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A Dynamic, Distributed Hydrologic Model for the Blue Earth River Watershed, Minnesota With Implications Regarding Land Use and Water Quality

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A DYNAMIC, DISTRIBUTED HYDROLOGIC MODEL FOR THE BLUE EARTH RIVER WATERSHED, MINNESOTA WITH IMPLICATIONS REGARDING LAND USE AND WATER QUALITY

BY

MICHAEL MERLINI

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Date:

This Thesis paper has been examined and approved.

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ABSTRACT

A DYNAMIC, DISTRIBUTED HYDROLOGIC MODEL FOR THE BLUE EARTH RIVER WATERSHED, MINNESOTA WITH IMPLICATIONS REGARDING LAND USE AND WATER QUALITY

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December 2014

The Blue Earth River (BER) watershed covers approximately one million acres of south-central Minnesota and northern Iowa. Modern farming practices have led to the loss of over 90 percent of the watershed's original wetlands. Corresponding changes in runoff and stream flow have led to dramatically reduced water quality in the BER's main stem following most precipitation events. The purpose of this research is to examine the relationships among precipitation, infiltration, base flow, and runoff in the Blue Earth River watershed basin.

This study developed a calibrated numerical hydrologic model for BER watershed using the distributed flow model, *Vflo*™. The model was developed the seven major runoff events for the 2008 monitoring season (March – June). The research showed the importance of soil depth, hydrologic conductivity, and initial saturation in simulating peak flow volume. Where as overland roughness and channel roughness were found to attenuate the timing of the peak flow volume within the channel. The calibrated model is able to simulate flows where flows have not been observed in the field in both temporal and spatial dimensions. The model is able to accurately depict the onset of the rising limb event and peak discharges to within ten percent of each event. Results of this research provide a better understanding of the hydrologic regime, prediction of flow rate, depth, and flow-weight total contaminant loads, of the BER watershed. These results therefore provide an objective means for improving best management practices within the Blue Earth River watershed.

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CHAPTER I

INTRODUCTION

1.1 Description of Blue Earth River (BER) Watershed

One of the most productive agricultural areas in the world is located in the United States, more specifically the Western Corn Belt Ecoregion. In the Minnesota portion of the Western Corn Belt, over 84 percent of the available acres are cultivated row crops (MPCA 2005). Cultivation leads to non-point pollution of the streams and rivers in the Western Corn Belt. Bohn and Kershner (2002) stated that non-point source pollution now accounts for over half of the water quality impairments in the United States. Principal pollutants are total suspended sediment (TSS), nutrients, and biomass.The Minnesota River is one of twenty rivers in the nation seriously threatened by pollution (MRBJPB 2002). Boone (2002) stated that the Minnesota River is the largest single source of pollution to the Mississippi River.

According to the Metropolitan Council, approximately 625,000 tons per year of sediment is transported by the Minnesota River (Senjem et al. 2002). The Greater Blue Earth River Watershed Basin contributes nearly 55 percent, 343,750 tons, of the sediment load to the Minnesota River (MPCA 2005). The hydrologic regime of the Blue Earth River has been transformed tremendously by land uses changes. According to the United States Corps of Engineers (USACE 2006) the water moves through the watershed mainly by artificial drainage networks consisting of field drain tiles and excavated ditches.

The lower Minnesota River has been listed as being impaired since 1992 (MPCA 2001). Efforts to clean the river have been largely unsuccessful in that the Minnesota River is still listed on the impaired waters list. The river's tributaries are the principal contributors of nutrient and sediment loads and scientific evidence indicates that pollution reductions must occur in these tributaries to meet downstream total maximum daily load goals (MPCA 2001).

The largest tributary to the Minnesota River is the Blue Earth River (MPCA 2005). The Blue Earth River Watershed has an area of approximately 992,034 acres. The Blue Earth River's flow is comprised of flow from the Le Sueur River and Watonwan River and delivers approximately 46 percent of the flow to the Minnesota River at Mankato. The Le Sueur's River flow is only occasionally as much as the Blue Earth River and the Watonwan River's flow is substantially less than either the Blue Earth River or the Le Sueur River.

