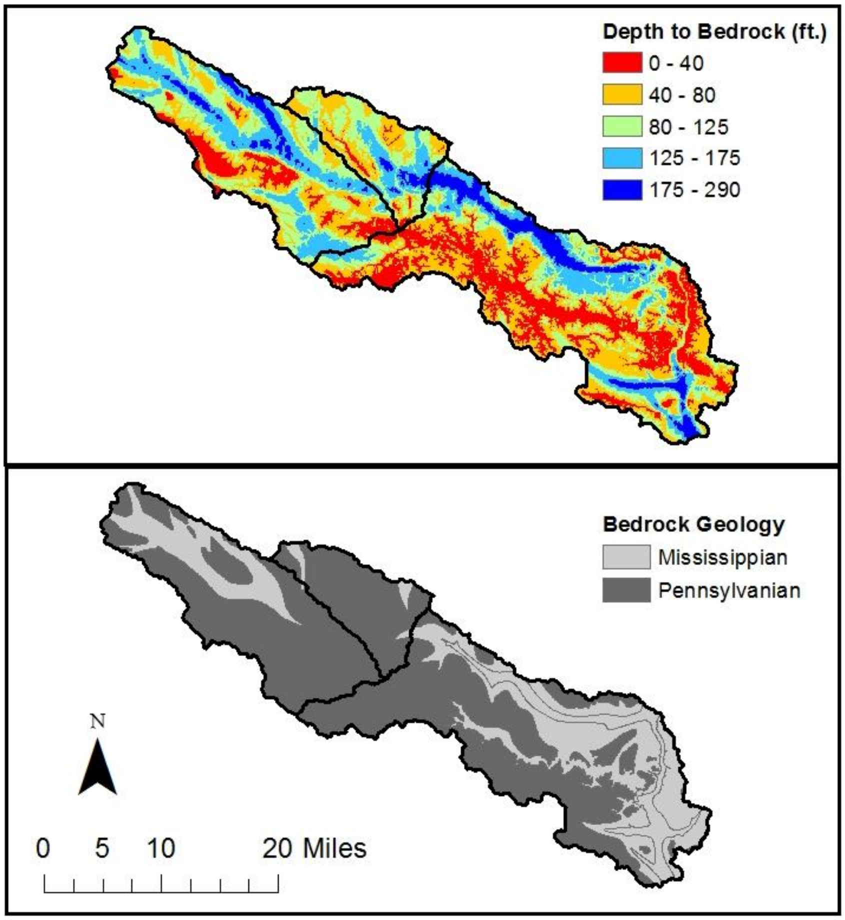

Figure 3.7: Geology of Cedar Creek. Top: Depth from the surface to bedrock. Bottom: Geologic group of bedrock (Iowa Geological Survey, 2015).

3.3.2 Soils

The Cedar Creek watershed contains eight different soil types as classified by the United States Department of Agriculture (Soil Survey Staff, NRCS, USDA, 2015). The distribution of these soil types across the watershed is shown in Figure 3.8, while the percentage of watershed area for each soil type is tabulated in Table 3.1. Silty clay loam and silt loam account for 88% of the watershed area, with silty clay loam dominating the upland region of the watershed and silt loam the region near the watershed outlet. These soil types are common in agricultural regions throughout Iowa and are known to be well drained soils advantageous for agricultural production.

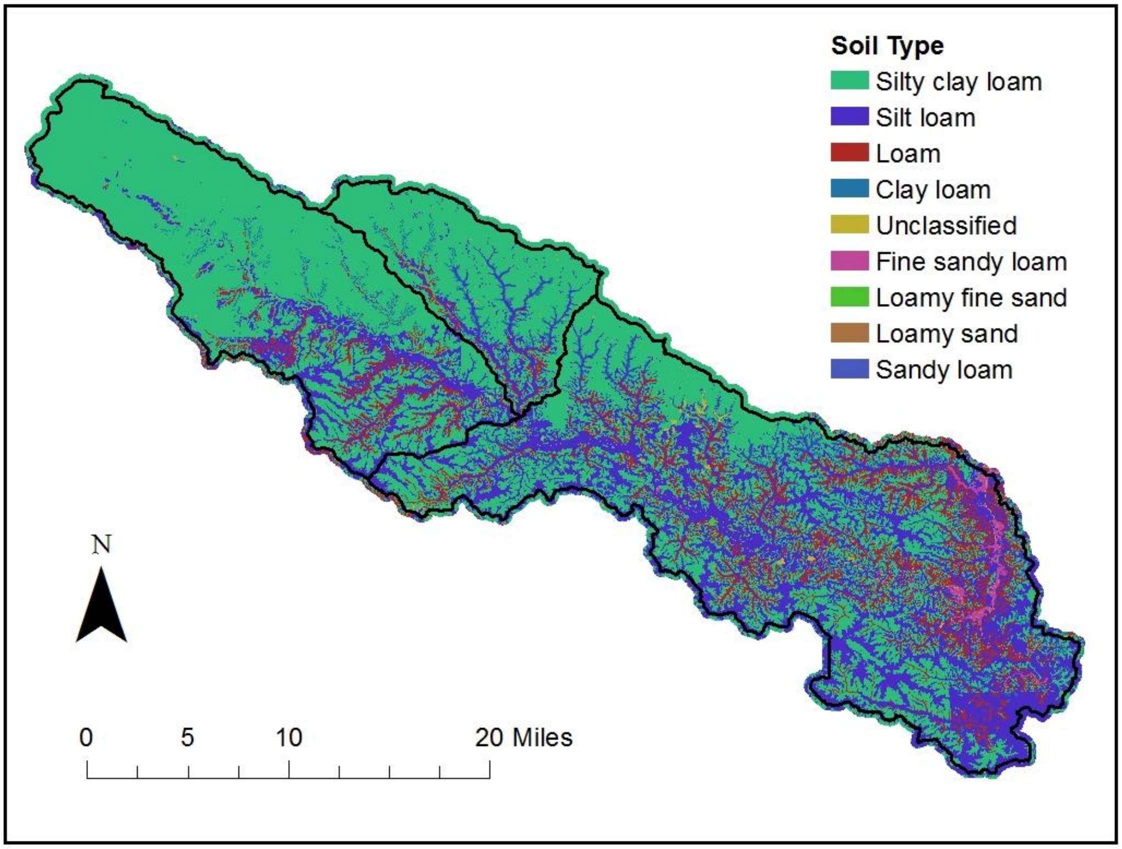

Figure 3.8: Soil types within the Cedar Creek watershed

Table 3.1: Soil types as fraction of Cedar Creek watershed area

Soil Type	Percent of Watershed Area
Silty clay loam	59.17
Silty loam	29.09
Loam	8.48
Clay loam	1.84
Unknown	0.71
Fine sandy loam	0.58
Loamy fine sand	0.08
Loamy sand	0.03
Sandy loam	0.02

3.3.3 Topography

A digital elevation model resulting from the collection of LIDAR data measuring the position of the land surface is important in understating how surface runoff is routed over the Cedar Creek watershed. The measured elevation for the Cedar Creek watershed ranges from 260 meters to 175 meters above sea level (Iowa Department of Natural Resources and Iowa Geological Survey, 2003-2014). The total relief of 85 meters (279 feet) is illustrated in the elevation and slope distributions shown in Figure 3.9. The variability of the terrain, from steep slopes near the outlet to flat landscapes in the upland region, is common for watersheds in the Southern Iowa Drift Plain (Iowa Department of Natural Resources, 2006).

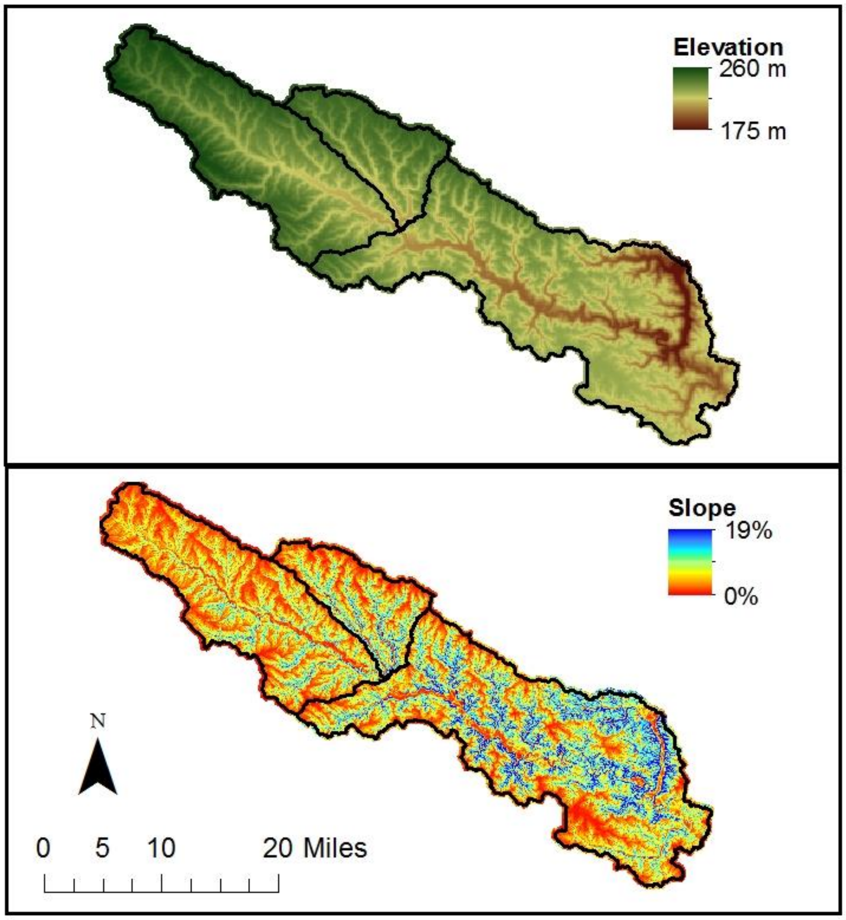

Figure 3.9: Topography of Cedar Creek watershed. Top: Surface elevation. Bottom: Surface slope (Iowa Department of Natural Resources and Iowa Geological Survey, 2003-2014).

3.3.4 Land Use

The Cedar Creek watershed is predominantly agricultural, as is common for watersheds in Iowa. Cultivated crops account for 63% of the watershed area and pasture accounts for 14% of the watershed area (Homer, et al., 2015). While agriculture accounts for 77% of the watershed area, the proportions of different cultivated crops is unknown for any given year. It has been estimated that 53% of the Cedar Creek watershed is used for row crops (Schilling & Libra, 2000). The third most common land use type in the Cedar Creek watershed is forest, accounting for 10% of the watershed and concentrated most heavily in the southern portion of the watershed. The developed areas in the watershed account for 7% of the total area, largely due to the city of Fairfield, Iowa near the center of the watershed. The land use distribution is shown in Figure 3.10, with the breakdown of land use area as a fraction of the watershed area shown in Table 3.2.

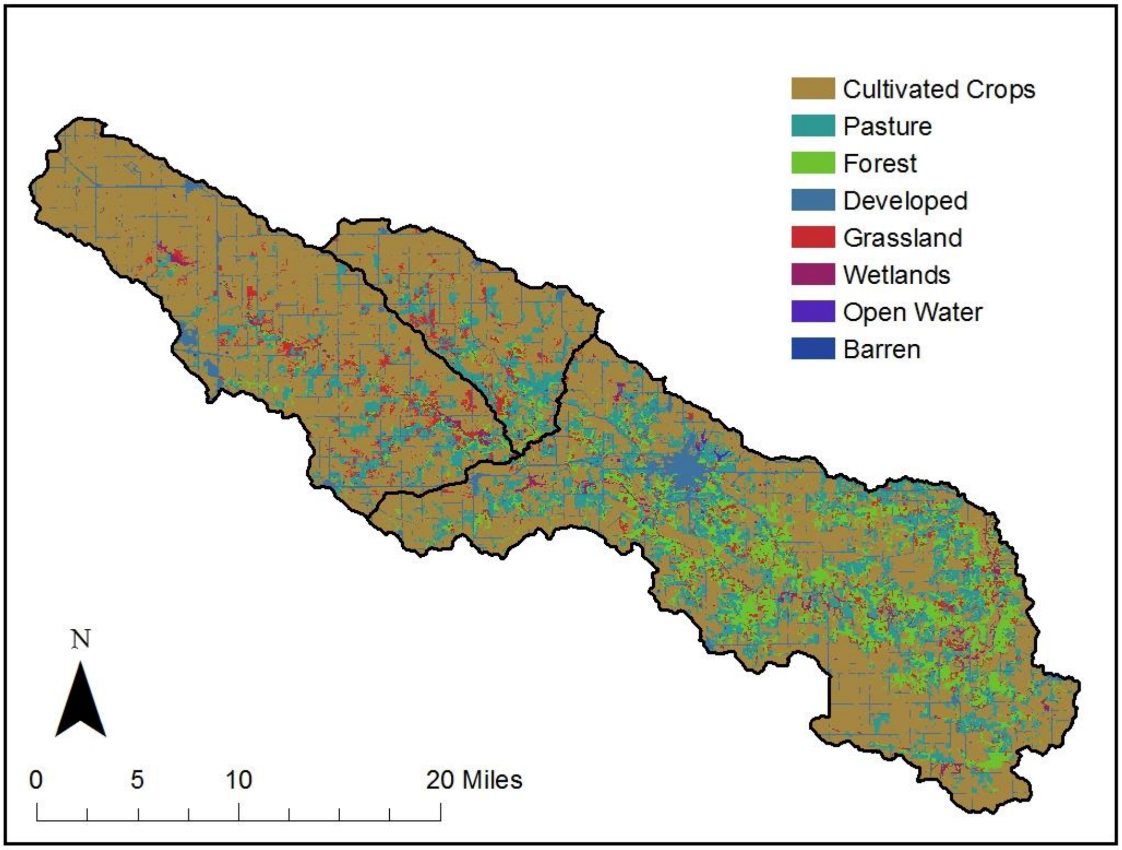

Figure 3.10: Land use type in Cedar Creek watershed

Table 3.2: Land use as fraction of Cedar Creek watershed area

Land Use Type	Percent of Watershed Area
Cultivated crops	62.59
Pasture	14.38
Forest	10.50
Developed	6.66
Grassland	4.22
Wetlands	1.34
Open water	0.31
Barren	0.01

3.3.5 Instrumentation in the Watershed

There are several devices that have been installed in the Cedar Creek watershed to measure streamflow, groundwater depth, water quality, and precipitation. These instruments are important in developing an understanding of the current, and historical, conditions within the watershed. Of these devices, four are currently in operation and one has been retired. A USGS groundwater well (USGS 405451091483301) collected 15-minute resolution measurements of the depth of the groundwater level below the ground surface from December 2008 until it was retired in October 2014. The instruments currently in operation within the Cedar Creek watershed include a stream gauge, water quality sensor, and two precipitation gauges.

A USGS stream gauge (USGS 05473400) near the outlet of Cedar Creek has collected daily discharge and stage measurements since July 1977 and 15-minute resolution discharge and stage measurements since October 2007. An IIHR water quality sensor (IIHR WQS0034) collected 5-minute resolution measurements of nitrate and nitrite as nitrogen concentration at a location just below the confluence of Competine Creek with Cedar Creek. Two NOAA weather stations are located within the Cedar Creek watershed. A NOAA station at the Fairfield Municipal Airport (NOAA 72649804925) and a NOAA station at the Ottumwa Industrial Airport (NOAA 72546514950) have collected 15-minute precipitation data since 1995 and 1973 respectively. The locations of all five instruments are shown in Figure 3.11 and the period of record for each instrument is outlined in Table 3.3.

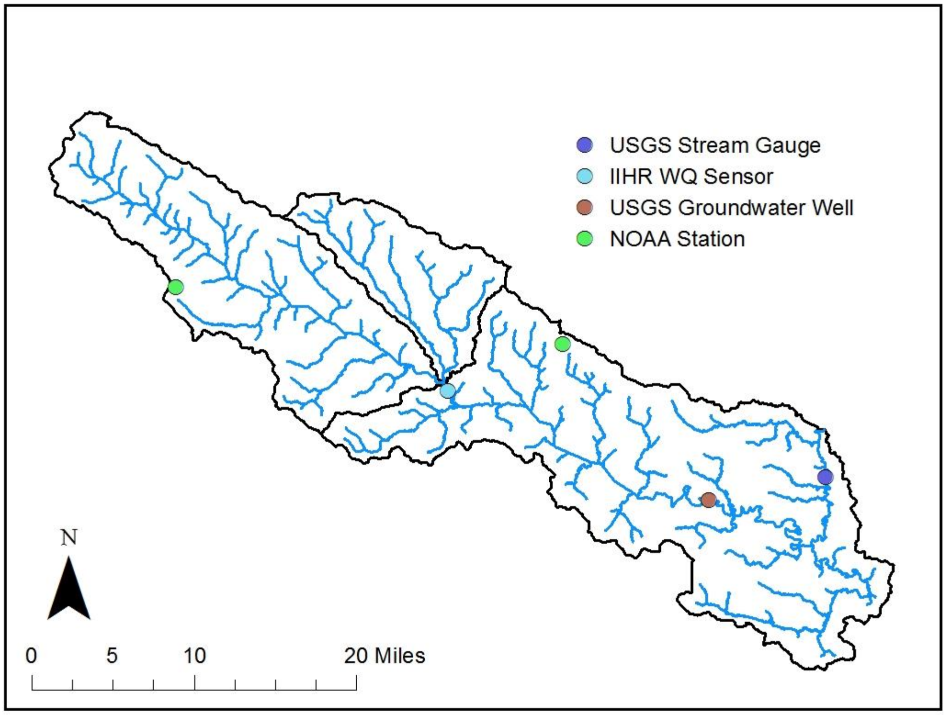

Figure 3.11: Instruments within Cedar Creek watershed include USGS stream gauge 05473400, IIHR water quality sensor WQS0034, historical USGS groundwater well 405451091483301, and NOAA stations 72649804925 at Fairfield, IA and 72546514950 at Ottumwa, IA.

Table 3.3: Period of record for instruments within Cedar Creek watershed

Instrument	Period of Record
USGS Stream Gauge on Cedar Creek near Oakland Mills, IA	7/1/1977 - Present
IIHR Water Quality Sensor on Cedar Creek	4/5/2016 - Present
USGS Groundwater Well in Jefferson County, IA	12/3/2008 – 10/23/2014
NOAA Station at Fairfield, IA	4/23/1995 - Present
NOAA Station at Ottumwa, IA	1/1/1973 - Present

3.4 Chapter Summary

A firm grasp of the physical characteristics of a watershed is a crucial step in building a useful and accurate hydrologic model of that watershed. This chapter summarized the important physical properties of the Cedar Creek watershed. The Cedar Creek watershed consists of the HUC 10 watersheds Headwaters Cedar Creek (0708010706), Competine Creek (0708010705) and Cedar Creek (0708010707). The watershed experiences a mean annual precipitation of 38 inches, the majority falling in the months of May through September. Of this 38 inches, approximately 70% becomes evapotranspiration and 30% becomes streamflow annually. Baseflow accounts for 46% of the streamflow leaving Cedar Creek. Two-thirds of the mean annual stream flow volume leaves Cedar Creek between March and July. June and May are the months with the highest mean streamflow and are the months in which the annual peak streamflow is most likely to occur.

The 567 mi^2 watershed lies in the Southern Iowa Drift Plain and is marked by a variable terrain with well-defined catchments due to a long period of erosion from natural streams. The bedrock is dominated by an impermeable Pennsylvanian geology in the upper half of the watershed and a fractured limestone Mississippian geology in the lower half. The bedrock extends as far down as 290 feet in some regions and extends into the surface in several places in the watershed, especially along the channel near the outlet of the watershed. The topography of the watershed is common for regions in the Southern Iowa Drift Plain, exhibiting a flat profile in the upper half of the watershed and steeper slopes in catchments near the outlet. The watershed is dominated by silty clay loam and silt loam soils, both known to be well suited for agriculture. The land use in the watershed is dominated by agricultural use, with crops and pasture accounting for 77% of the total watershed area. Streamflow, water quality, groundwater, and climatology data have all been collected within the watershed in recent years. While the groundwater data has been retired since 2014, this data will guide the development and calibration of the Cedar Creek hydrologic model.