The Blue Earth River is one of the most polluted rivers in Minnesota (Steil 2005). The Blue Earth River's headwaters begin in northern Iowa and flow north into southern Minnesota to its confluence with the Minnesota River in Mankato. Agriculture, primarily cultivated row crops, accounts for 92 percent of the watersheds land use. The river delivers approximately 55 percent of the total suspended sediment load and 69 percent of the nitrate nitrogen load (MPCA 2005). Figure 1.1 displays the Blue Earth River

Watershed with respect to the Iowa and Minnesota state borders.

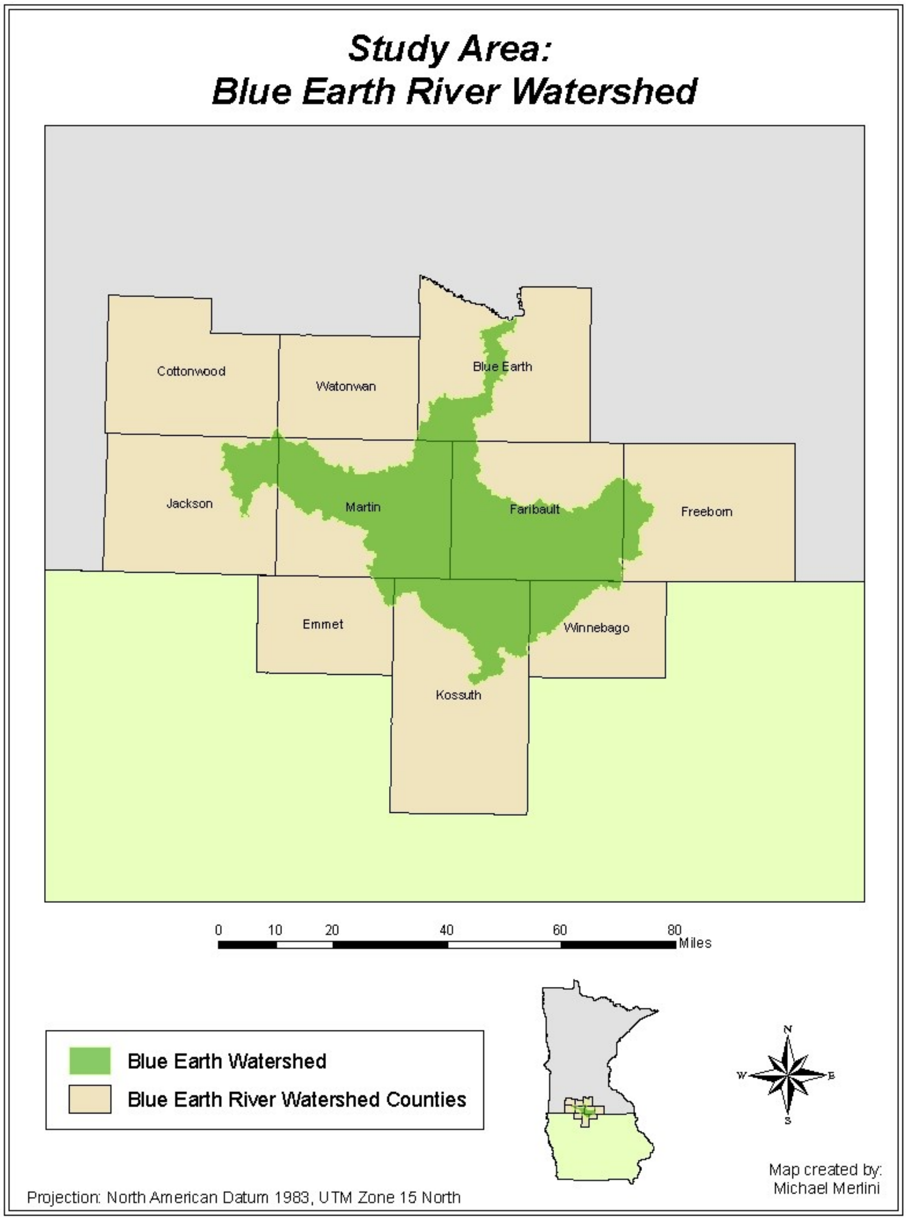
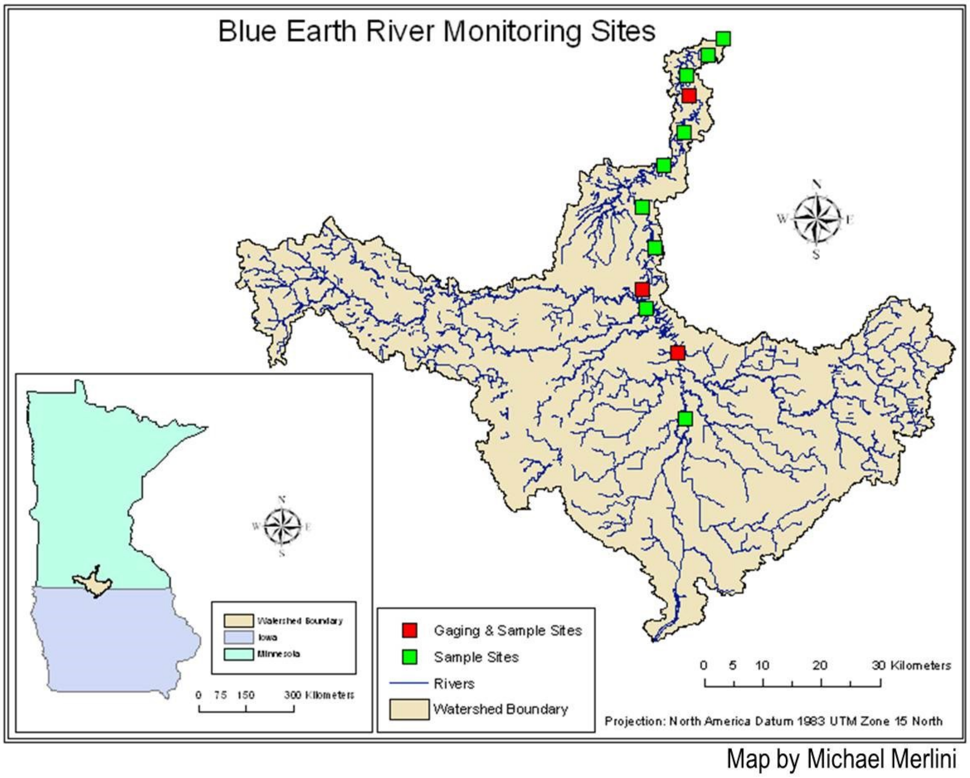