CHAPTER 4: CEDAR CREEK MODEL DEVELOPMENT

4.1 Introduction

This chapter outlines the development of the Cedar Creek hydrologic model. The model for Cedar Creek was developed using MIKE SHE, a software developed by DHI in Copenhagen, Denmark (DHI, 2014). The creation of the Cedar Creek model involved the processing and preparation of geographic information using ESRI ArcGIS. A tool within the MIKE program was then used to convert raster files into the equivalent files readable by MIKE SHE. In this way, publicly available data regarding the Cedar Creek watershed could be transformed into the necessary model inputs.

4.2 Selection of MIKE SHE and Limitations of the Model

MIKE SHE is a coupled surface/subsurface, physically based, distributed hydrologic model that includes a water quality module called ECOLAB. Physical models such as MIKE SHE define hydrologic processes using parameters and physical properties that can be measured. Distributed models allow for some spatial variation in the definition of physical properties within the model. While this variation is not reasonably chosen to be as high as the natural world, it does offer a closer representation to natural variations in physical properties than a lumped model does. Coupled surface/subsurface models allow for the exchange of water from the surface to the subsurface, the movement of water through the subsurface, and the reemergence of water as baseflow to the river network. The routing of baseflow and surface runoff out of the watershed is conducted in MIKE SHE with a coupled one dimensional river model called MIKE 11. A summary of the hydrologic processes in MIKE SHE is shown in Figure 4.1. Not shown in this schematic are the advection/dispersion and water quality modules for MIKE SHE. The water quality module, called ECOLAB, allows the modeler to solve a set of user defined differential equations governing the concentration of user defined chemical species within the model.

MIKE SHE was chosen to model the Cedar Creek watershed for several important reasons. First, MIKE SHE was selected due to its ability to integrate all processes in the hydrologic cycle with the fate and transport of chemical species into a single model. This allows the user to model water depth and discharge along the river network, the concentration of key nutrients throughout the watershed, and the position of the water table at each model time step in each model grid cell. By moving water throughout the watershed in this physical way, MIKE SHE can easily be used to diagnose problems such as flooding within a watershed and test how different solutions could alleviate the problem. Second, being a model commonly used by practicing engineers across the world, MIKE SHE is less computationally expensive than a more research-focused model such as Hydrogeosphere (Brauer, 2015). This means that MIKE SHE is able to run models on the types of computers common to hydrologic engineers in industry.

While MIKE SHE is a distributed model, its formulation relies on the segmentation of all surface and subsurface inputs and climatological inputs into spatial categories. An application of radar rainfall data as an input would mean the specification of a unique precipitation time series for each model grid cell. Although this represents a drawback of MIKE SHE, its benefits as a model outweigh this limitation.

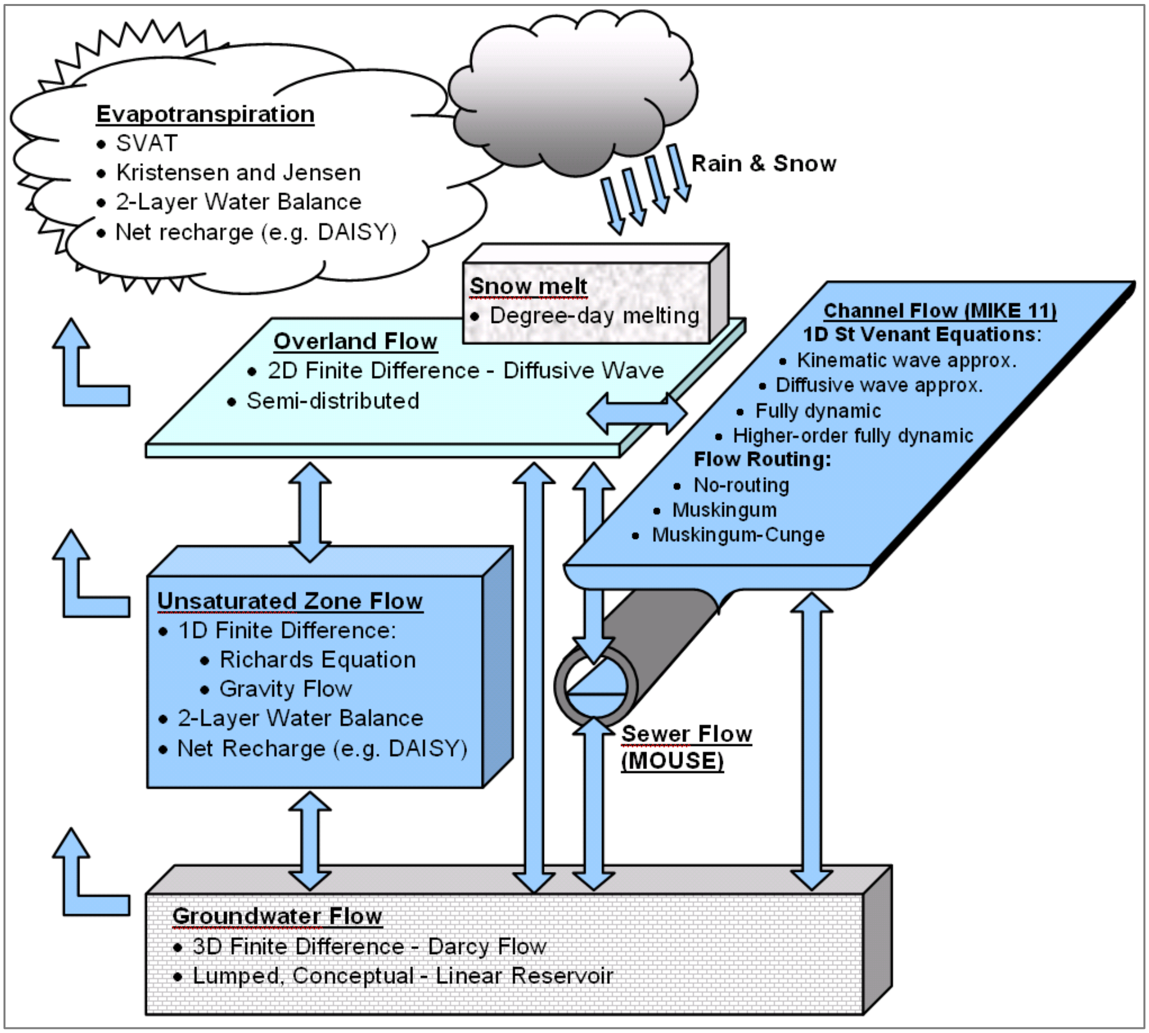

Figure 4.1: Schematic of the processes in MIKE SHE (DHI, 2014)

4.3 Model Construction

The process of constructing the hydrologic model for the Cedar Creek watershed is first defined by the specification of the physical properties of the watershed. These properties include the physical boundary of the watershed, its stream network, the surface elevation measurements, the soil properties and the land use types. The climatological forcings for the watershed that drive the hydrologic processes within the watershed are included in the model as precipitation and potential evapotranspiration.

4.3.1 Stream Network and Watershed Boundary

The watershed boundary and stream network are important starting points for building a model of that watershed. These model properties define the extent over which physical properties must be defined and the network for which river cross sections must be estimated. There are several ways to determine boundary and stream network for a watershed, ranging in complexity and resolution. For the purpose of the Cedar Creek watershed model, it was important to have a high resolution view of the stream network and an accurate watershed boundary.

Obtaining appropriate watershed boundary and stream network estimates involves performing a series of geographic analyses on a high resolution digital elevation model (DEM) of the area near the Cedar Creek watershed. Through these analyses, the slope of the landscape can be used to define sub catchments and the channelized links that route water through, and from, them. The boundary of the watershed is therefore given to be the line surrounding all of the sub catchments that drain to the outlet point of the watershed. In this case, the outlet point is chosen to be the confluence of Cedar Creek with the Skunk River as shown in Figure 4.2 below. The delineation of the stream network and watershed boundary for Cedar Creek was done as part of a greater floodplain mapping study conducted by the Iowa DNR and the Iowa Flood Center (Iowa Flood Center and Iowa DNR, 2015). The results of this study included the delineation of the stream network of all HUC 10 watersheds in the state of Iowa. For the modeled stream network in MIKE 11, only streams of order two and higher were included, based on the order specified in the results of the floodplain mapping project for Cedar Creek (Iowa Flood Center and Iowa DNR, 2015). The modeled stream network and watershed boundary are shown in Figure 4.3. Cross sections for this modeled stream network were spaced approximately 1,000 meters apart and extracted from a digital elevation model using a tool from the MIKE SHE software. The chosen 3 meter resolution digital elevation model was obtained from the Iowa DNR Natural Resources Geographic Information System for the area surrounding the Cedar Creek watershed (Iowa Department of Natural Resources and Iowa Geological Survey, 2003-2014).

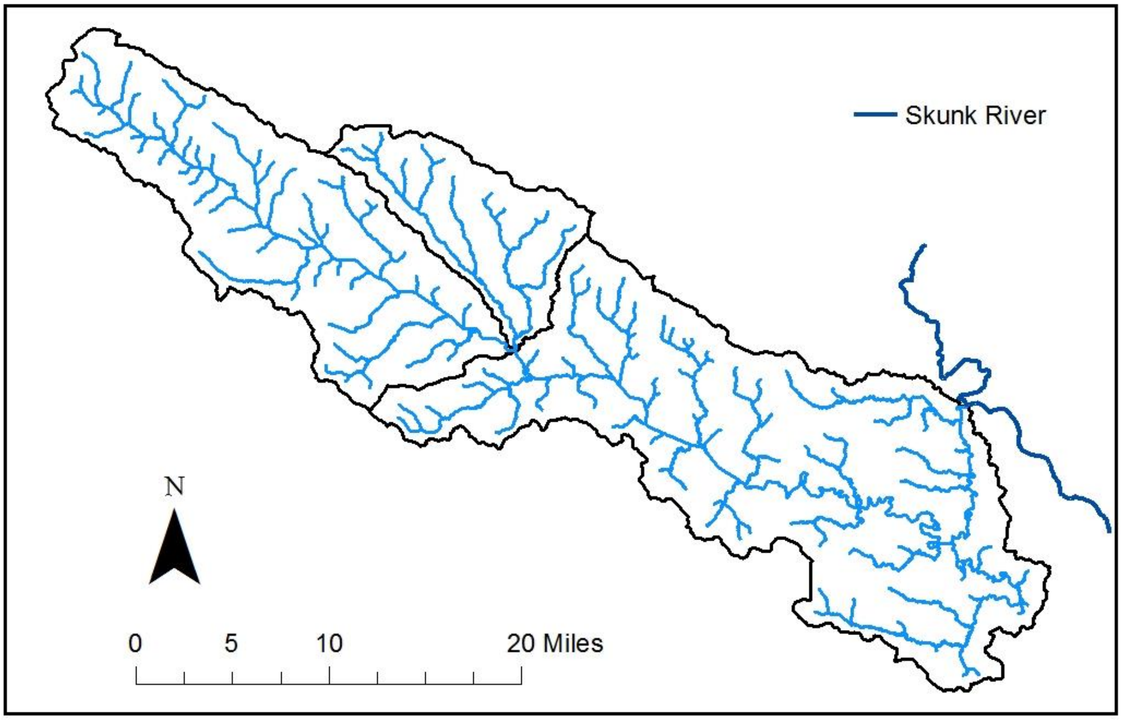

Figure 4.2: Cedar Creek boundary and full stream network shown with a segment of the Skunk River near its confluence with Cedar Creek

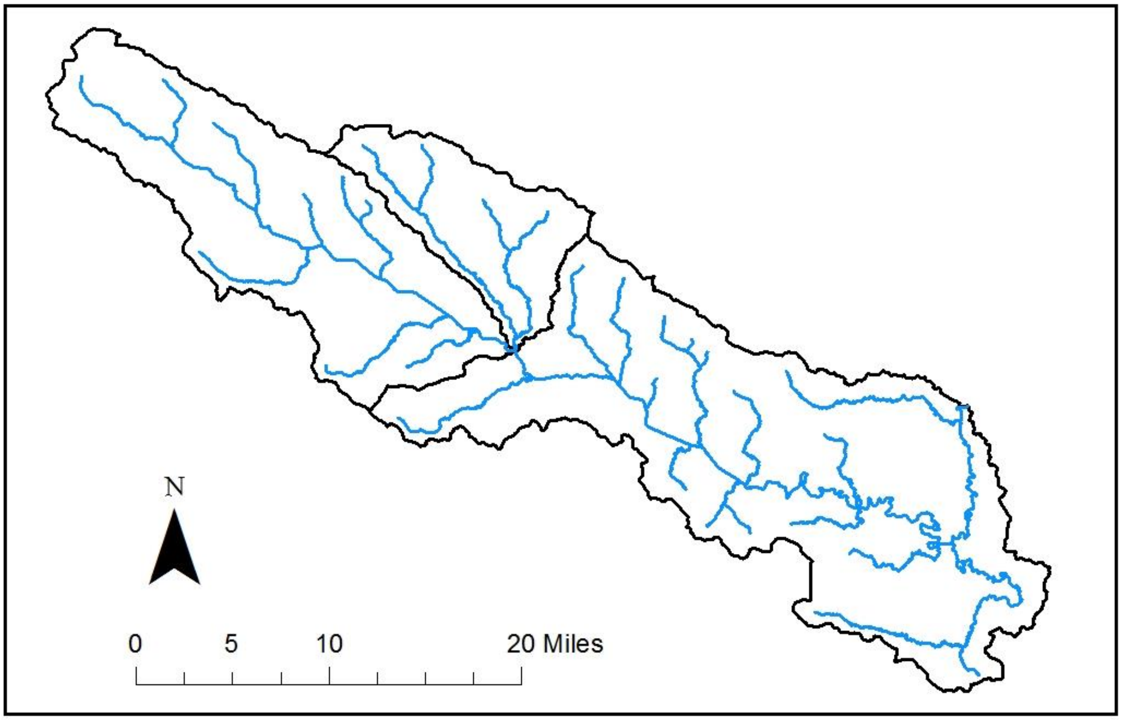

Figure 4.3: Model watershed boundary and stream network

4.3.2 Surface Grid Development

MIKE SHE uses a rectangular model grid constrained only by the size of the grid cells and the origin of the grid. For the Cedar Creek watershed model, a grid size of 200 meters by 200 meters was chosen. This choice was made based on a qualitative balance between resolution and the time required to run a simulation using MIKE SHE. This grid size is similar to those used by Brauer (2015) in a Hydrogeosphere model for a watershed in Iowa and by Refsgaard et al. (2014) in two MIKE SHE models for watersheds in Denmark. The origin point of the surface grid was chosen to correspond with the origin point of all raster files for physical properties of the watershed after processing in ESRI ArcGIS. The grid chosen for the Cedar Creek watershed model is shown in Figure 4.4 below.

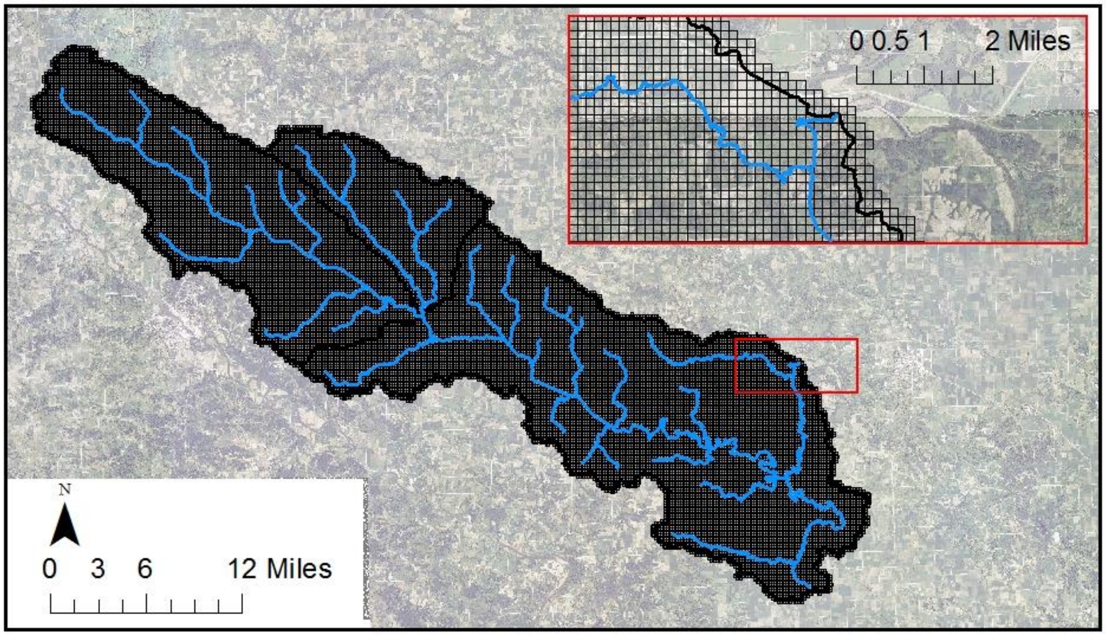

Figure 4.4: Rectangular 200 m by 200 m grid chosen for the Cedar Creek model

4.3.3 Modification of Elevation Data

A digital elevation model (DEM) was obtained from the Iowa DNR Natural Resources Geographic Information System for the area surrounding the Cedar Creek watershed. (Iowa Department of Natural Resources and Iowa Geological Survey, 2003-2014). This 10 meter resolution DEM was aggregated using ESRI ArcGIS to the same 200 m resolution as the model grid. A set of ESRI ArcGIS processes were completed in order to hydrologically condition the 200 m DEM in order to avoid any hydrologic routing problems caused by its low resolution (ESRI, 2010).

The process of hydrologically conditioning a DEM reduces the effect of roads and other man made features in artificially limiting the movement of surface runoff from the landscape to the river network. By performing a number of geographical operations on a DEM, this practice results in a DEM that routes water in a more natural, realistic way. The first step in this process is to convert the original file to a grid of points. Then, using the original DEM, a tool is used to fill in any sinks, or local low points. Next, an analysis is done to determine the flow direction, or the direction in which the neighboring cell is lowest, for each cell in the filled DEM. The flow accumulation to each cell can then be determined using the flow direction. A new flow network is then computed from the using the flow accumulation data. This flow network and the original

DEM that was converted to points are then used to generate the new hydrologically conditioned 200 m resolution DEM. This new DEM ensures that there will be less unnatural ponding on the surface and that water will be routed from the landscape to the stream throughout the watershed.

4.3.4 Development of Lower Boundary

The subsurface is partitioned into two connected regions in the Cedar Creek model. The unsaturated zone defines the region extending from the surface to the water table and the saturated zone defines the region extending below the water table. Based on this definition within the MIKE SHE framework, the lower boundary of the unsaturated zone is constantly fluctuating in each grid cell. However, a physical lower boundary must be specified in the model to serve as the deepest position the water table may fall to. The bedrock depth was used as this lower boundary for the unsaturated zone, except in cases where the bedrock depth was less than 2 meters. In this case, a value of 2 meters below the surface was used as the lower boundary. This choice was made due to the uncertainty inherent in the bedrock elevation data and limitations within MIKE SHE about the minimum length of the unsaturated zone (Iowa Geological Survey, 2015).

The bedrock is estimated to extend as far as 85 meters below the surface at some places within the watershed. For this reason, the lower boundary of the saturated zone was chosen to be a constant value of 100 meters below the surface. This choice ensures that an impermeable saturated layer below the bedrock will be at least 15 meters thick.

4.3.5 Three Dimensional Grid Development

The three dimensional subsurface grid is also partitioned into two connected regions in the Cedar Creek model. After the surface layer and the bedrock layer have been defined, the vertical grid resolution for the unsaturated zone of the model must be chosen. Important aspects to consider in developing the cell size in the unsaturated zone are that the resolution be high enough near the surface to accurately simulate soil evaporation, infiltration, uptake of soil water by plants, and interaction with the water table. As these processes most often occur in the upper 10 meters of the soil, this region has a finer resolution than the region extending below 10 meters, if applicable for that cell. The chosen vertical discretization of the unsaturated zone for the Cedar Creek model is outlined in Table 4.1 below.

Table 4.1: Vertical discretization of the unsaturated zone for Cedar Creek watershed

Depth	Cell Height	Number of Cells
0 m – 0.05 m	0.025 m	2
0.05 m – 1 m	0.05 m	19
1 m – 10 m	0.2 m	45
10 m – 100 m	1 m	90

The discretization of the saturated zone in the Cedar Creek watershed model is different than the discretization of the unsaturated zone due to the differences in how the zones are handled by MIKE SHE. The saturated zones is divided into two computational layers, one being a soil layer that overlaps the defined unsaturated zone and the other being an aquifer layer that extends below the bedrock. Governing equations in the subsurface are calculated at the interface between these zones and between the soil layer of the saturated zone and the unsaturated zone at the position of the water table. As an example to illustrate this formulation, if the water table were located at a depth of 5 m and the bedrock were located at a depth of 15 m there would be two computational cells in the saturated zone. One cell, the soil layer, would extend from 5 m to 15 m below the surface and the other, the aquifer layer, would extend from 15 m to 100 m below the surface.

4.3.6 Model Boundary Conditions

The Cedar Creek watershed model requires the specification of several boundary conditions. At the surface, a no flow condition is applied along the watershed boundary. This ensures that water leaves the model domain only through the outlet of the river network. Similarly, in the subsurface, a no flow boundary condition is applied at the lower boundary and lateral watershed boundary. The MIKE 11 river model requires the specification of both upstream and downstream boundary conditions. Upstream boundary conditions for each branch of the stream network were defined to not have any constant discharge value. The river network will therefore be fed only by baseflow and surface runoff. A critical depth condition was specified for the outlet of the stream network.

4.4 Model Properties

The properties of the Cedar Creek model are specified in MIKE SHE into modules that represent the different model components. The unsaturated zone and saturated zone describe the properties of the subsurface, the overland flow component describes surface properties and the evapotranspiration properties describe the processes that govern evaporation and transpiration at the surface. Each module, and its properties defined in the Cedar Creek MIKE SHE model, will be explained in the following sections.

4.4.1 Unsaturated Zone Properties

The unsaturated zone describes the region of the subsurface from the ground surface to the water table. Properties for this zone were defined to extend from the surface down to 100 m below the surface. This depth was chosen to ensure that the water table would never fall below the lower boundary of the unsaturated zone, terminating any model simulations, and based on the fact that all unsaturated zone properties are overridden by saturated zone properties below the water table. Soil properties such as hydraulic conductivity, porosity, the Van Genuchten parameters (α and n), and an empirical pore connectivity parameter, L, are defined based on the soil type of the given cell. The soil properties were assigned based on the surface soil texture given by the SSURGO soil data for the Cedar Creek watershed (Soil Survey Staff, NRCS, USDA, 2015). The soil properties of the stream bed were changed from those specified by the SSURGO soil data in order to better replicate the known sandy characteristics and the interaction between the stream and subsurface. The soil properties chosen for each soil type were assigned based on the *ROSETTA Class Average Hydraulic Parameters* (Schaap, Leij, & Van Genuchten, 2001). A summary of these properties is shown in below.

Table 4.2: Soil type and soil properties used in the Cedar Creek watershed model based on the *ROSETTA Class Average Hydraulic Parameters* (Schaap, Leij, & Van Genuchten, 2001).

Soil Type	Saturated Hydraulic Conductivity (m/s)	Porosity	α (1/cm)	n	L
Silty clay loam	1.29×10^{-6}	0.48	0.008	1.521	-0.156
Silty loam	2.11×10^{-6}	0.44	0.005	1.663	0.365
Loam	1.39×10^{-6}	0.40	0.011	1.472	-0.371
Clay loam	9.47×10^{-7}	0.44	0.016	1.416	-0.763
Fine sandy loam	4.43×10^{-6}	0.39	0.027	1.449	-0.861
Loamy fine sand	1.22×10^{-5}	0.39	0.035	1.746	-0.874
Loamy sand	1.22×10^{-5}	0.39	0.035	1.746	-0.874
Sandy loam	4.43×10^{-6}	0.39	0.027	1.449	-0.861
Stream (Sand)	7.44×10^{-5}	0.38	0.035	3.177	-0.930

4.4.2 Saturated Zone Properties

The saturated zone describes the region from the water table to the lower boundary of the model. Properties for this zone were defined for the full extent of the subsurface model domain. This choice ensures that the water table is allowed to rise to the ground surface. As a result, the same soil properties chosen for the unsaturated zone were used to define the portion of the saturated zone between the ground surface and the bedrock. The horizontal hydraulic conductivity, as well as the properties of macropores and subsurface drainage in the saturated zone, will be discussed in the following chapter. Below the bedrock, a uniform aquifer was given properties based on the known bedrock geology of the Cedar Creek watershed (Iowa Geological Survey, 2015). The properties given to the aquifer layer were a uniform horizontal and vertical saturated conductivity of 1×10^{-10} m/s.

4.4.3 Overland Flow Properties

Overland flow properties for the Cedar Creek watershed were defined for each surface grid cell. These surface properties of the model describe how water infiltrates into the subsurface or is routed into the river network. The Manning’s roughness coefficient, n, is the property used by the MIKE SHE model to describe how water interacts with the surface. This property can be estimated from the land use type obtained from the 2011 National Land Cover Database (NLCD) for the Cedar Creek watershed (Homer, et al., 2015). A summary of the Manning's roughness coefficients estimated for each land use type in the Cedar Creek watershed is shown in Table 4.3.

Table 4.3: Manning's roughness coefficient based on land use type, derived from Thomas (2015)

Land Use Type	n (s $m^{-1/3}$)
Cultivated crops	0.07
Pasture	0.07
Forest	0.12
Developed	0.10
Grassland	0.07
Wetlands	0.05
Open water	0.03
Barren	0.07

4.4.4 Evapotranspiration Properties

Evapotranspiration properties for the Cedar Creek watershed are assigned to surface grid cells. Some properties are assigned for the full watershed domain and others are defined based on the land use type given to each surface grid cell. The role of these properties in the model is to control how water at the surface and in the soil evaporates and how water is transpired by vegetation. A limited number of evapotranspiration parameters are defined uniformly across the watershed. These properties include canopy interception and the gravity flow and Richards parameters used for evapotranspiration estimation (Kristensen & Jensen, 1975). The default value for canopy interception in MIKE SHE of 0.05 mm was used, while the Kristensen and Jensen evapotranspiration parameters that were used were determined as part of the calibration process.

Root depth and leaf area index (LAI) are the properties that control transpiration rates for surface grid cells across the watershed. These properties were defined by aggregating the land use definitions for each cell into five categories. The values of root depth and time series estimates of LAI for each land use category were derived from Thomas (2015). Tabulated values for root depth used in the Cedar Creek watershed model are shown in Table 4.4. The LAI time series used for each land use category are shown in Figure 4.5 below. No values are shown for LAI at grid cells defined to be streams because the LAI is constant and zero at these cells.

Table 4.4: Root depth derived from Thomas (2015)

Land Use	Root Depth (m)
Agriculture	1.00
Grassland	0.93
Forest	2.00
Developed	1.00
Stream	0.00

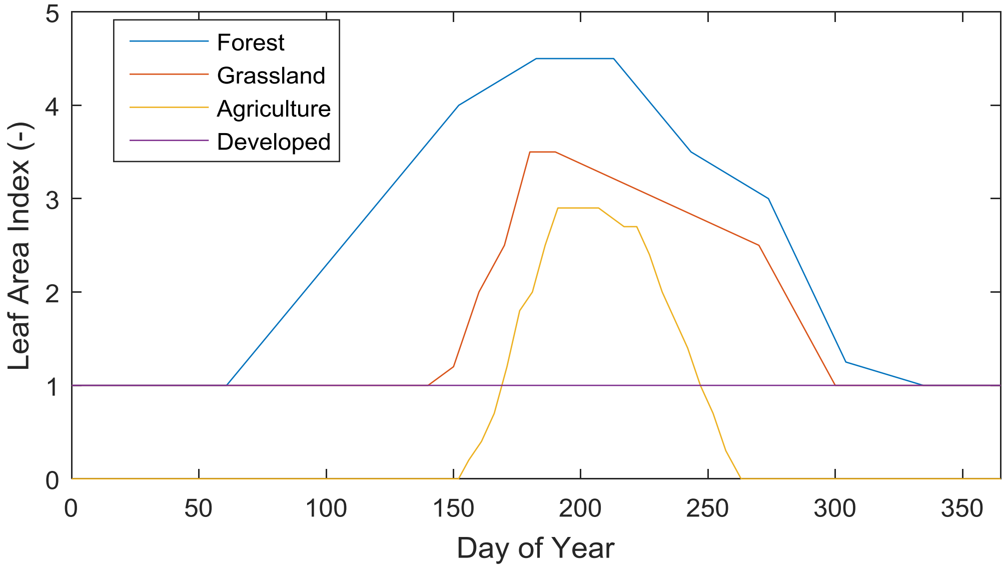

Figure 4.5: LAI for each land use category derived from Thomas (2015)

4.5 Model Inputs

The MIKE SHE model of the Cedar Creek watershed also required the specification of climatological inputs. These inputs include precipitation data and potential evapotranspiration (PET) data. Each of these inputs were obtained from measurements taken within, or near, the Cedar Creek watershed and are responsible for driving the hydrological processes within the model. The details of each input will be explained in the following sections.

4.5.1 Rainfall Data

Rainfall data for the Cedar Creek watershed model was chosen based on the desire to have a model input with high spatial and temporal resolution. While the two NOAA rain gauge stations within the watershed, one at the Fairfield Municipal Airport (NOAA 72649804925) and one at the Ottumwa Industrial Airport (NOAA 72546514950), have 15-minute resolution rainfall data, they would be unable to characterize the full spatial variability of rainfall in the Cedar Creek watershed. Instead, hourly radar rainfall Stage IV Data was obtained with a 4 km by 4 km spatial grid resolution (Lin, 2017). For use in the Cedar Creek model, the radar rainfall data was aggregated into 10 zones, as shown in Figure 4.6. The rainfall time series for each zone was determined by taking the arithmetic average of the radar rainfall time series whose radar pixel center falls within that zone. This method improves the spatial resolution of the rainfall input while incurring a minor reduction in the temporal resolution from 15-minute to hourly inputs.

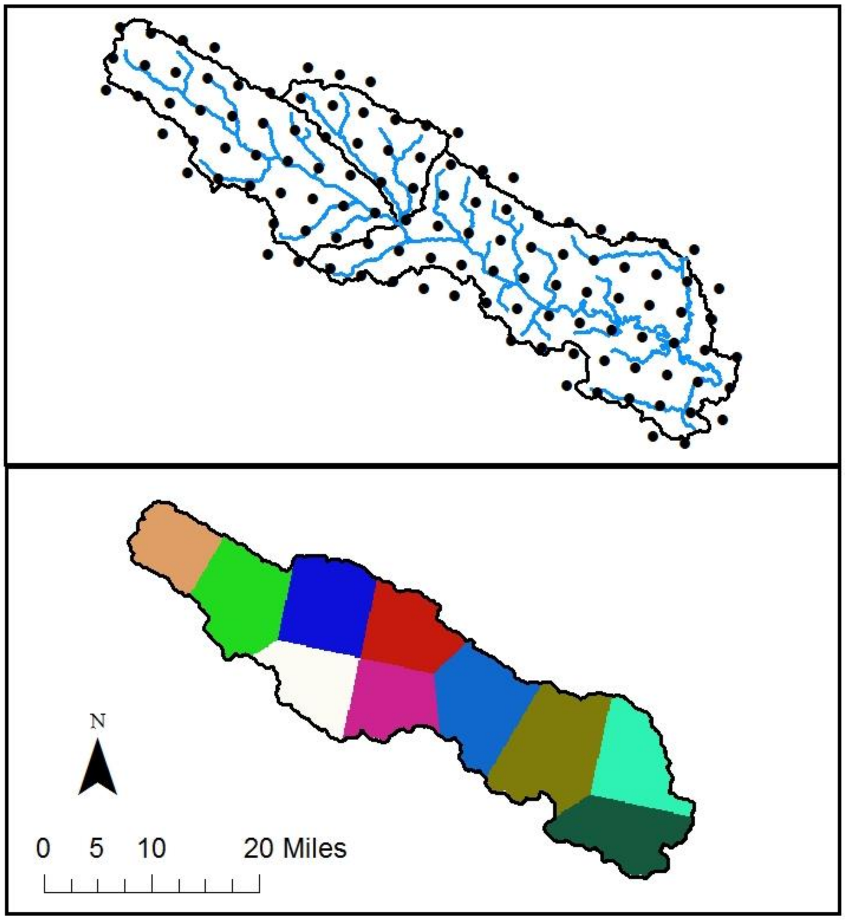

Figure 4.6: Top: Radar rainfall pixels over Cedar Creek watershed. Bottom: Aggregated rainfall zones.

4.5.2 Potential Evapotranspiration Data

Daily potential evapotranspiration (PET) data for the Cedar Creek watershed was obtained from the Iowa State University Soil Moisture (ISUSM) network station in Crawfordsville, Iowa (ISUSM CRF14). While this station is located outside of the Cedar Creek watershed boundary, as shown in Figure 4.7, it is the ISUSM PET station closest to the watershed. PET estimates have been measured for this station since January 1, 1988. The station was formerly operated under the Iowa State University Agricultural Climate network until 2013. A gap in the PET data at this site from April 1, 2014 to August 18, 2014 was filled using PET estimates derived from an application of the Penman-Monteith approach with weather data from Charles City, a city in eastern Iowa (Thomas, 2015).

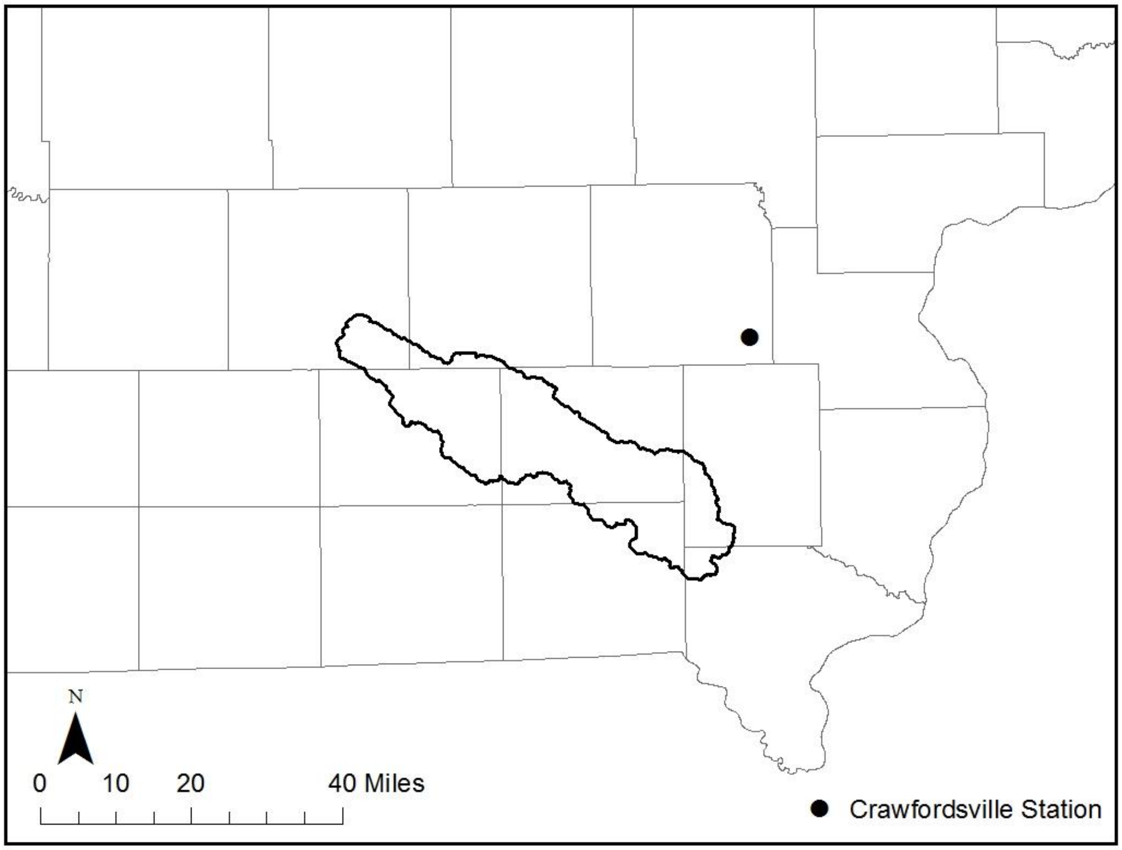

Figure 4.7: Crawfordsville, Iowa PET site (ISUSM CRF14)

The PET data inputs were modified to account for the impact of agriculture on evapotranspiration. This modification involved the application of a crop coefficient (K_c) to the daily PET estimate for surface grid cells with an agricultural land use type. The crop coefficient estimates were derived from the growing degree day base 50 method (HPRCC, 2015; Thomas,2015). The crop coefficient amplifies PET values during the growing season and reduces PET values during the remainder of the year, as shown in Figure 4.8. The crop coefficent chosen to apply to agricultural land use is the one estimated for corn. This application of the corn crop coefficient to agricultural watersheds in Iowa has been successfully used in other modeling projects (Thomas, 2015; Brauer, 2015).

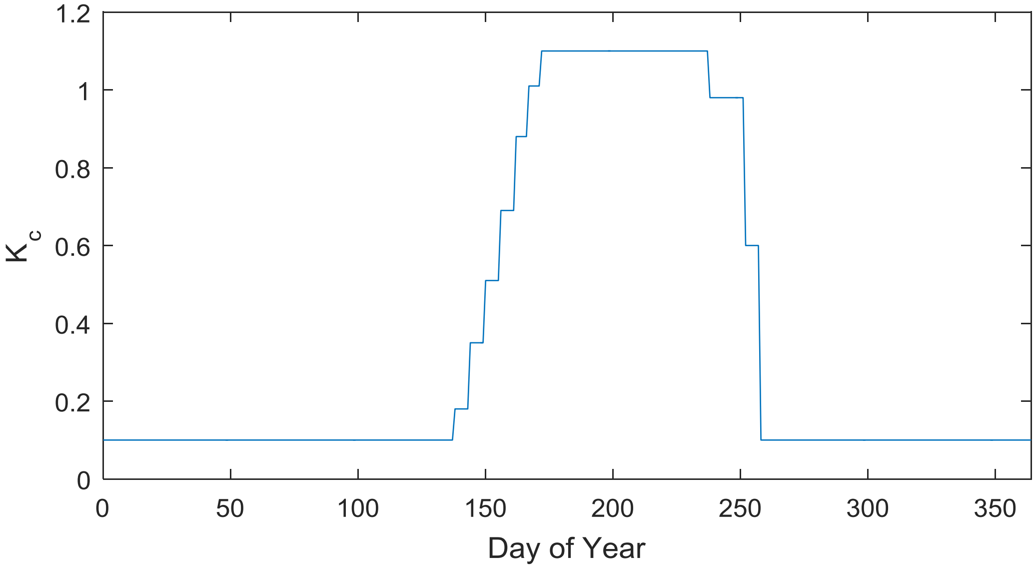

Figure 4.8: Crop coefficient over a year (Thomas, 2015)

4.6 Chapter Summary

MIKE SHE modeling software was used to create a coupled surface/subsurface, physically based, distributed hydrologic model of the Cedar Creek watershed. This model is defined by a rectangular surface computational grid that extends into the subsurface model domain. The upper boundary of the model is defined based on a high resolution surface DEM while the lower boundary of the model is defined to be a constant depth that is deep enough to ensure it does not impact relevant hydrological processes. The subsurface resolution of the model is defined such that there is high resolution near the surface and less resolution far from the surface. This model specification ensures that soil evaporation, transpiration and infiltration are properly simulated.