Figure 1.1 The Blue Earth River Watershed



Gaging and sampling sites in the study area.

Figure 1. 2 Blue Earth River Watershed Gaging and Sample Sites. Gaging and sample sites are located along the mainstem of the Blue Earth River allowing for monitoring of major tributaries to the Blue Earth River including the East Branch Blue Earth and Elm Creek systems.

Figure 1.2 displays the sample sites along with the gaging sites along the main stem of the Blue Earth River. The sample sites, green squares, were sites where water samples were taken from the river. The gaging and sample sites, red squares, were sites where water samples were collected along with gage measurements of the rivers' flow.

1.2 Brief Overview of Hydrologic Modeling

Bedient et al. (2008) states that one method for greater understanding of discharge and pollutant loading in watersheds is through hydrologic modeling. Hydrologic models are an intricate combination of various equations used to describe the hydrologic transport processes throughout a watershed. The input parameters for a hydrologic model are complex and numerous. Rainfall intensity, rainfall duration, watershed size, slope, shape, morphology, channel type, land use and land cover, soil type, and percent of impervious surfaces are all input parameters that affect infiltration and runoff characteristics of a watershed (Bedient et al. 2008). The outputs of hydrologic models, for example *Vflo*™, include predictions of flow rates and depth at any location within the watershed. Hydrologic models offer advantages of providing important information on areas of the stream or river where flow characteristics are not available and the model allows multiple options to be tested quickly. Model inaccuracy is a major limitation of numerical studies of watersheds and is largely dependent on the accuracy of the input and observed data used in model calibration (Bedient et al. 2008).

1.3 Significance of Study

The Blue Earth River contributes 46 percent of the flow of the Minnesota River at the confluence in Mankato, Minnesota. The Blue Earth River is the largest tributary of the Minnesota River and contributes significantly more nitrate than any other tributary to the Minnesota River (MPCA 2000). The large amount of nitrate present within ditches and streams in south-central Minnesota has been linked to land uses change (Magner et al. 2003). The abundance of nitrate found in the streams and drainage ditches maybe contributing to the development of an oxygen depleted ‘dead zone’ located in the Gulf of Mexico (Magner et al. 2003). The shift from natural prairie land to intense agriculture has greatly increased the subsurface and surface drainage within the watershed.