Physical properties of the watershed were then defined onto the computational model grid. Soil properties were defined in the unsaturated and saturated zones of the model based on SSURGO soil data for the watershed. Similarly, properties of an aquifer layer were defined for the saturated zone based on geological measurements. Subsurface drainage and macropores were also defined in the model. Surface properties of the watershed were defined based on land cover from the NLCD 2011.

Precipitation and PET model inputs were derived from Stage IV radar rainfall estimates and PET observations near the Cedar Creek watershed. Radar rainfall data was aggregated into ten zones within the watershed based on an arithmetic average of the rainfall time series for radar pixels within each zone. The PET data inputs were collected from an ISUSM site near the Cedar Creek watershed. The observations for agricultural areas in the watershed were adjusted using a time-varying crop coefficient.

CHAPTER 5: CEDAR CREEK MODEL CALIBRATION

5.1 Introduction

Despite the fact that physically based models are defined by measured physical properties of the watershed, some calibration of certain parameters is still needed. This calibration adjusts parameters within a reasonable range to ensure that the model accurately represents the way in which water moves throughout the watershed. For this project, the calibration involved running the model with known climatological inputs for several years and comparing the output with streamflow measurements. Model parameters were then adjusted to improve the match between the simulated and measured outlet hydrograph based on statistical efficiency tests. This iterative process was conducted until an appropriate simulated result was achieved. The calibration procedure for the Cedar Creek watershed, including the initial conditions used, and the final set of calibration parameters selected will be discussed in this chapter.

5.2 Development of Initial Conditions

The initial conditions for a model have a strong impact on simulated model results and the calibration process (Seck, Welty, & Maxwell, 2015). Unfortunately, the fully distributed state of a watershed at a given time would require a network of instruments that would pose a financial problem for most watershed modeling projects. While there are several instruments in the Cedar Creek watershed, there are not nearly enough to completely characterize the hydrologic state of the watershed at any given moment in time. There are several ways to initialize a hydrologic model without knowing the true initial conditions. The first method, used successfully by Brauer (2015) and Thomas (2015) in separate studies, involves starting with a fully saturated condition for the full watershed domain and simulating the same climatological forcing year after year until a convergence criteria has been met for the simulated results. A different method used by Seck et al. (2015) involves starting with an arbitrary initial condition and simulating several years using their measured climatological inputs. This spin-up period allows the model to shed any influence from the chosen initial conditions. The length of the spin-up period can be computationally expensive for some modeling approaches, but does offer a robust way to avoid the problem of developing initial conditions (Seck, Welty, & Maxwell, 2015).

The Seck approach was used for the development of initial conditions for the Cedar Creek model. The initial conditions for the 2007 model year were achieved by starting from a fully saturated condition in the watershed on January 1, 2003 and running the model with observed climatological forcings through the end of 2006. The USGS monitoring well and USGS stream gauge located within the watershed would provide a means for comparing simulation results to measurements. As mentioned in a previous chapter, the USGS monitoring well collected water table measurements from 2008 to 2014, as shown in Figure 5.1, and the USGS stream gauge has been collecting 15-minute resolution stream flow measurements since 2007 (USGS, 2017).

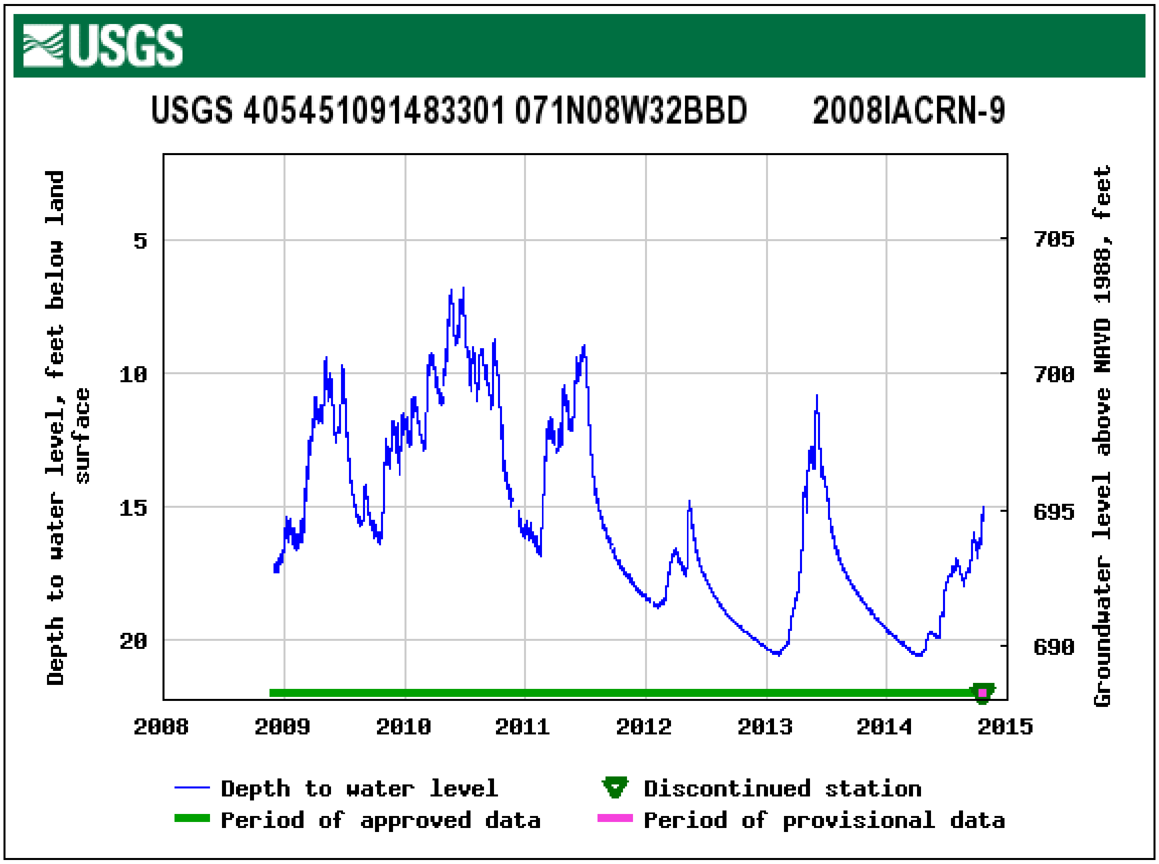

Figure 5.1: USGS groundwater well (USGS 405451091483301) full period of record (USGS, 2017)

Throughout the spin-up simulation, the water table depth at the point corresponding to the USGS groundwater well (USGS 405451091483301) was tracked in order to assess whether or not the model had been appropriately initialized. This assessment was made by ensuring that the spin-up period was long enough to remove any influence from the starting, fully saturated condition and by comparing the simulated water table depth to the measured water table depth at the USGS ground water well (USGS 405451091483301) location. This comparison, shown in Figure 5.2, was largely qualitative in nature and aimed to determine if the model was able to accurately depict the annual trends in the water table over the period of data collection at the USGS groundwater well. The simulation results between the years of 2008 and 2014 show that that model does represent the movement and trends in the water table in a sufficiently accurate way. While there are quantitative differences between measured and simulated water table depth values, the initialization was determined appropriate because uncertainty surrounding subsurface soil physical properties can impact the water table depth at a given point in time. However, by matching annual trends in the water table at a point in the watershed, the initialization shows that the model is no longer tied to its fully saturated beginnings and is ready for the calibration process.

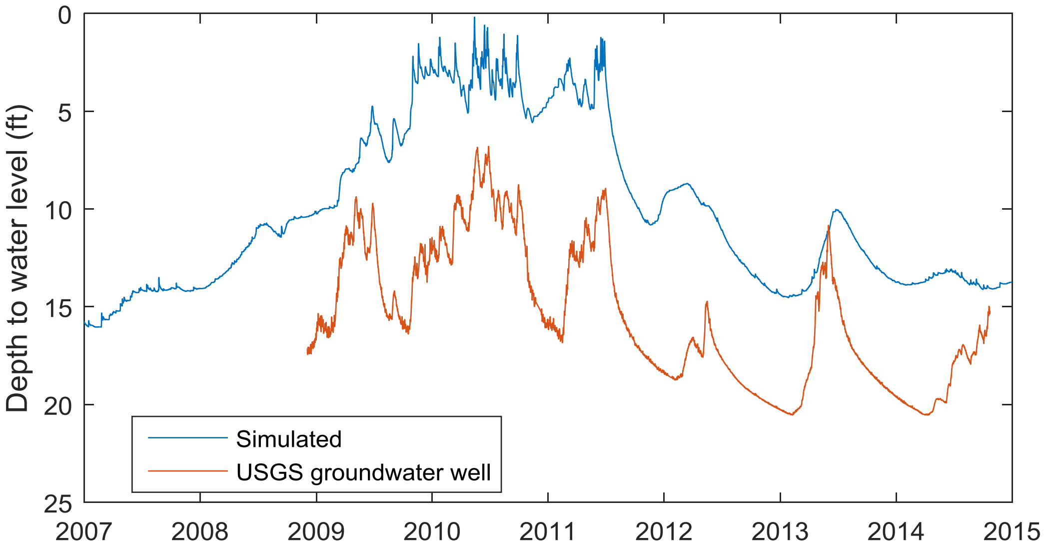

Figure 5.2: Simulated depth to water table compared with measurements at USGS groundwater well (USGS 405451091483301) (USGS, 2017)

5.3 Calibration Targets

Before the calibration process can begin, targets must be established for evaluating the success of the model in simulating natural processes and the impact of changes in the calibration parameters. These targets are tailored to the specific needs of the modeling project and are therefore not necessarily applicable to all types of models. For the Cedar Creek watershed model, the targets are based on annual measurements and hydrologic balances. Special attention is given to 2014, as this was determined to be an average hydrologic and climatological year. Calibration targets for the Cedar Creek watershed include annual ratios between hydrologic balance terms and statistical performance measures for simulated hydrographs.

Five different hydrologic balance ratios were used as targets for calibrating the Cedar Creek model. These include the ratio between annual discharge and annual precipitation (Q/P), annual evapotranspiration to annual precipitation (ET/P), annual evaporation to annual evapotranspiration (E/ET), annual transpiration to annual evapotranspiration (T/ET) and annual baseflow to annual discharge (Q_b/Q). Target values were determined based on examples found in the literature and analysis of measured data within the Cedar Creek watershed. The target value for the Q_b/Q ratio was determined using a hydrograph separation analysis performed on the full period of record for the USGS stream gauge (USGS 05473400) within the Cedar Creek watershed (Engel, 2004). The target for each ratio is shown in Table 5.1 below.

Table 5.1: Ratios of annual hydrologic balance components used in calibration process. Q is annual discharge, P is annual precipitation, ET is annual evapotranspiration, E is annual evaporation, T is annual transpiration and Q_b is annual baseflow.

Ratio	Target Value	Literature Values	Source
Q/P	0.35	0.35 0.24	Sanford & Selnick (2013) Schilling & Helmers (2008)
ET/P	0.65	0.65 0.76	Sanford & Selnick (2013) Schilling & Helmers (2008)
E/ET	0.30	0.26, 0.33 0.35, 0.23	Kang et al. (2003) Wang et al. (2013)
T/ET	0.70	0.74, 0.67 0.65, 0.77	Kang et al. (2003) Wang et al. (2013)
Q_b/Q	0.46	0.46	Engel (2004)

The USGS stream gauge (USGS 05473400) near the outlet of the Cedar Creek watershed makes it possible to perform statistical analyses that compare the simulated hydrograph with the measured one. For the Cedar Creek model, two statistical measures were used for the calibration process. The first measure is the Nash-Sutcliffe efficiency (NSE), a coefficient used specifically to assess the skill of hydrologic models (Nash & Sutcliffe, 1970). NSE values range from negative infinity to 1, with an NSE of 1 being a perfect model fit. The second measure is the percent bias (PBIAS), a coefficient that characterizes the tendency of a model to over or under predict relative to measured data (Gupta, Sorooshian, & Yapo, 1999). Positive PBIAS values indicate underestimation, negative values indicate overestimation and a value of 0 indicates no model bias. Target values for each measure were found in the literature and are shown in Table 5.2.

Table 5.2: Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) daily target values used in calibration process

Coefficient	Target Value	Literature Values	Source
NSE	0.50	> 0.50	Moriasi et al. (2015)
PBIAS	±15%	< ±15%	Moriasi et al. (2015)

5.4 Calibration of Parameters

Using the sufficiently initialized model, certain model parameters were adjusted in order to achieve model results that meet the relevant calibration targets. The hydrologic calibration involved running the model from 2003 through 2014 using a fully saturated starting condition. Simulation results were compared to hydrologic balance ratio targets and hydrograph efficiency parameters for year 2014. Based on this comparison, certain model properties were adjusted to improve the accuracy of the model. These calibration parameters included the subsurface hydraulic conductivity, subsurface drainage density, subsurface macropores and evapotranspiration parameters. An iterative process was used where properties were incrementally adjusted, building on the improvement in model accuracy gained from the previous iteration.

5.4.1 Evapotranspiration Parameters

The Kristensen Jenson evapotranspiration parameters impact the amount of evaporation and transpiration that occurs for the watershed. These four MIKE SHE model parameters, C1, C2, C3 and Aroot, must be calibrated in order to replicate the expected evapotranspiration properties for the Cedar Creek watershed (Kristensen & Jensen, 1975). For this reason, when calibrating these parameters, only the hydrologic ratios were considered. Several initial qualitative simulation trials were conducted to determine how significantly the four different parameters affected model outputs. After these tests, three sets of the Kristensen Jensen parameters were chosen for assessment as part of the calibration process. These parameter sets are shown in Table 5.3 below.

Table 5.3: Kistensen Jensen parameters used in the calibration process

Parameter	Set 1	Set 2	Set 3
C1 (-)	0.9	0.7	0.5
C2 (-)	0	0	0
C3 (mm/day)	20	20	20
Aroot (1/m)	0.25	0.25	0.25

The results of these calibration simulations showed that increasing C1 increased the amount of transpiration in the watershed without significantly impacting the amount of evaporation. This increase results in an increase in the amount of evapotranspiration relative to precipitation. The hydrologic ratios resulting from these simulations for 2014 are shown in Table 5.4.

Table 5.4: Results from the Kristensen Jensen parameter calibration simulations. The results from calibration set 3 were determined to be the best based on the ET/P calibration target for the 2014 simulated year.

Ratio	Target	Set 1	Set 2	Set 3
Q/P	0.35	0.21	0.21	0.22
ET/P	0.65	0.76	0.75	0.72
E/ET	0.30	0.40	0.44	0.48
T/ET	0.70	0.60	0.56	0.52
Q_b/Q	0.46	0.51	0.51	0.50

5.4.2 Subsurface Parameters

The properties defined in the subsurface model impact the movement of water through the soil and the interaction of soil water with the river network. The presence of subsurface drainage, macropores and the hydraulic conductivity are the three subsurface parameters calibrated in order for the Cedar Creek model to replicate measured stream flow and hydrologic ratios. Three sets of subsurface parameters were chosen for testing as part of the calibration process, as outlined in Table 5.5. In order to define the subsurface drainage properties, the spatial extent, drainage depth and drainage time constant must be determined. For calibration parameters sets that included subsurface drainage the spatial extent was chosen to be the full watershed domain due to the fact that 77% of the watershed area had an agricultural land use (Homer, et al., 2015). The depth and time constant for these sets was chosen to be 1 meter and the default value of 1 x 10^{-7} s^{-1} respectively. For calibration parameter sets that included macropores, the MIKE SHE simple by-pass flow method was chosen.

While the vertical hydraulic conductivity was defined based on the surface soil properties given by the SSURGO soil data for the Cedar Creek watershed, the horizontal hydraulic conductivity was not explicitly defined (Soil Survey Staff, NRCS, USDA, 2015). For some parameter sets, the horizontal hydraulic conductivity was assumed to be the same as the vertical hydraulic conductivity. For calibration set 4, the horizontal hydraulic conductivity was increased by an order of magnitude, an increase that literature has shown to be reasonable (Chen, 2000).

Table 5.5: Subsurface parameters used in the calibration process

Component	Set 4	Set 5	Set 6
Subsurface drainage	Excluded	Included	Included
Macropores	Excluded	Excluded	Included
Horizontal hydraulic conductivity	K_h increased by factor of 10	No change	No change

The results of these calibration simulations show that including subsurface drainage and macropores in the manner outlined above improves the skill of the model in simulating discharge. These attributes tend to underestimate baseflow, as it is reported by MIKE SHE, when used without altering the horizontal hydraulic conductivity. The hydrologic ratios and hydrograph fit coefficients from these three calibration simulations are shown in Table 5.6 and Table 5.7 below.

Table 5.6: Results from the subsurface parameter calibration simulations. The results show that there are modest differences between the calibration sets based on hydrologic ratio targets.

Ratio	Target	Set 4	Set 5	Set 6
Q/P	0.35	0.28	0.25	0.25
ET/P	0.65	0.63	0.64	0.63
E/ET	0.30	0.35	0.33	0.34
T/ET	0.70	0.65	0.67	0.66
Q_b/Q	0.46	0.36	0.27	0.28

Table 5.7: Detailed results from the subsurface parameter calibration simulations. The results show that calibration set 6 had the most skill in simulating discharge based on NSE and PBIAS values for the 2014 simulated year.

Coefficient	Target	Set 4	Set 5	Set 6
NSE	0.50	0.52	0.52	0.55
PBIAS	15%	4.6%	4.0%	3.9%

5.5 Calibrated Model Performance

After the calibration process was finished, final parameter properties were chosen and the performance of the calibrated model was evaluated. The final parameter properties were chosen based on the results of the evapotranspiration calibration and subsurface calibration trials. Parameter sets that resulted in high NSE values and PBIAS values close to zero were more desirable than those that produced relatively weaker NSE and PBIAS values but resulted in hydrologic ratios closer to the calibration targets. These calibrated Kristensen Jensen evapotranspiration properties are summarized in Table 5.8 below. The properties of the subsurface calibration parameters are shown in Table 5.9 and Table 5.10. The final macropore parameterization chosen to be used in the Cedar Creek model is the simple by-pass flow method.

Table 5.8: Final evapotranspiration calibration parameter values used in Cedar Creek model

Kristensen Jensen parameters	Calibrated values
C1 (-)	0.5
C2 (-)	0
C3 (mm/day)	20
Aroot (1/m)	0.25

Table 5.9: Final subsurface drainage properties used in Cedar Creek model

Subsurface drainage property	Parameter value
Spatial extent	Full domain
Depth	1 m
Time constant	1 x 10^{-7} s^{-1}

Table 5.10: Final hydraulic conductivity values used in Cedar Creek model

Soil Type	Horizontal Hydraulic Conductivity (m/s)	Vertical Hydraulic Conductivity (m/s)
Silty clay loam	$1.29\text{x}10^{-6}$	$1.29\text{x}10^{-6}$
Silty loam	$2.11\text{x}10^{-6}$	$2.11\text{x}10^{-6}$
Loam	$1.39\text{x}10^{-6}$	$1.39\text{x}10^{-6}$
Clay loam	$9.47\text{x}10^{-7}$	$9.47\text{x}10^{-7}$
Fine sandy loam	$4.43\text{x}10^{-6}$	$4.43\text{x}10^{-6}$
Loamy fine sand	$1.22\text{x}10^{-5}$	$1.22\text{x}10^{-5}$
Loamy sand	$1.22\text{x}10^{-5}$	$1.22\text{x}10^{-5}$
Sandy loam	$4.43\text{x}10^{-6}$	$4.43\text{x}10^{-6}$
Stream (Sand)	$7.44\text{x}10^{-5}$	$7.44\text{x}10^{-5}$

The calibrated model's performance was evaluated over the period for which high resolution stream flow data was being collected at the USGS stream gauge on Cedar Creek near Oakland Mills, Iowa. This period includes the years of 2007 through 2014. The hydrologic ratios, NSE and PBIAS values for these simulated years are shown in Table 5.11 below. The measured and simulated hydrographs for each year at the location of the USGS stream gauge are shown in Figure 5.3 through Figure 5.10.

Table 5.11: Calibrated model hydrologic ratios, NSE and PBIAS. Model results show that average hydrologic ratios for the 8 simulated years are similar to target values and average NSE and PBIAS exceed target values.

Year	Q/P	ET/P	E/ET	T/ET	Q_b/Q	NSE	PBIAS
2007	0.31	0.58	0.32	0.68	0.23	0.74	-29.1%
2008	0.41	0.53	0.37	0.63	0.27	0.48	13.9%
2009	0.48	0.48	0.38	0.62	0.26	0.58	3.7%
2010	0.54	0.45	0.48	0.52	0.26	0.48	24.4%
2011	0.46	0.67	0.33	0.67	0.30	0.59	-7.7%
2012	0.21	1.09	0.26	0.74	0.37	0.41	-156.3%
2013	0.27	0.65	0.27	0.73	0.26	0.47	33.4%
2014	0.25	0.63	0.34	0.66	0.28	0.55	3.9%
Average	**0.37**	**0.64**	**0.34**	**0.66**	**0.28**	**0.54**	**-14.2%**
Target	**0.35**	**0.65**	**0.30**	**0.70**	**0.46**	**0.50**	**±15%**

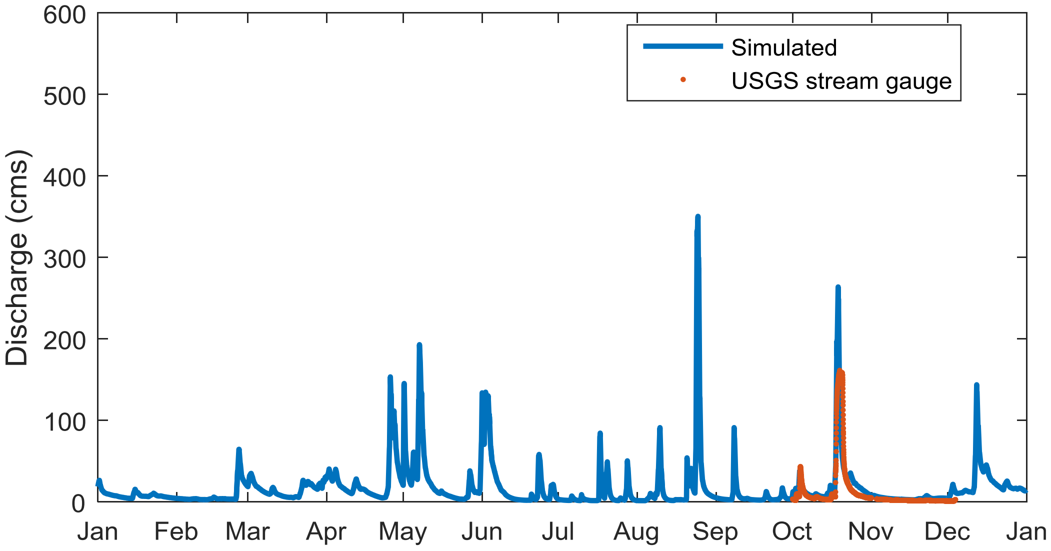

Figure 5.3: 2007 hydrograph comparison (NSE = 0.74, PBIAS = -29%)

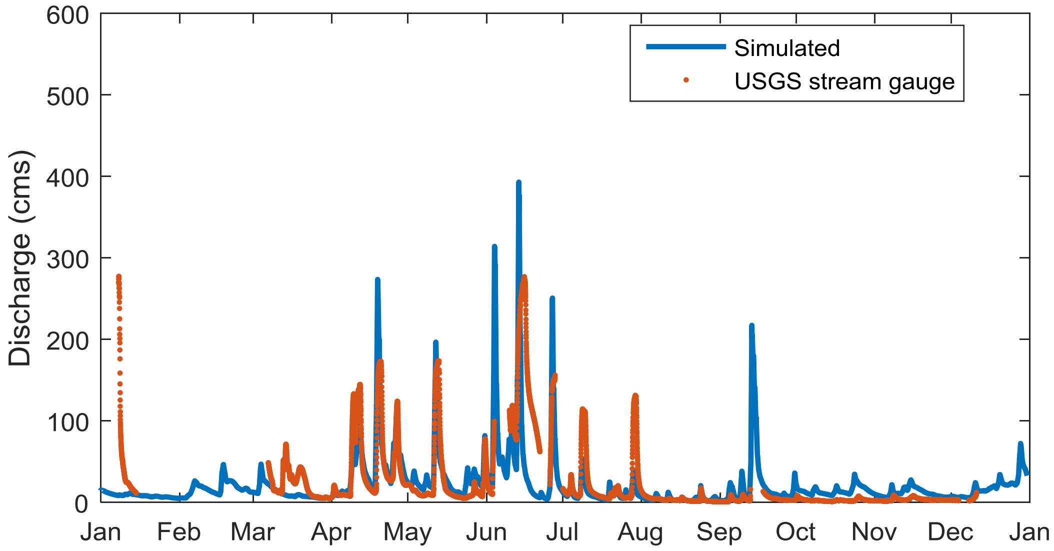

Figure 5.4: 2008 hydrograph comparison (NSE = 0.48, PBIAS = 14%)

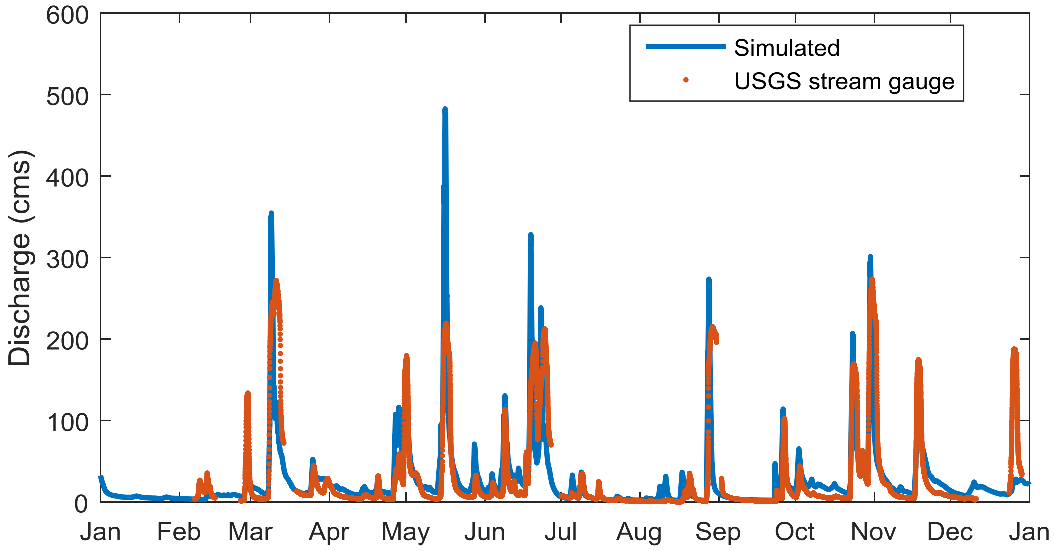

Figure 5.5: 2009 hydrograph comparison (NSE = 0.58, PBIAS = 4%)

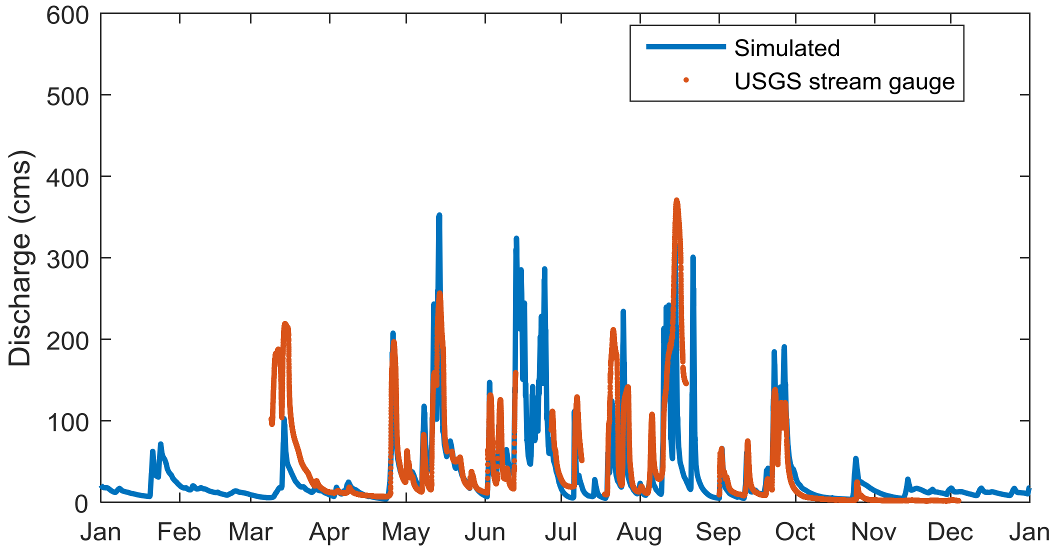

Figure 5.6: 2010 hydrograph comparison (NSE = 0.48, PBIAS = 24%)

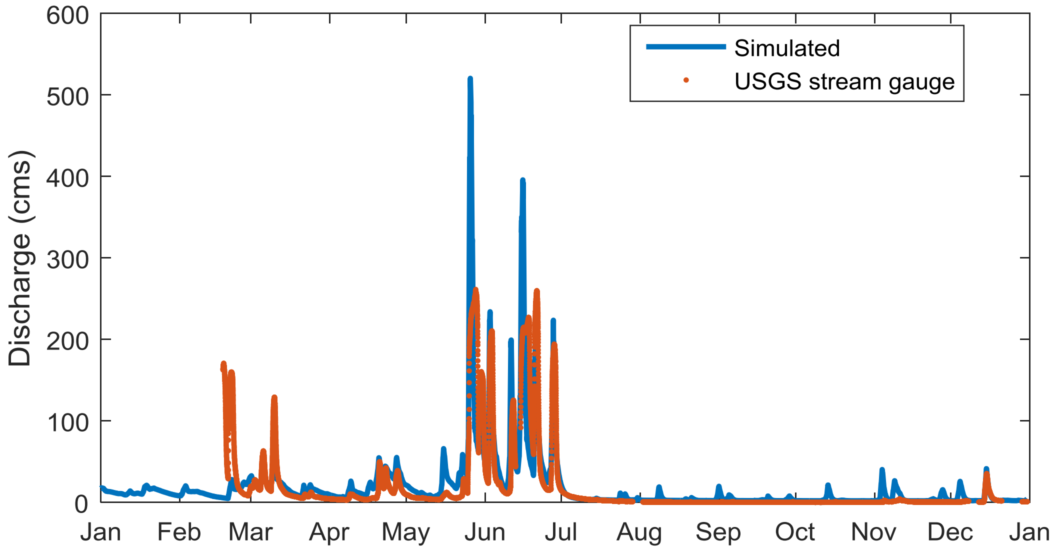

Figure 5.7: 2011 hydrograph comparison (NSE = 0.59, PBIAS = -8%)

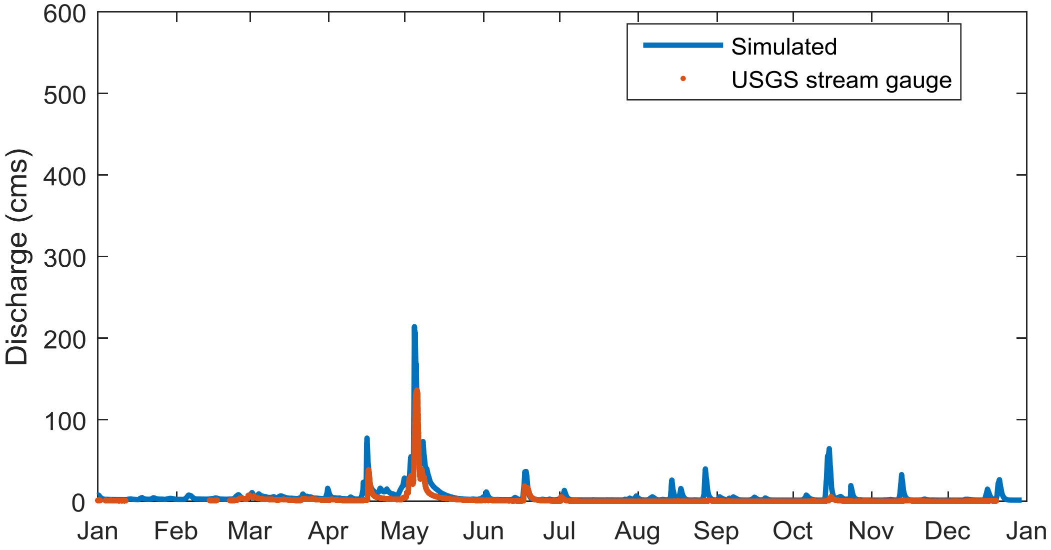

Figure 5.8: 2012 hydrograph comparison (NSE = 0.41, PBIAS = -156%)

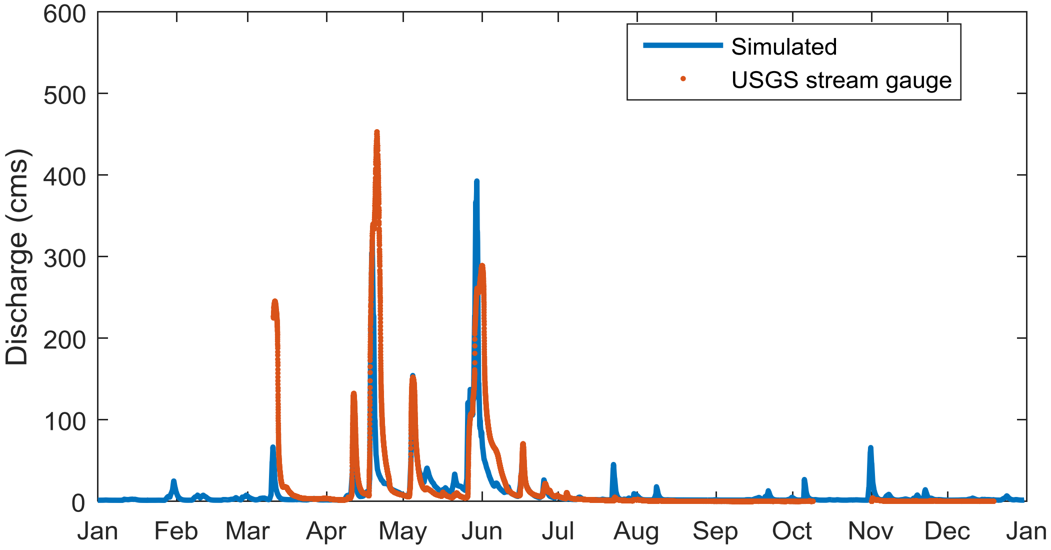

Figure 5.9: 2013 hydrograph comparison (NSE = 0.47, PBIAS = 33%)

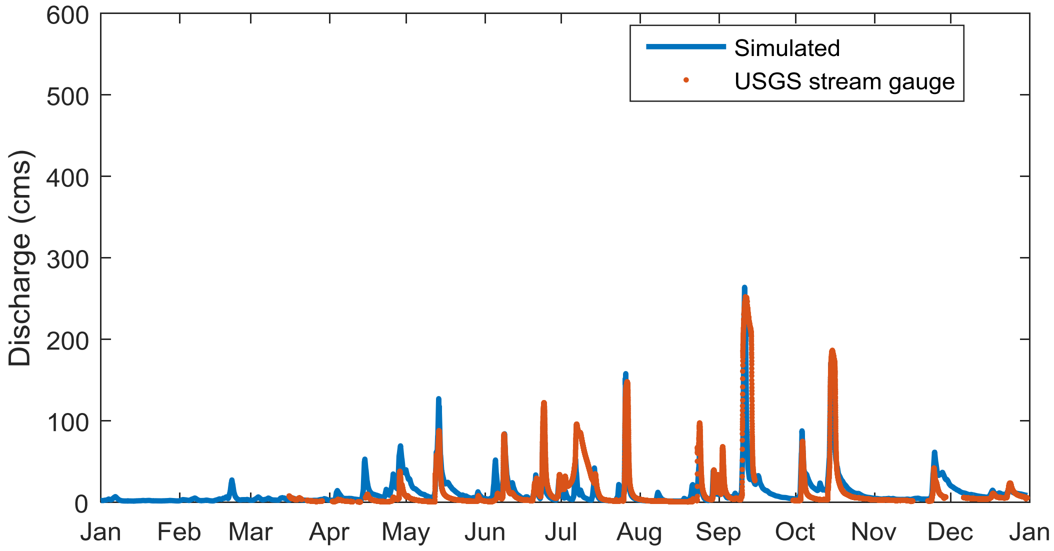

Figure 5.10: 2014 hydrograph comparison (NSE = 0.55, PBIAS = 4%)

5.6 Chapter Summary

The calibration of certain parameters within the Cedar Creek model ensured that the model best represented natural watershed responses and hydrologic properties. Before beginning the calibration process, adequate initial conditions for the model needed to be achieved. The initial conditions for the model were developed by starting from a fully saturated state and applying measured climatological forcings for the years of 2003 through 2006. Model outputs regarding water table depth were compared to measurements from the USGS monitoring well in order to determine when the model began to respond in a qualitatively similar way. The length of the initialization period ensured that influence of the fully saturated beginning was minimized and the comparison to measured data

Using these initial conditions for the Cedar Creek model, certain parameters were calibrated to improve the skill of the model in replicating expected annual hydrologic ratios and measured hydrographs. The calibration parameters included the Kristensen Jensen evapotranspiration parameters, the presence and density of subsurface drainage, the presence of macropores, and horizontal hydraulic conductivity. Several different sets of these parameters were used in model simulations in order to determine how each parameter affected the model outputs and which set achieved the calibration targets. The hydrologic ratios used as calibration targets included the ratio between annual discharge and annual precipitation (Q/P), annual evapotranspiration to annual precipitation (ET/P), annual evaporation to annual evapotranspiration (E/ET), annual transpiration to annual evapotranspiration (T/ET) and annual baseflow to annual discharge (Q_b/Q). In addition to these ratios, the NSE and PBIAS were computed using measured stream flow from the USGS stream gauge on Cedar Creek near Oakland Mills, Iowa.

The calibration process selected the single set of parameters that best represented the behavior of the Cedar Creek watershed. Each calibration target was met, or exceeded, by the final, calibrated Cedar Creek model. This hydrologically calibrated model will be used to investigate different water quality scenarios and improve the understanding of how nitrate moves within the watershed.

CHAPTER 6: SIMULATED WATER QUALITY SCENARIOS

6.1 Introduction

After calibration and evaluation, the Cedar Creek model was used to investigate different water quality scenarios. These simulated scenarios were chosen in order to determine the most appropriate way to simulate in-stream nitrate concentration for a watershed using the tools within the MIKE SHE model framework. Water quality simulation goals were the same for each scenario, relying on comparisons to measured concentration. The five scenarios developed for this project intend to provide a conceptually simple description of how nitrate moves through a watershed that accurately predicts nitrate concentration in the stream at sub-hourly and monthly time scales.

The first three water quality scenarios that were simulated focused on comparison to the real time nitrate concentration data collected by the IIHR water quality sensor on Cedar Creek in 2016. A simplified scenario uses the existing Cedar Creek model’s grid to specify water quality properties throughout the watershed. The next scenario uses a similar approach with a higher resolution subsurface grid. A recursive hydrologic forcing scenario is then investigated as an alternative way to initialize the water quality scenarios.