A hydrological model is a numerical model that is used to simulate stream flow and describe hydrologic transport processes in space and time (Bedient et al. 2008). The completed numerical model of the Blue Earth River watershed yields multiple benefits. For example, the model is able to provide hydrographs in areas where observed flow characteristics are not available. This tends to lead to a better understanding of the hydrologic and sediment transport regimes. The model relates precipitation, physiography, and land use to examine their inter-relationships. The model highlights temporal and spatial characteristics of runoff that lead to the pollution problem in the Blue Earth River and in other downstream rivers. This better understanding of the hydrologic regime will in turn help regulatory agencies create and modify strategies for limiting erosion, pollutant loads, and water impairment policies.

1.4 Research Objectives

The Null Hypothesis to be tested:

1) After major precipitation events, runoff and discharge do not vary throughout the watershed.

This hypothesis will be tested by answering the following objectives:

1) Develop and calibrate a dynamic distributed hydrologic model for the Blue Earth River watershed, Minnesota using *Vflo*™.

2) What extent do geomorphic factors, soil properties, and hydrologic parameter influence runoff and discharge?

3) How does surface water and groundwater interact with respect to when the Blue Earth River is in influence or effluence?

4) What is the relationship between rainfall intensity, rainfall duration and runoff?

CHAPTER II

LITERATURE REVIEW

2.1 Background on Hydrological Models

The purpose of this section is to examine the basis of the numerical hydrologic models that are commonly used by hydrologists. Hydrologic models offer the advantage of providing simulated flows where observed flows are not available. They also provide the advantage of being able to test many different model parameters quickly. Hydrologic models also have disadvantages in the limitation of the models. They are limited by the amount of data available for the study area. Also model accuracy is limited to the accuracy of the input data and spatial variability representation at a given cell resolution (Vieux et al. 2004). An excellent explanation of why hydrologic models are important is provided by Bedient et al. (2008):

> “Despite their limitations, simulation models still provide the most logical and scientifically advanced approach to understanding the hydrologic behavior of complex watershed and water resources systems.”

Hydrologic models can be generally categorized into two different groups: Lumped parameter and distributed physics based models. Models are further divided into those that address single event or continuous flow simulation models (DeVries and Hromadka 1993).

Lumped parameter models, for example, the Stanford Watershed Model (Crawford and Linsey 1966), are the older of the two having been first developed in the 1960's. The advantage of lumped parameter models is they are proficient in accurately predicting flows with minimal input data (Cooper and Bottcher 1993). Lumped parameter models require considerably less time and effort to run than physics-based models (Fernandez et al. 2006). The disadvantage of lumped parameter models is that the models they provide are an inaccurate representation of input parameters that vary temporally or spatially across a given watershed. Carpenter and Georgakakos (2006) found that lumped parameter models were able to produce flows within 20 percent of observed peak flows for less than seven precipitation events out of twenty five total precipitation events.

Distributed physics-based models route runoff through a drainage network that allows for interior locations to be monitored (Vieux et al. 2004). Examples of distributed physics-based models included CASC2D (Julien and Saghafian 1991), European Hydrological System (SHE) (Abbott et al. 1986a, b), *Vflo*™ (Vieux and Vieux 2002), and *r. water.fea* (Vieux and Gauer 1994). The major advantage of distributed physic-based models is the ability to provide flow simulations at interior locations. Another advantage is the ability to allow for better flow simulation at the outlet points by providing an accurate portrayal of watershed parameters that vary spatially across the watershed (Moreda et al. 2006). More importantly the distributed physics-based models provide a better understanding of the environment along with the building blocks for environmental monitoring. For example watershed water quality monitoring and sediment transportation (Moreda et al. 2006). Distributed physics-based models also have disadvantages. For example they are complex and you can create simulated flow hydrographs that match observed flow hydrographs, but with input parameters that are not necessarily correct. The accuracy of the model is largely dependent on the correctness of the input data and availability of input data (Bedient et al. 2008). Fernandez et al. (2006) states that physics-based models maybe difficult to use due to the problems with calibration in large watersheds and the intense data requirements.

Today there are numerous lumped and distributed hydrologic models, far too many to review for this paper. This section will provide a review the distributed physics based hydrologic model, *Vflo*™. *Vflo*™ was originally created as *r. water.fea* for the Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, Illinois (CERL) in 1993 (Vieux et al. 2004). A physics-based distributed (PBD) model uses a finite element approach to simulate watershed responses to precipitation events (Vieux et al. 2004). Numerical methods like the finite element or finite difference methods are needed in part when analytic solutions to runoff governing equations for a watershed are not generally obtainable (Singh and Woolhiser 2002). *Vflo*™ incorporates a methodology unique from previous finite element solution in that it utilizes a single chain of finite elements for solving overland flow (Vieux et al.2004). Simulation of spatially variable watershed surfaces is possible with this difference without having to break the watershed subareas (Vieux et al. 2004). The current *Vflo*™ is detailed in Vieux and Vieux 2002. The *Vflo*™ model uses a kinematic wave method for deriving hydrographs. The kinematic wave method is defined in Bedient et al. 2008:

> “The kinematic wave process represents a nonlinear runoff response compared with linear unit hydrograph methods. The kinematic wave method relies on parameters that are generally measurable from a basin such as slope, land use, lengths, channel shape, roughness, and area”

2.2 NEXRAD Rainfall Data

The current *Vflo*™ model allows for rainfall to be entered into the model as rain gauge measurements, distributed radar inputs, or a user designed storm. Radar inputs provide a tremendous advantage over the other options in that it offers extremely high resolution rainfall inputs that are spatially distributed across the basin. Precipitation inputs have been found to have large effect on the accuracy of stream flow predictions developed from hydrologic models (Carpet et al. 2001; Gourley and Vieux 2005). Looper et al. (2009) states that physics-based distributed models such as *Vflo*™ benefit from more accurate and representative precipitation inputs. The spatially regular estimation of precipitation provided in radar data is thought to improve the accuracy of rainfall intensities and totals relative to data produced through traditional rain gauge networks (Goodrich et al. 1995). Bedient et al. (2000) found that a numerical model utilizing NEXRAD data for the Brays Bayou watershed in Houston, Texas was more accurate than a comparable model that used rain gauge data.

S-band weather Surveillance Radar – 1988 Doppler, more commonly known as NEXRAD consists of a network of approximately 160 radar stations across the United States (Crum and Alberty 1993; Klazura and Imy 1993). The network is operated by three federal agencies including the National Weather Service (NWS), the Federal Aviation Administration (FAA), in addition to the Air Force Air Weather Service and the Naval Oceanography Command (Fulton et al. 1998). Along with the three standard base products: reflectivity, Doppler velocity, and spectrum width; NEXRAD generates numerous other products available to forecasters (Klazura and Imy 1993). For example, composite reflectivity, one hour precipitation, three hour precipitation, storm total precipitation, and many more. The reader should refer to Klazura and Imy (1993) for a list of all the products with a more detailed explanation of these products and Fulton et al. (1998) for more detailed explanations of the algorithms used to convert reflectivity into rainfall estimates.

2.3 Background on the Blue Earth River Watershed

The study area is the Blue Earth River Watershed located in the southern Minnesota counties of Blue Earth, Brown, Cottonwood, Faribault, Freeborn, Jackson, Le Sueur, Martin, Steele, Waseca, and Watonwan, and the northern Iowa counties of Emmet, Kossuth, and Winnebago (Fig. 2.1). The Greater Blue Earth River watershed drains an area of 3,486 square miles, or 2,231,040 acres, of which 831 square miles are within the Watonwan River subwatershed and 1,089 square miles are within the Le Sueur River subwatershed. The Blue Earth River watershed drains a total area of 1550 square miles, or 992,034 acres (MPCA 2001).