The next two water quality scenarios focused on the skill of the Cedar Creek model in predicting monthly nitrate concentrations in Cedar Creek measured as part of the Iowa DNR ambient stream monitoring network. The first of these scenarios uses a conceptualization similar to the one used in the recursive hydrologic forcing scenario applied to a longer time period. The final water quality scenario applies a time-varying water quality conceptualization to a longer time period. Each of these scenarios will be described in the following sections of this chapter.

Each water quality scenario developed for this study uses the hydrologic results generated by the calibrated Cedar Creek model. The water quality scenarios were selected through a process of iterative corrections and improvements based on simulated results and revelations regarding the ways in which the construction of the Cedar Creek model was affecting the movement of nitrate within the watershed.

6.2 Water Quality Simulation Targets

In executing each water quality scenario, it is important to understand what makes one scenario more successful than another. The development of water quality scenarios was undertaken with the qualitative goal of using a conceptualization of how nitrate is distributed within the Cedar Creek watershed that is as simple as possible. Each scenario was chosen to add a layer of complexity onto the previous one based on the perceived, and measured, shortfalls of that scenario. The performance of a water quality scenario is evaluated using NSE to measure skill, PBIAS to measure bias and correlation coefficient squared (R^2) to measure potential skill. For nitrate data, monthly averaged values were used to compute all three coefficients (Moriasi, Gitau, & Daggupati, 2015). The target values for this analysis are shown in Table 6.1. For scenarios focusing on 2016, simulated results were compared to the 15-minute resolution nitrate concentration measurements collected by the IIHR water quality sensor location midway through the Cedar Creek watershed, as shown in Figure 2.7. For scenarios focusing on historical nitrate concentrations, simulated results were compared to the monthly nitrate concentration measurements collected at the same location as the USGS stream gauge on Cedar Creek near Oakland Mills, Iowa as part of the Iowa DNR ambient stream monitoring program.

Table 6.1: Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) monthly target values used in water quality calibration process

Coefficient	Target Value	Literature Values	Source
NSE	0.35	> 0.35	Moriasi et al. (2015)
PBIAS	$\pm$30%	< $\pm$30%	Moriasi et al. (2015)
R^2	0.30	> 0.30	Moriasi et al. (2015)

6.3 Scenario 1: Simplified Conceptualization

The first water quality scenario tested the limits to which a simple model can replicate the complex processes that deliver nitrate from the soil to the stream. The model used to execute this water quality scenario was derived from the calibrated hydrologic model of Cedar Creek discussed in the previous chapter. The goal of this scenario was to replicate the high resolution nitrate concentration data measured by the IIHR water quality sensor on Cedar Creek. Due to the fact that this sensor is located at the confluence of Competine Creek and Cedar Creek, the watershed boundary for the model of this scenario was defined to be the boundary of the

Competine Creek (0708010705) and Headwaters Cedar Creek (0708010706) only. This sub watershed boundary and its corresponding modeled stream network are shown in Figure 6.1 below. The surface grid, subsurface grid and all vertical boundaries were not altered relative to the original Cedar Creek model's development.

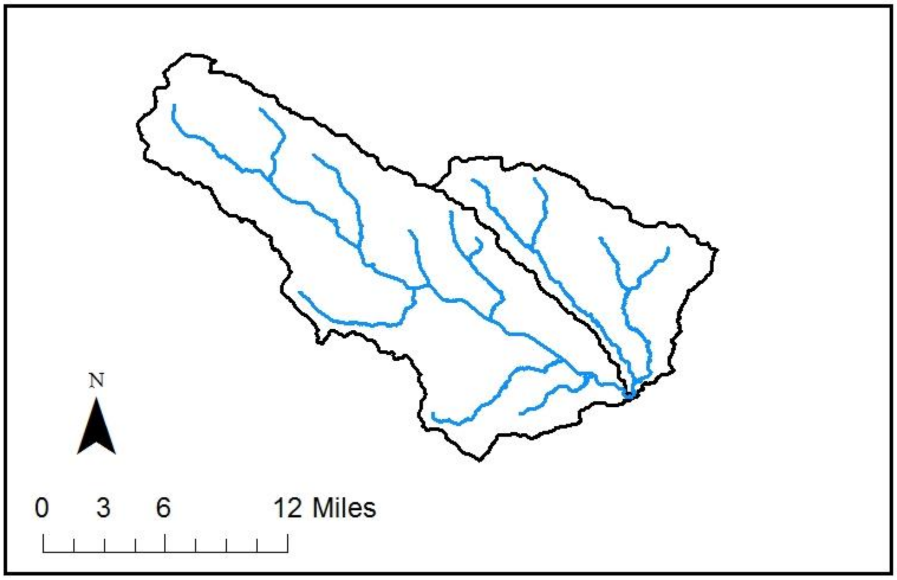

Figure 6.1: Simplified water quality conceptualization scenario watershed boundary and stream network

The model properties used for this scenario are identical to those used in the hydrologically calibrated model except for the addition of the water quality advection/dispersion module in MIKE SHE. This water quality module was activated in the overland flow component, the unsaturated zone component, the saturated zone component and the MIKE 11 stream network. No water quality processes were included in the water quality module. The single species defined, nitrate, was allowed only to advect from the watershed surface, through the soil, into the stream network and out of the watershed. Nitrate was not allowed to leave the soil through the process of transpiration. In the subsurface domain, two zones of fixed nitrate concentration were specified as sources of the nutrient. The zones were only defined for regions within the model domain that were at least 400 meters away from the modeled stream network. This allowed for a mixing zone in the soil adjacent to the stream. This region is shown in Figure 6.2 below. In the unsaturated zone, the meter just below the surface is fixed at 50 mg nitrate / L. In the saturated zone, from 20 meters below the surface to the lower model boundary the concentration is fixed at 1 mg nitrate / L. The concentration values in these two subsurface zones were chosen based on soil nitrate concentration measurements taken in Nashua, Iowa, shown in Figure 6.3 (Malone, et al., 2014). It is important to note that due to the fact that the saturated zone is defined to exist below the water table, the fixed concentration in the unsaturated zone will apply from the surface to the water table when the water table is at, or above, a 1 meter depth. A fixed concentration of 1 mg nitrate / L was also prescribed to all precipitation.

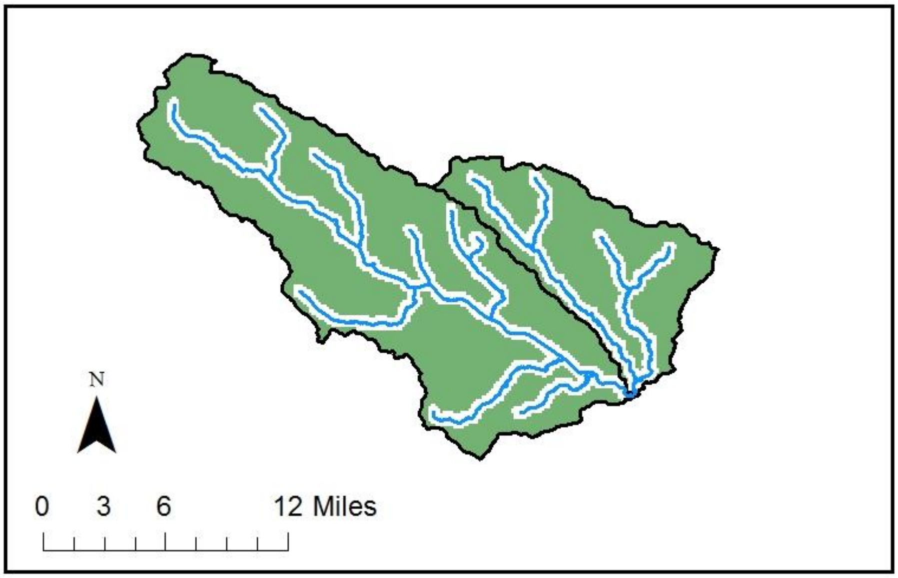

Figure 6.2: Region of model domain where zones of fixed nitrate concentration were defined (shown in green)

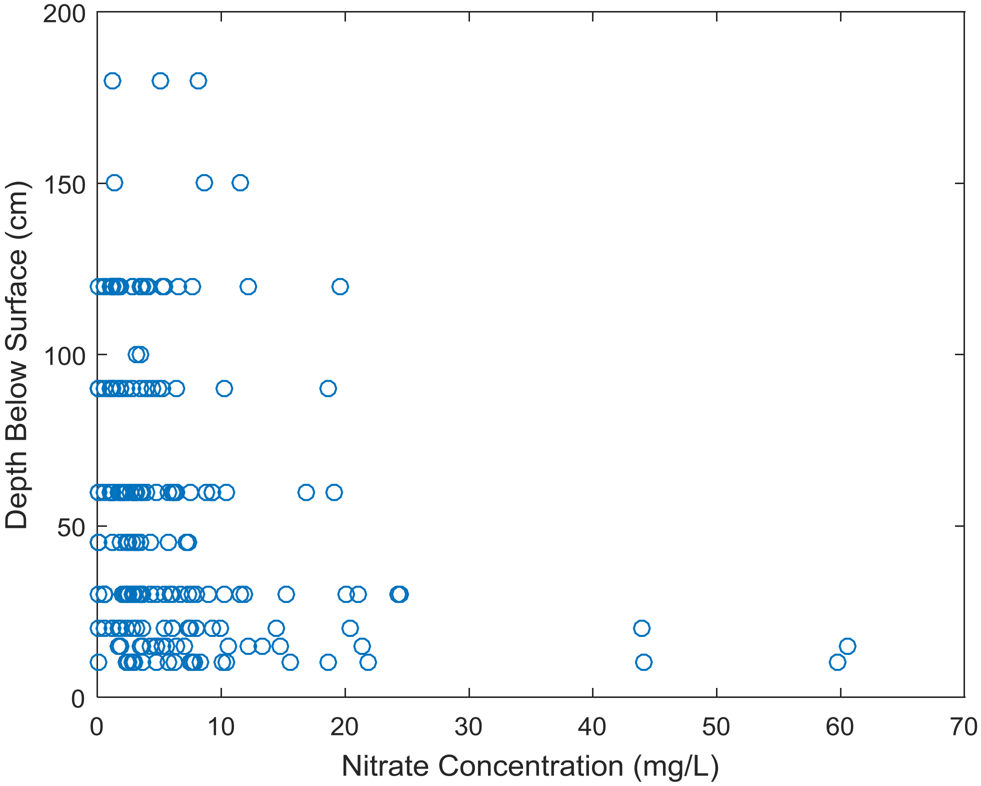

Figure 6.3: Nitrate depth concentration profile measured in Nashua, Iowa (Malone, et al., 2014)

In order to simulate the nitrate concentration in 2016 properly, the Cedar Creek model for this scenario had to be initialized. The scenario simulation was started on January 1, 2015 with an initial concentration of 1 mg/L at all locations in the subsurface, an initial in-stream concentration of 0.33 mg/L and no initial nitrate on the surface. The initial in-stream concentration was selected as an estimated baseline concentration observed from the 2016 data collected by the IIHR water quality sensor on Cedar Creek. The zones of fixed concentration were initiated immediately after the simulation began. The simplified water quality conceptualization scenario model was run through the end of 2016. The simulated and measured in-stream concentration at the IIHR water quality sensor location are shown in Figure 6.4.

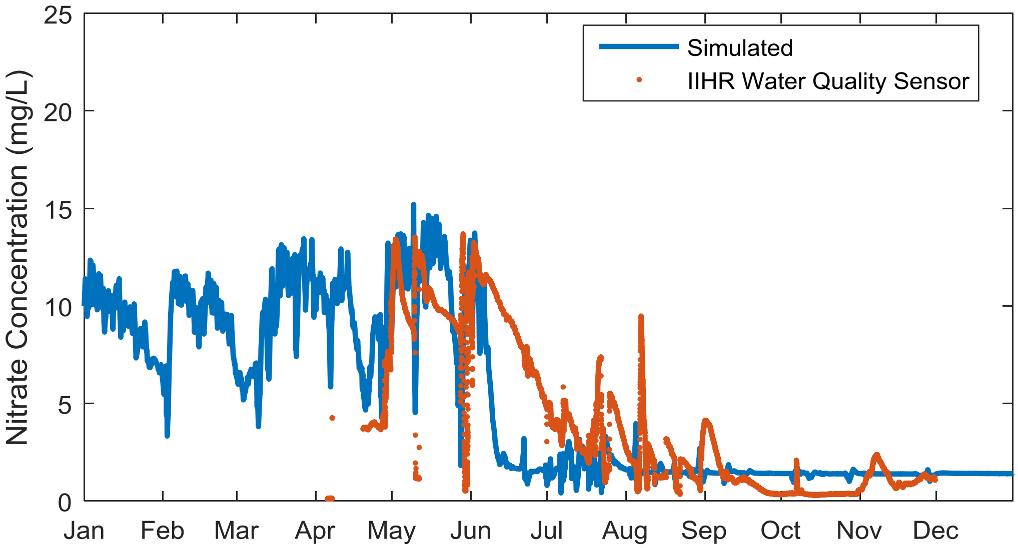

Figure 6.4: 2016 nitrate concentration comparison for simplified water quality conceptualization scenario (NSE = 0.62, PBIAS = 17%, R^2 = 0.67)

The simulation results show that the model has success in predicting monthly average nitrate concentration due to the fact that the NSE of 0.62, PBIAS of 17% and R^2 of 0.67 all exceed water quality simulation targets. However, there are two key features of the simulated nitrate concentration that show problems with the simplified conceptualization. The first feature is the sharp reduction of concentration during the month of June 2016. Over this month, the simulated concentration failed to replicate the gradual reduction in concentration from approximately 14 mg/L to 5 mg/L. This sharp simulated reduction is due to the fact that after the simulated water table drops below a depth of 1 meter the subsurface drainage is no longer delivering water with high concentration to the stream. Instead, the water originating in the 50 mg/L zone must pass through the saturated zone before it reaches the stream, becoming diluted in the process. This property of the saturated and unsaturated zones as defined by MIKE SHE does not pose a significant problem hydrologically but does pose a problem when considering water quality simulations.

The second feature that implies a fundamental problem in the conceptualization is the relative unresponsiveness in the second half of 2016. This issue is caused by the lack of resolution in the saturated zone. Based on the Cedar Creek model properties, there are two computational cells below the water table in each surface grid cell. This was a sufficient resolution for the hydrologic calibration but is not a sufficient resolution for water quality simulations. The two computational cells are, on average, 50 meters thick. Effectively, the water below the water table is restricted to a uniform value. Due to the fact that the concentration in the soil was fixed at 1 mg/L from 20 meters below the surface to the lower boundary, this uniform value is approximately 1 mg/L. This lack of resolution limits the ability of the subsurface model to develop a natural concentration depth profile in the soil and exhibit a range of concentration values when the water table is below the subsurface drainage.

6.4 Scenario 2: Higher Subsurface Resolution

The second water quality scenario was developed to address the resolution problem in the saturated zone component of the Cedar Creek model. As with the first water quality scenario, the goal of the second scenario was to replicate the high resolution nitrate concentration data measured by the IIHR water quality sensor on Cedar Creek. The model used to execute this scenario had the same construction and properties as the one used in the previous scenario with the exception of the saturated zone computational resolution and subsurface fixed concentration zones. For this scenario, the number of computational layers in the saturated zone was increased from two to nine. The layers were spaced closely near the surface and farther apart deeper in the saturated zone, following a vertical resolution similar to the one used in a different MIKE SHE water quality modeling study (Christierson, et al., 2015). In this higher resolution Cedar Creek model, a zone of 20 mg/L was fixed from the surface down to 1 meter in the unsaturated zone in the same buffered region shown in Figure 6.2. No zones of fixed concentration were used in the saturated zone of the model for this scenario. As before, a fixed concentration of 1 mg/L was prescribed to all precipitation.

Due to the fact that a new subsurface grid was defined for this scenario, new hydrologic results were produced for the evaluation period of 2007 through 2014. The results from this higher resolution Cedar Creek model had slight differences with the original calibrated Cedar Creek model but still satisfied all calibration targets. A summary of the higher resolution Cedar Creek model performance can be found in the Appendix. The simulation for this scenario was initialized following the same procedure as the previous scenario. The simulated nitrate concentration for this scenario and the measured in-stream concentration at the IIHR water quality sensor are shown in Figure 6.5.

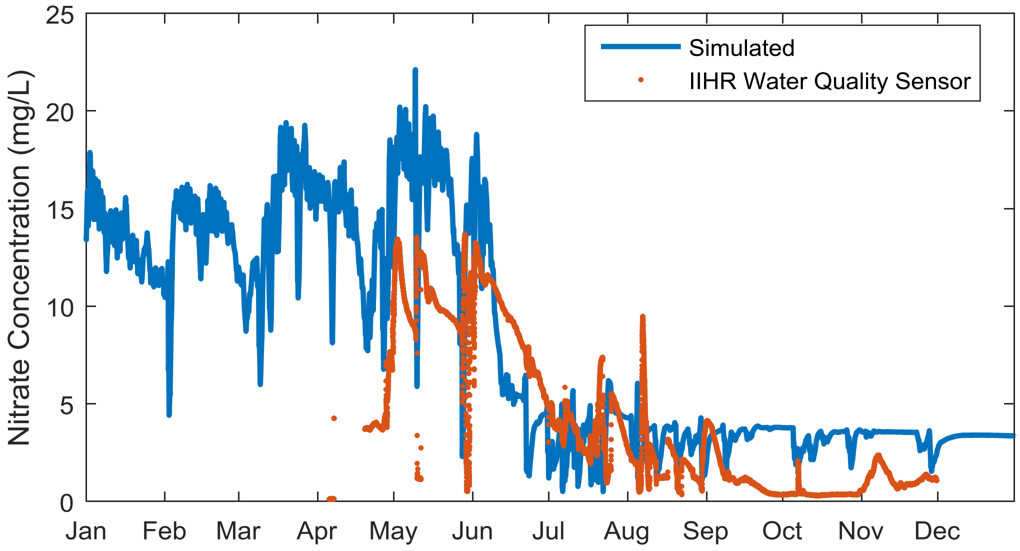

Figure 6.5: 2016 nitrate concentration comparison for higher resolution subsurface scenario (NSE = 0.34, PBIAS = -45%, R^2 = 0.73)

The simulation results for this scenario indicate that this model formulation has less skill in predicting monthly average nitrate concentration compared to the first water quality scenario due to the fact that the NSE of 0.34 and PBIAS of -45% do not meet simulation targets. The potential skill, as measured by the R^2 of 0.73, indicates this model scenario has a higher potential skill than the previous scenario. Qualitatively, this scenario does replicate the response of in-stream nitrate concentration more successfully during the second half of the year. This is a result of the fact that the higher resolution of computational layers in the saturated allows for a more natural vertical nitrate concentration profile in the soil. The simulated nitrate concentration profile, an example of which is shown in Figure 6.6, produces a wider range of nitrate concentrations during periods for which the water table is below the subsurface drainage layer. These results indicate that high concentration penetrates only the top 2 meters of the subsurface and that a longer simulation period could lead to a concentration profile that matches the measured concentration profile more closely.

An important feature of the results from the high resolution subsurface scenario is the sharp reduction in concentration during the month of June. This feature is similar to the one found in the results of the first scenario. The sharp reduction in concentration is caused by the inherent properties of subsurface drainage in the MIKE SHE modeling framework, as outlined in the previous section. The scenarios outlined in the following sections will test potential solutions to this issue by supplying more nitrate into the subsurface in an attempt to increase the concentration of in-stream nitrate during periods where the water table is below the subsurface drainage.