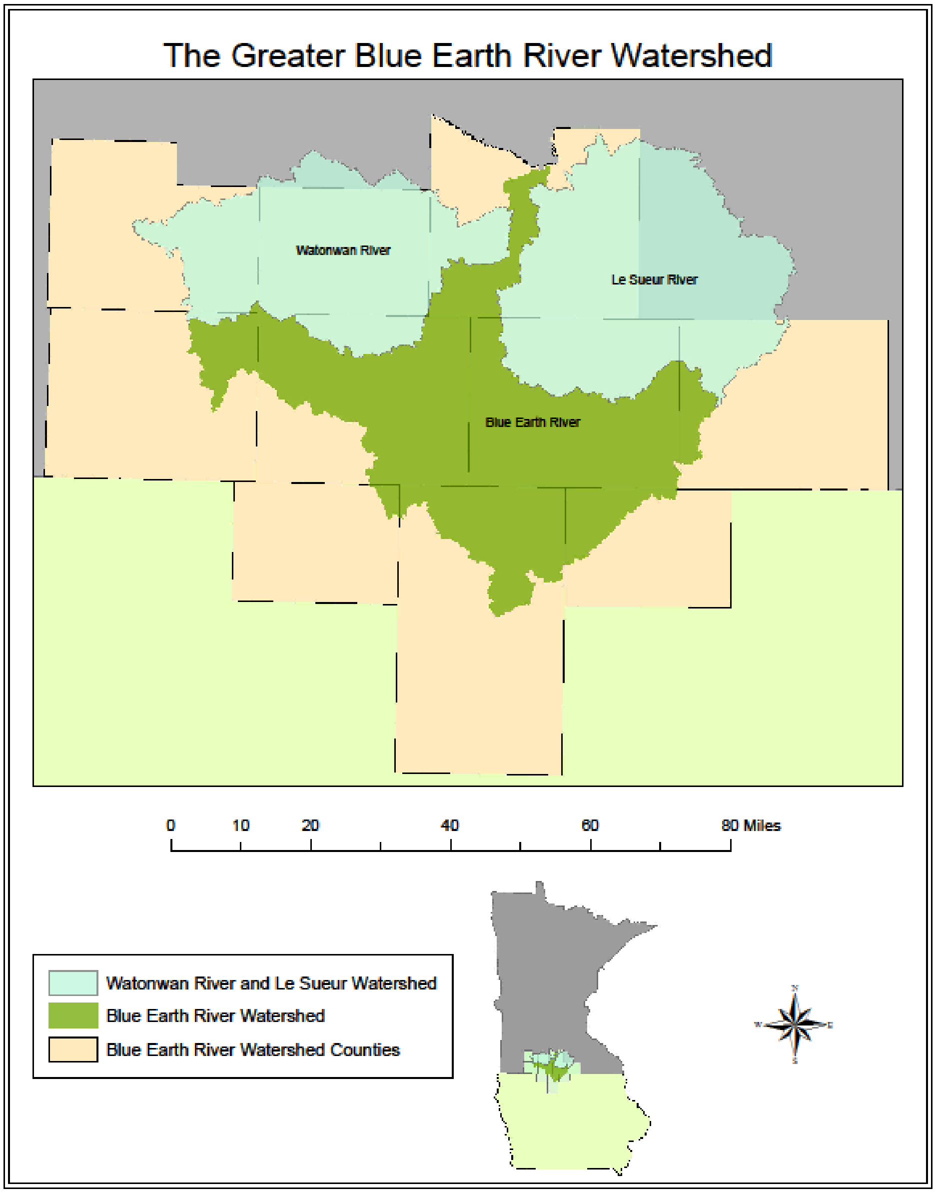


Figure 2.1 Greater Blue Earth River Watershed. The watershed is thusly named because of the significant contributions from the Watonwan and Le Sueur Rivers prior the Blue Earth River joining the Minnesota River in Mankato, Minnesota.

The Blue Earth River

“The Blue Earth River took its name from the bluish green earth that was used by the Sisseton Dakota as a pigment, found in a shaley layer of the rock bluff of this stream about three miles from its mouth” (MRDBC 2003). The Blue Earth River is the largest tributary to the Minnesota River (Waters, 1977).

Watershed

The Blue Earth River watershed comprises approximately 16 percent of the Minnesota River watershed (MRDBC 2000). The BER watershed represents only 0.1 percent of the Mississippi River drainage area but supplies approximate 2 percent of the nitrate load to the Gulf of Mexico’s hypoxia zone (Magner et al. 2004). Eighty to ninety percent of the land in the Blue Earth River watershed is used for agricultural purposes (MRDBC 2000). Most croplands in the watershed are in a two-year corn and soybean rotation, while the remaining 8 percent of the acreage are comprised of small grains, hay, wetlands, and grasslands that are enrolled in the Conservation Reserve Program (MPCA 2005). “The majority of the croplands within the watershed are classified as highly productive and are considered to be among the finest agricultural lands within the United States.” (MPCA 2005).