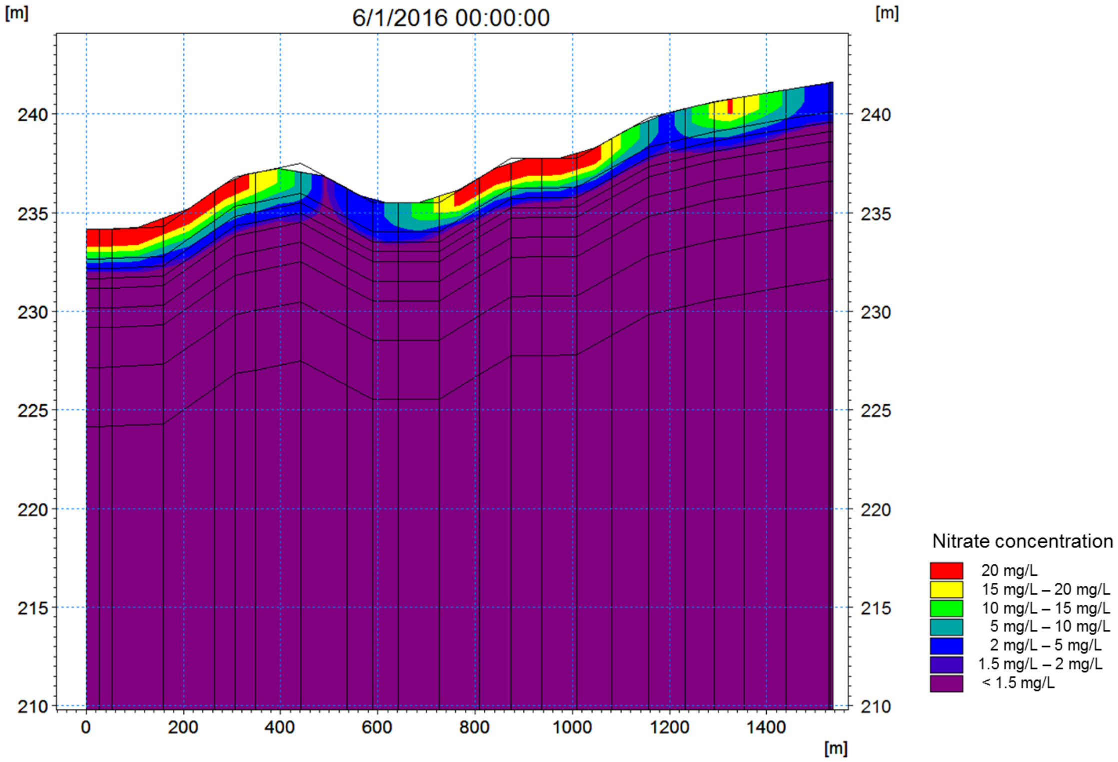

Figure 6.6: Vertical nitrate concentration profile on June 1, 2016 extracted near the outlet of the model watershed. Computational grid shown over simulated concentration.

6.5 Scenario 3: Recursive Hydrologic Forcing

In order to address the lack of a fully developed vertical nitrate concentration profile in previous scenarios, a recursive water quality scenario using 2016 hydrologic and climatological forcings was developed. The properties of the model used for this scenario were identical to those used in the previous water quality scenario except for the definition of the zone of fixed concentration. In the model used to simulate the recursive forcing of 2016, a zone of 50 mg/L was fixed from the surface down to 0.25 meters in the unsaturated zone. As before, a fixed concentration of 1 mg/L was prescribed to all precipitation. The simulation for this scenario was initialized following the same procedure used with previous scenarios. After initialization, a simulation using 2016 forcing was run recursively for three years. The duration of three years was chosen because, including the initialization, the simulated scenario would be twice as long as the previous two scenarios. The simulated nitrate concentration for the final year of the recursive forcing scenario and the measured in-stream concentration at the IIHR water quality sensor are shown in Figure 6.7.

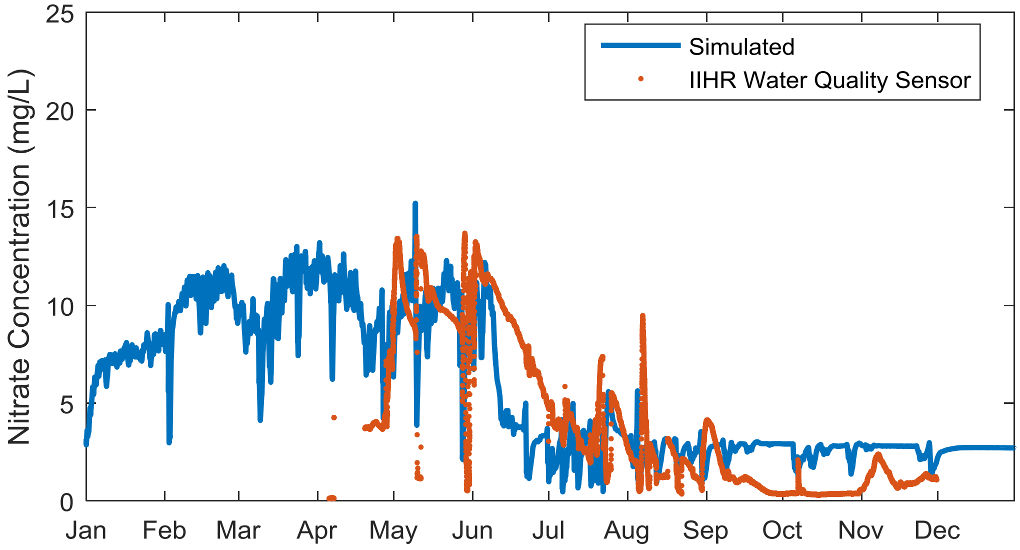

Figure 6.7: 2016 nitrate concentration comparison for recursive hydrologic forcing scenario (NSE = 0.75, PBIAS = -4%, R^2 = 0.78)

While the simulation results for this scenario prove it to be the most successful, the issue of the sharp reduction in concentration during the month of June has not been resolved. The success of the recursive forcing scenario in predicting monthly average nitrate concentration, as evidenced by achieving a NSE of 0.75, PBIAS of -4% and R^2 of 0.78 for 2016, does not directly translate to predicting sub-monthly responses. The simulated nitrate concentration profile, an example of which is shown in Figure 6.8, shows that high concentration penetrates the top 2 meters of the subsurface. This result resembles the one from the previous scenario and indicates that the model is not able develop a natural vertical concentration profile after four simulated years.

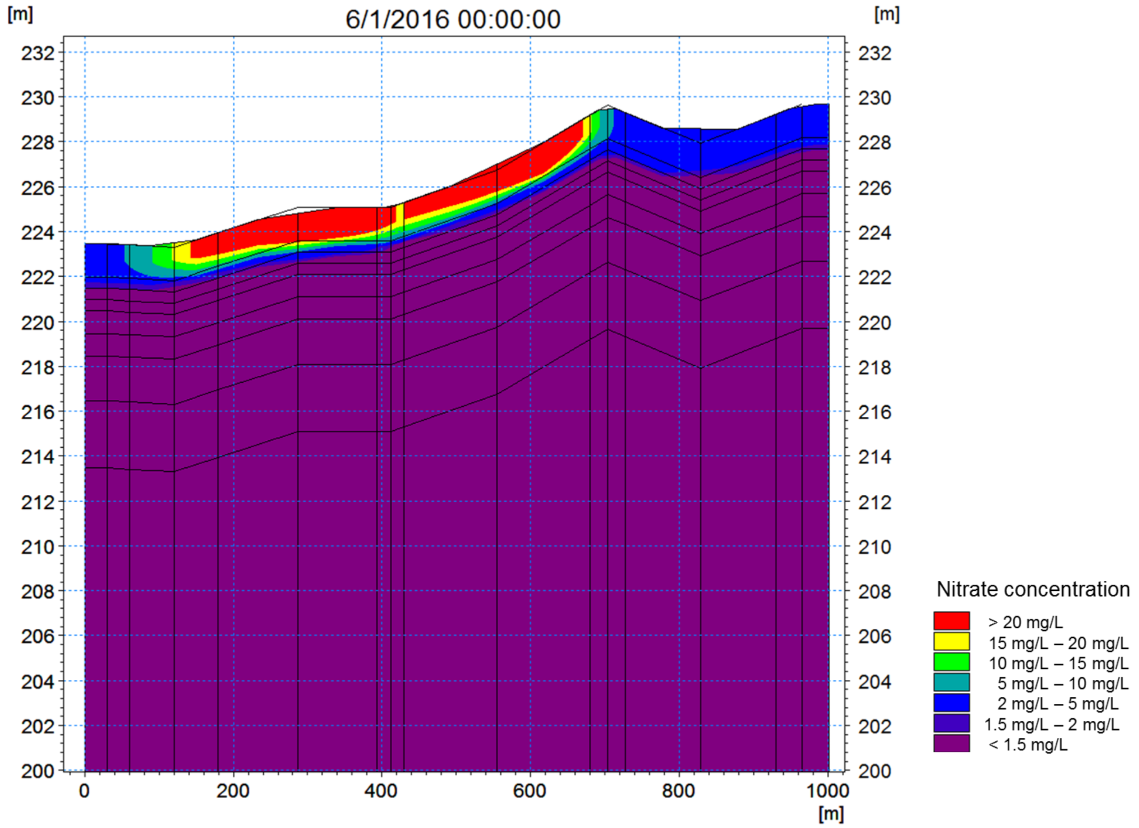

Figure 6.8: Vertical nitrate concentration profile on June 1, 2016 extracted near the outlet of the model watershed. Computational grid shown over simulated concentration.

6.6 Scenario 4: Long Term Water Quality Comparison

Previous scenarios have demonstrated the ability of the Cedar Creek model to replicate monthly nitrate concentration and its failure to replicate sub-monthly responses in 2016. A long term scenario was developed to evaluate how the Cedar Creek model performs when compared to monthly nitrate concentrations collected as part of the Iowa DNR ambient stream monitoring program at the location of the USGS stream gauge on Cedar Creek near Oakland Mills, Iowa. The model used for this scenario shared the same properties as the previous scenario but uses the full watershed as the model domain. The watershed boundary, modeled MIKE 11 stream network and region for which a fixed nitrate concentration is applied are shown in Figure 6.9. A zone of 20 mg/L was fixed from the surface down to 0.25 meters in the unsaturated zone and a fixed concentration of 1 mg/L was prescribed to all precipitation. The model used for this scenario was initialized in a way similar to the previous scenarios. The simulation was started on January 1, 2006 with an initial concentration of 1 mg/L at all locations in the subsurface, an initial in-stream concentration of 0.33 mg/L and no initial nitrate on the surface. The model was run through the end of 2008, producing a period of two simulated years for comparison to measured nitrate concentration. The simulated nitrate concentration for these years and the measured in-stream concentration from the Iowa DNR ambient stream monitoring program are shown in Figure 6.10 below.

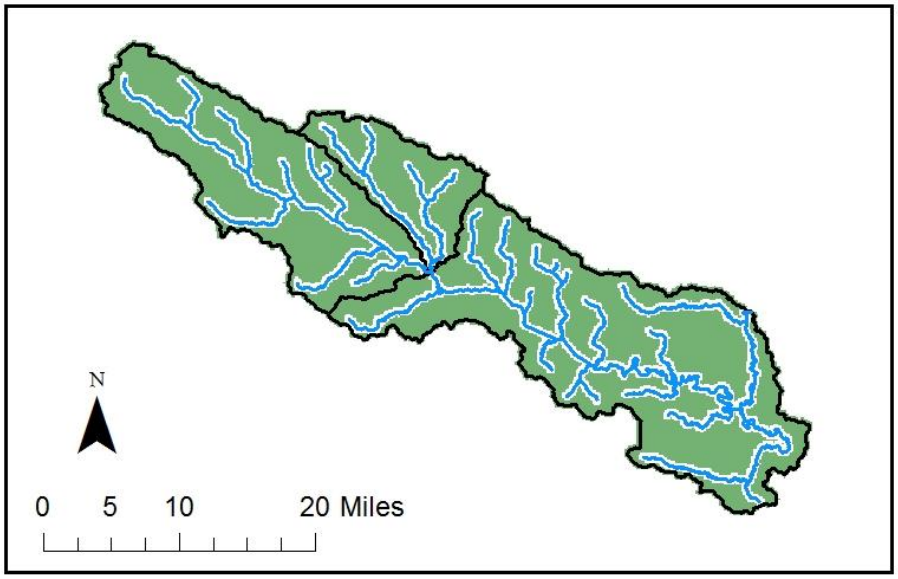

Figure 6.9: Region of full watershed model domain where zones of fixed nitrate concentration were defined (shown in green)

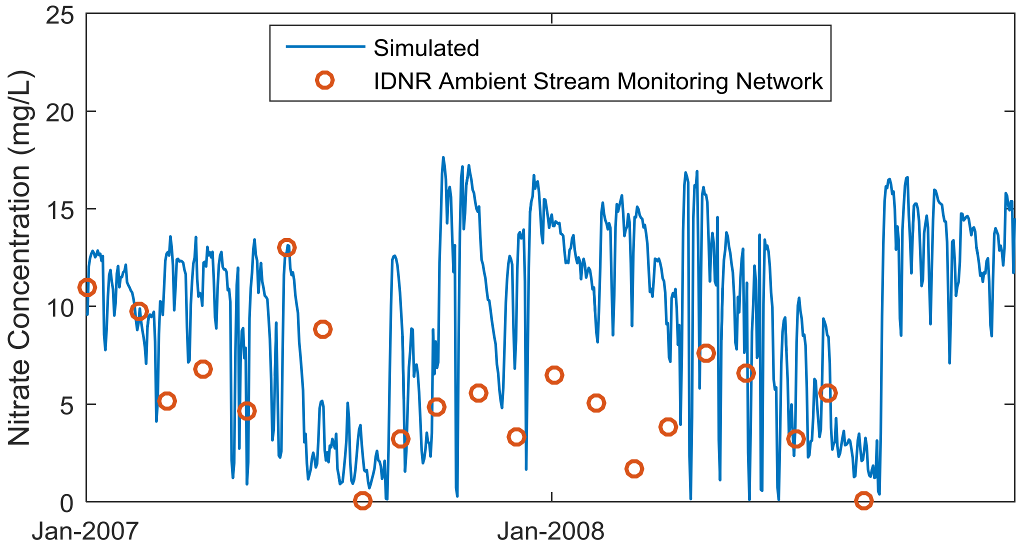

Figure 6.10: Nitrate concentration comparison for 2007 and 2008 (NSE = -2.33, PBIAS = -66%, R^2 = 0.0002)

The poor performance of this scenario simulation in replicating monthly nitrate concentration near the outlet of the Cedar Creek watershed indicate a problem with the conceptualization of nitrate in the subsurface. By fixing a concentration in the upper 0.25 meters of the unsaturated zone, nitrate accumulates in the watershed as the simulation moves forward in time. The overestimation of nitrate concentration shown by the results of this scenario simulation, primarily in the second simulated year of 2008, indicate that this accumulation is problematic. Using this scenario, heavy rainfall events will initially dilute in-stream nitrate concentration before causing a sharp, unrealistic increase in concentration. An example of this kind of response is found in September 2008. The problem of accumulating nitrate, stemming from the choice to use a fixed concentration source in the unsaturated zone, was not apparent in previous scenario simulations because they were too short or limited by dry conditions late in the year. The success of the recursive hydrologic forcing simulation for 2016 was likely dependent on the fact that dry conditions dominated the second half of that year. Less precipitation during this period meant less water would pass through the unsaturated zone, and therefore less high concentration water would be introduced into the subsurface. This is why recursively forcing the 2016 hydrologic year produced stable, and relatively accurate, in-stream nitrate concentration estimates.

6.7 Scenario 5: Time-varying Conceptualization

In order to limit the negative impacts associated with using a fixed concentration source, a time-varying nitrate concentration source scenario was developed. As with the previous scenario, the goal of this scenario was to evaluate how the Cedar Creek model performs when compared to monthly nitrate concentrations collected as part of the Iowa DNR ambient stream monitoring program at the location of the USGS stream gauge on Cedar Creek near Oakland Mills, Iowa. The model used for this scenario has properties identical to those used in the previous model scenario with the exemption of a time-varying nitrate concentration source. A fixed concentration of 1 mg/L was prescribed to all precipitation and a fixed nitrate concentration zone was defined from the surface down to 0.25 meters in the unsaturated zone. The nitrate concentration in this zone was defined to be 10 mg/L from January through March, 30 mg/L during April, 50 mg/L from May through June, 30 mg/L during August and 10 mg/L for the remainder of the year. A depiction of the time-varying concentration used for this scenario, including the initialization period, is shown in Figure 6.11 below. The model used for this scenario was initialized in the same way as the previous scenario and run through the end of 2008. The simulated nitrate concentration and the measured in-stream concentration from the Iowa DNR ambient stream monitoring program are shown in Figure 6.12.

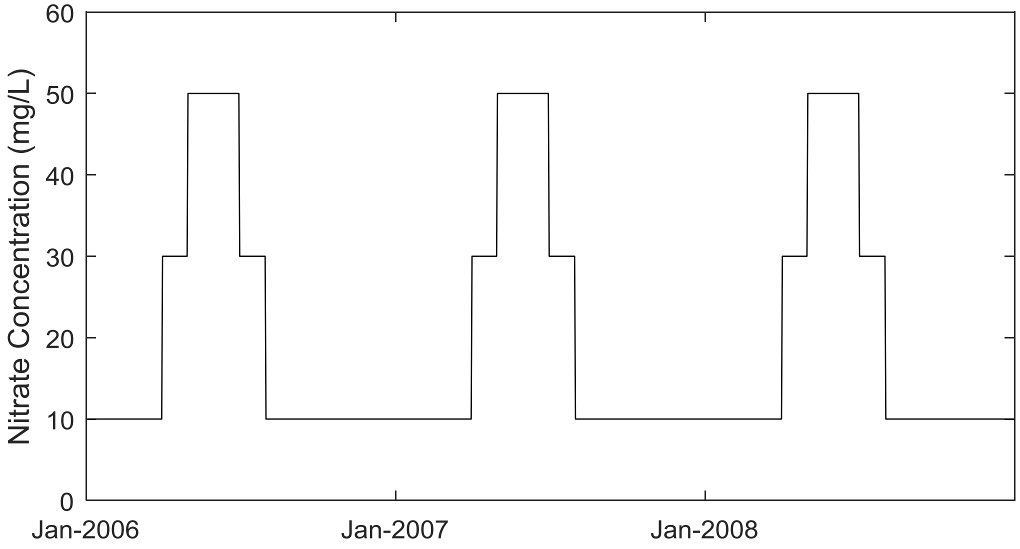

Figure 6.11: Time-varying fixed nitrate concentration in upper 0.25 meters of the unsaturated zone

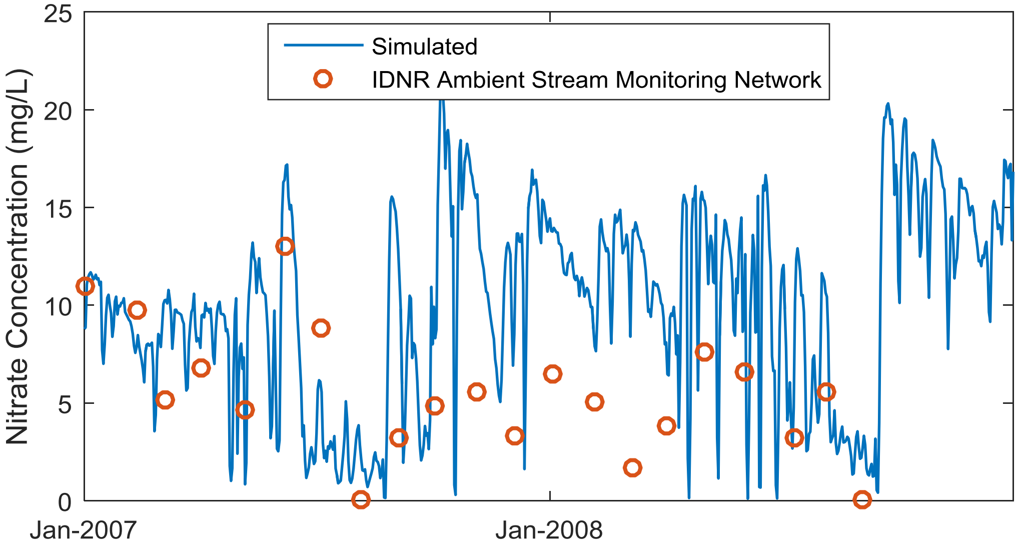

Figure 6.12: Time-varying conceptualization scenario simulated nitrate concentration comparison for 2007 and 2008 (NSE = -2.26, PBIAS = -66%, R^2 = 0.002)

The results of the simulation for this scenario show poor model performance similar to that of the previous scenario. The similarities in simulated nitrate concentration indicate that the problem of nitrate accumulation in the subsurface has not been resolved by using a time-varying nitrate concentration source. In order to address this problem, an adjustment was made to the nitrate concentration source and a longer simulation period was adopted.

Under this adjusted scenario, nitrate concentration in the top 0.25 meters of the unsaturated zone was defined to be 5 mg/L from January through March, 15 mg/L during April, 25 mg/L during May, 15 mg/L during June and 5 mg/L for the remainder of the year. A depiction of the time-varying concentration used for this scenario, including the initialization period, is shown in Figure 6.13. The adjusted model used for this scenario was initialized as before and run through the end of 2016. The simulated nitrate concentration and the measured in-stream concentration from the Iowa DNR ambient stream monitoring program are shown in Figure 6.14. The simulated nitrate concentration for 2016 at the location of the IIHR water quality sensor and the in-stream nitrate concentration measured by that sensor are shown in Figure 6.15.

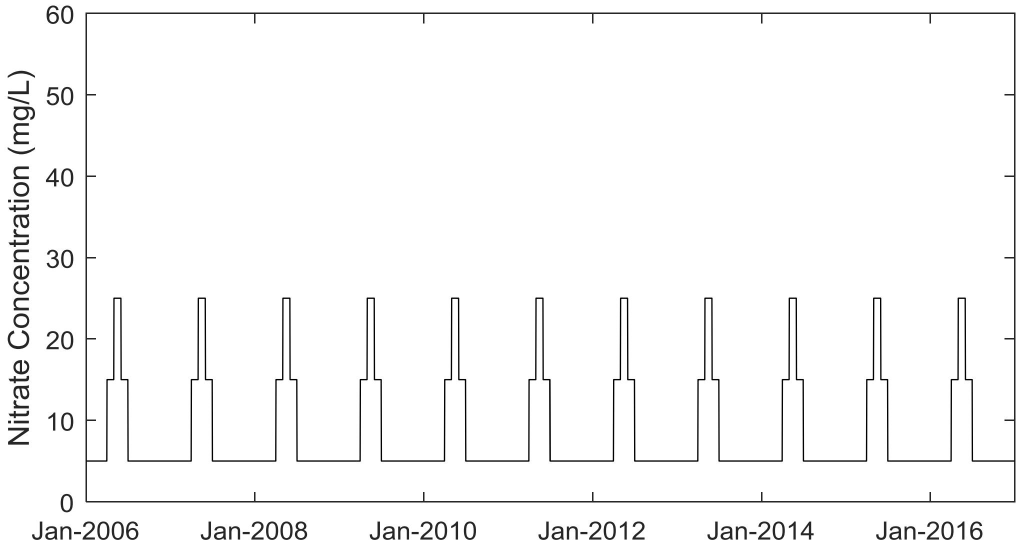

Figure 6.13: Adjusted time-varying fixed nitrate concentration in upper 0.25 meters of the unsaturated zone

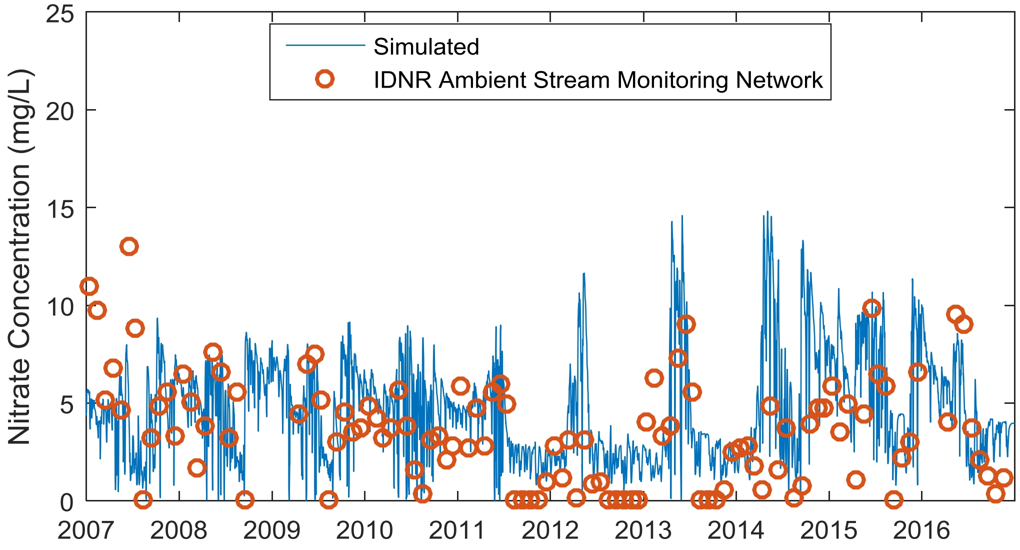

Figure 6.14: Adjusted time-varying conceptualization scenario simulated nitrate concentration comparison for 2007 through 2016 (NSE = -0.09, PBIAS = -26%, R^2 = 0.15)

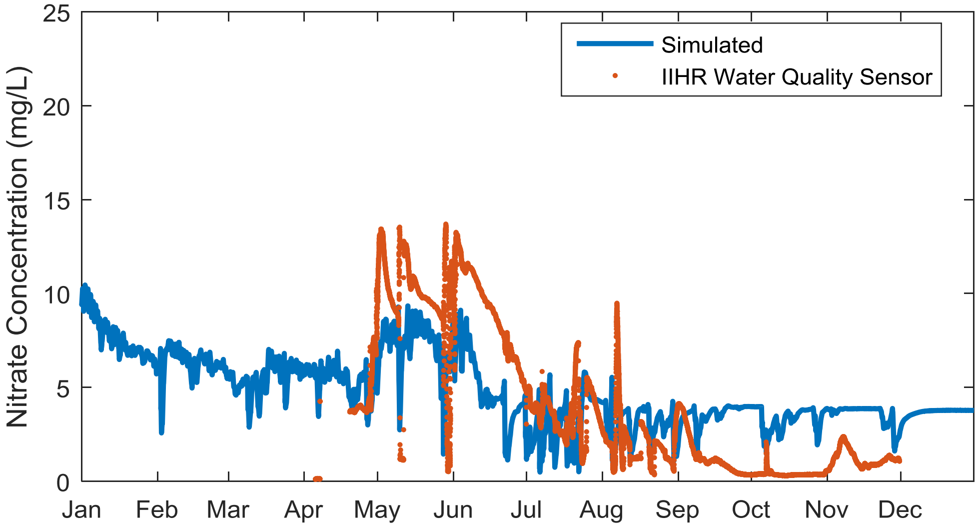

Figure 6.15: Adjusted time-varying conceptualization scenario simulated nitrate concentration comparison for 2016 at IIHR water quality sensor (NSE = 0.52, PBIAS = -5%, R^2 = 0.72)

While the results of the adjusted time-varying source scenario show an improvement relative to the first time-varying source scenario and the fourth scenario, they do not meet the water quality simulation targets. With a NSE of -0.09, the model has poor skill in predicting monthly average nitrate concentration over a ten-year period. The PBIAS is within the target value, indicating that the model does not significantly over- or under-estimate nitrate concentration. The potential skill over the full simulation period, as evidenced by a R^2 of 0.15, indicates that the model is approaching the target value for that measure. The success of the model in predicting monthly in-stream nitrate concentration in 2016 demonstrates the fact that the model can be successful for some years, while underperforming over longer time domains. The results of this simulation qualitatively suggest that the problem of nitrate accumulation found in previous scenarios has been resolved, or avoided. The failure of this scenario therefore lies in the model's inherent hydrologic simplifications regarding the subsurface drainage network. The inability of the Cedar Creek model to route soil water to the stream during periods for which the water table is below the subsurface drainage depth makes the use of a simple water quality model inappropriate.

6.8 Chapter Summary

Using the calibrated Cedar Creek model, five water quality scenarios were simulated in order to determine the best method for modeling the movement of nitrate within the watershed. The scenarios were chosen to offer a simple description of the sources of nitrate in the upper layer of the subsurface. The first three scenarios target the ability of the Cedar Creek model to predict the in-stream nitrate concentration during 2016. The final two scenarios were designed to replicate monthly nitrate concentration over the span of several years. The target of each scenario was based on achieving a NSE of 0.35, PBIAS below 30% and R^2 of 0.30.

In the first scenario, a constant nitrate concentration was applied to the top meter of soil. While the results of this simulation were successful when compared to measured nitrate concentration in 2016, there were two important concerns. The model was unresponsive to changes during dry periods and underestimated the reduction in concentration occurring during the month of June 2016. To improve the responsiveness of the model, the second scenario was designed using a higher resolution subsurface grid. This scenario showed an improvement during the dry part of the year, but performed poorly during the rest of the year. In the third scenario, the constant nitrate concentration was applied to the top 0.25 meters of the soil and the simulation was run recursively for 3 years. This scenario produced the most successful results, achieving a NSE of 0.75, PBIAS of -4% and R^2 of 0.78, but could not replicate the concentration reduction during the month of June 2016.

The fourth and fifth scenarios sought to investigate the ability of the model to predict monthly nitrate concentrations over a period of several years. In the fourth scenario, a fixed nitrate concentration was applied to the top 0.25 meters of soil to simulate 2007 and 2008. The results showed that by using a constant nitrate source, nitrate would accumulate in the soil quickly. This led to simulated concentration values much higher than measurements. In the final scenario, a time-varying source for nitrate was tested for the years of 2007 through 2016. While the accumulation problem was resolved, the results of the model did not meet water quality targets. The poor NSE value produced under this scenario indicates that simple water quality models fail to predict monthly nitrate concentrations when used in a complex, physically-based hydrologic model. However, the potential skill of the model, and its performance for a sample of results in 2016, indicate that the model is successful in predicting nitrate concentration for some time scales.

CHAPTER 7: SUMMARY AND CONCLUSIONS

This thesis has outlined the development of a hydrologic and water quality model for Cedar Creek and its application in predicting stream flow and nitrate concentration over a period of several years. The goals set at the onset, to develop a hydrologic and water quality model for the Cedar Creek watershed, were accomplished using MIKE SHE software. The model was calibrated using data collected by instruments within the watershed. This calibrated model was then used to evaluate the effectiveness of different scenarios for simulating the transport of nitrate. Using this modeling approach, the goals of the thesis were accomplished.

7.1 Development of the Cedar Creek Model

MIKE SHE, a physically-based, distributed, surface/subsurface hydrologic modeling software, was used to create the Cedar Creek model. This software includes a module that was used to simulate the transport of nitrate within the modeled watershed. Using the MIKE SHE framework, a rectangular surface computational grid with 36,740 cells was defined. The surface grid was also defined by the Cedar Creek watershed boundary and a simplified stream network. The modeled subsurface was split into an unsaturated zone and a saturated zone. The unsaturated zone was defined by high resolution layers near the surface and lower resolution layers away from the surface. Below the water table, the saturated zone was defined by two simplified layers. The resulting computational framework was a surface grid with 36,740 rectangular 200 meter cells and a maximum of 158 subsurface layers below each cell.

Properties of the subsurface, overland flow, and evapotranspiration components were defined within the computational grid using parameters obtained from observed physical properties and from the literature. Subsurface soil and aquifer properties were defined based on estimated soil types from SSURGO data and Iowa Geological Survey estimated bedrock characteristics respectively. Surface roughness and land use type from NLCD data defined the overland flow properties of Cedar Creek. NLCD data, along with literature values, were used to define model evapotranspiration properties.

Climatological model inputs were used to drive the Cedar Creek model. Precipitation estimates were obtained from hourly Stage IV radar rainfall data. The radar pixels covering the watershed were aggregated into 10 zones and averaged within those zones. In this way, rainfall inputs were able to adequately describe the natural spatial variation of precipitation over Cedar Creek. Evapotranspiration inputs were obtained from a site in Crawfordsville, Iowa near the Cedar Creek watershed. These inputs were adjusted using a crop coefficient based on a method from the literature relying on the predominance of corn as a crop in the watershed. Precipitation and evapotranspiration inputs, along with the model's construction and properties, complete the development of the Cedar Creek model.

7.2 Calibration of the Cedar Creek Model

After the completion of the Cedar Creek model development process, calibration was conducted on certain properties in order to ensure the model could accurately simulate the watershed's behavior. These properties included the Kristensen Jensen evapotranspiration parameters, subsurface drainage, macropores and the horizontal hydraulic conductivity. Calibration targets included matching annual hydrologic ratios and exceeding NSE and PBIAS values.

The Kristensen Jensen evapotranspiration parameters were adjusted to ensure that the simulated ratio between evaporation and transpiration matched relevant literature values. Three different sets of these parameters were tested and the most successful set was chosen for the calibrated model. Streamflow results were not considered during the calibration process for these parameters.

Subsurface drainage, macropore and horizontal hydraulic conductivity properties were calibrated jointly to ensure that simulated discharge ratios and both NSE and PBIAS values matched all relevant literature values. Three sets of these parameters were considered for the calibration process. These included the inclusion, or exclusion, or subsurface drainage and macropores and the adjustment of the horizontal hydraulic conductivity values relative to the vertical hydraulic conductivity values. The simulated NSE and PBIAS values were given the most importance during the calibration of these parameters. The results of this calibration showed that the inclusion of subsurface drainage and macropores with horizontal hydraulic conductivity values equal to the vertical hydraulic conductivity led to the most successful results.

7.3 Use of the Cedar Creek Model

After calibration, the final Cedar Creek model was evaluated based on the hydrologic calibration targets. The goal of this evaluation was to assess the ability of the model to replicate the measured streamflow in Cedar Creek. Next, several water quality scenarios were conducted in order to determine the ability of the model to replicate measured in-stream nitrate concentration. These water quality scenarios were developed as part of an iterative process aiming to identify a simple and effective method for simulating nitrate using a complex, physically-based hydrologic model. Common to each scenario was a simplified conceptualization regarding the sources of nitrate in a watershed.

7.3.1 Hydrologic Use of the Cedar Creek Model

The calibrated hydrologic model was evaluated over the full period of sub-hourly streamflow measurements in Cedar Creek. Over this period, the model demonstrated its skill in predicting streamflow by achieving a NSE value over 0.50 and PBIAS less than 15% in four of eight years. In 2014, the year to which the model was calibrated, the model achieved a NSE of 0.55 and PBIAS of 4%. While the results over the comparison period showed some drawbacks to the modeling approach, especially during unusually dry or wet years, the Cedar Creek model performed well during climatologically average years. The hydrologic model for Cedar Creek demonstrated its value to predict streamflow and its potential to be used as a tool to evaluate how changes made to the watershed would impact streamflow in an average year.

7.3.2 Water Quality Use of the Cedar Creek Model

The use of the Cedar Creek model in predicting water quality was evaluated through five different scenarios. First, a simple nitrate source conceptualization was tested in order to determine if such method could produce meaningful results. The scenario was tested on a sub watershed within the Cedar Creek watershed and its results were compared to measured nitrate concentration at the outlet of that sub watershed. The results of this scenario showed that the simple conceptualization was able to exceed the NSE, PBIAS and R^2 water quality simulation targets. However, the results were not able to replicate the behavior of in-stream nitrate concentration on time scales less than one month.

The second scenario offered a similar conceptualization to the first, but with an increased subsurface resolution. As before this scenario was tested on a sub watershed and compared to measured nitrate concentration at the outlet of that sub watershed. The increase in subsurface resolution led to a small improvement in the model’s ability to replicate the response of in-stream nitrate concentration during the year. Despite this improvement, the scenario failed to produce results that met NSE and PBIAS water quality simulation targets.

Next, the third scenario applied a recursive climatological forcing to the water quality model developed for the second scenario. This scenario produced the highest NSE, PBIAS and R^2 values, exceeding the targets for each. Similar to the previous scenarios, this one failed to reproduce the response of in-stream nitrate during parts of the year. Specifically during the month of June 2016, the results of this scenario dramatically underestimated the period over which nitrate concentration declined from high to low.

The fourth scenario was tested on the full Cedar Creek watershed and its results were compared to monthly nitrate concentration measurements taken near the watershed outlet. This scenario used a conceptualization identical to the one used in the third scenario but focused on comparing results to monthly measurements over a period of several years instead of a single year. This scenario produced poor NSE, PBIAS and R^2 values, indicating a problem with the conceptualization when applied to multi-year conditions.

Lastly, the fifth scenario tested applied a time varying nitrate concentration source to the model used for the fourth scenario. The results of the scenario were compared to monthly nitrate concentration measurements taken near the outlet of Cedar Creek from 2007 through 2016. The NSE, PBIAS and R^2 values for this scenario showed a strong improvement relative to the fourth scenario, but did not meet the targets. Targets for each measure were met when comparing a sample of simulated in-stream nitrate concentration for 2016 with real-time measurements. The overall failure of this scenario to predict monthly nitrate concentration matches the failure in previous scenarios and is likely related to the MIKE SHE design of its subsurface drainage component.

7.4 Final Remarks

The broad goals set out for this thesis were to develop a hydrologic and water quality model of the Cedar Creek watershed. The unforeseen challenges of developing a calibrated hydrologic model for use in water quality modeling shifted the focus of the project toward an investigation into conceptual water quality scenarios. The five water quality scenarios chosen in this thesis were all variations of the same simple, conceptual water quality model. These scenarios applied a nitrate concentration to a layer of soil and allowed it to advect through the complex, physically-based Cedar Creek model. While the results of these scenarios were mixed, showing success at small time scales and failure at longer ones, they do offer insight in the types of water quality modeling challenges that can arise when using a complex, physically-based hydrologic model. Accurate water quality models require a higher resolution of subsurface computational layers than a hydrologic one. This thesis demonstrated that two saturated zone layers were sufficient for the Cedar Creek calibrated hydrologic model, while nine were required to achieve an adequate water quality simulation. Similarly, accurate water quality models require a more natural definition of the subsurface drainage network than the simplified definition used by MIKE SHE for the Cedar Creek calibrated hydrologic model. The process of developing an accurate water quality model for a watershed is a continuous process that is improved with more in-stream measurements and more complex models. Simple, conceptual models serve as the starting point for more accurate ones.

APPENDIX

Table 7.1: Higher resolution model hydrologic ratios, NSE and PBIAS. Model results are similar to those of the calibrated Cedar Creek model and do not require a further calibration process.

Year	Q/P	ET/P	E/ET	T/ET	Q_b/Q	NSE	PBIAS
2007	0.38	0.59	0.34	0.66	0.25	0.61	-53.8%
2008	0.45	0.53	0.39	0.61	0.27	0.45	7.0%
2009	0.51	0.48	0.40	0.60	0.26	0.57	-2.7%
2010	0.55	0.45	0.49	0.51	0.25	0.48	23.3%
2011	0.45	0.66	0.34	0.66	0.27	0.58	-6.4%
2012	0.20	0.97	0.27	0.73	0.30	0.26	-146.1%
2013	0.30	0.65	0.27	0.73	0.23	0.51	23.1%
2014	0.27	0.62	0.35	0.65	0.27	0.52	-3.1%
Average	**0.39**	**0.62**	**0.36**	**0.64**	**0.26**	**0.50**	**-19.8%**
Target	**0.35**	**0.65**	**0.30**	**0.70**	**0.46**	**0.50**	**±15%**

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