Climate

The climatic regime within the watershed is considered to be a continental regime. The Koppen Climate classification for the entire Blue Earth River watershed is

Dfa zone, having cold dry winters and warm wet summers that are associated with a continental climate (Mitchell and Keinholz, 1997). The annual precipitation for the watershed averages between 27 to 30 inches, two thirds of the annual precipitation occurs during the growing season (NCDC 2014). The amount of annual precipitation in the watershed increases from west to east (MPCA 2005). As reported by Minnesota Department of Natural Resources (2004) the types of precipitation events vary through the season with spring precipitation events typically being widespread and summer precipitation events being typically convective thunderstorms producing short, localized, but highly intense precipitation. The 30 year average monthly temperatures for the watershed are 16 degrees Fahrenheit in the winter and 70 degrees Fahrenheit in the summer (MN DNR 2004). The Blue Earth River Watershed has the greatest runoff of all the watersheds within the Minnesota River Basin (MPCA 2005).

Geomorphology

The retreat of the Wisconsin glaciation caused the formation of lakes in depressions or behind moraines that were left behind as the glaciers retreated. Notable was Glacial Lake Minnesota that covered what is now the northeastern and eastern part of the watershed (Ojagankus and Matsch, 1982). A wide variety of sedimentary particles, from clay to cobble make up the sediment below the surficial soils. There are other areas within the watershed with mixed glacial landforms but are all dominated by till. The landscape of the Blue Earth River Basin can be described as rolling, hilly morainal belts to flat gently rolling lake plains with different soil types which include well to poorly drained deep silty loams, silty clay loams, and loams over dense blue-gray till (Magner et al. 2004). The slope of the watershed is minimal with slopes ranging from 0 percent (flat) to 6 percent.

The majority of the soil within the Blue Earth River Watershed consists of drift of the New Ulm phase of the late Wisconsin glaciation (Paulson et al.,1978). Glacial Lake Minnesota was formed towards the end of the last glaciation that covered the Blue Earth River Watershed (Ojagankus and Matsch, 1982). Lacustrine, deltaic, and outwash sediments were deposited as the glacier retreated. The Marna – Guckeen association have about 2 to 4 feet of silty clay and silty clay loam material (Paulson et al.,1978). This series of soils are poorly drained and are formed in clayey glacial lacustrine sediments over loamy glacial till (USDA 1980). The Waldorf – Collinwood association have approximately 4 to 25 feet of stratified silt loam or silty clay or clay over silt loam (Paulson et al.,1978). This series of soils are moderately slowly permeable and are poorly drained with slopes of 0 to 2 percent (USDA 1980).

Land Cover and Use

Pre-settlement land cover was predominately prairie and wet prairie. Of the 777,600 acres of the watershed in Minnesota 557,376 acres were prairie (Figure 2.2) and 147,739 acres (Figure 2.3) were wet prairie (Rassmussen 2012). The combined total acreage of the prairie and wet prairie for the historical land cover is 705,115 acres or 90.7 percent of

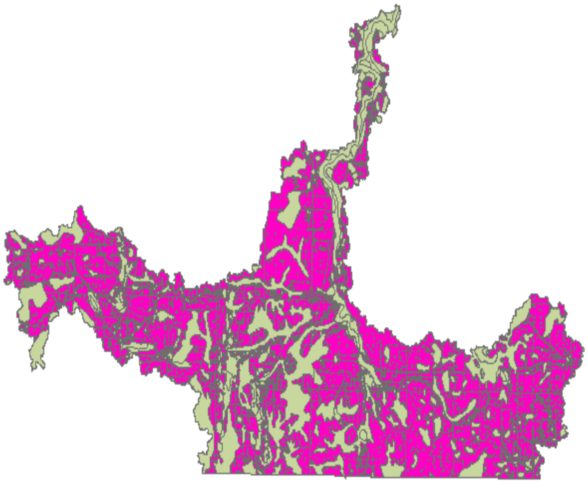


Figure 2.2 – Map of Prairie Lands Prior to European Settlement Rasmussen (2012). Prairies are indicated in purple and clipped to the Minnesota portion of the watershed.

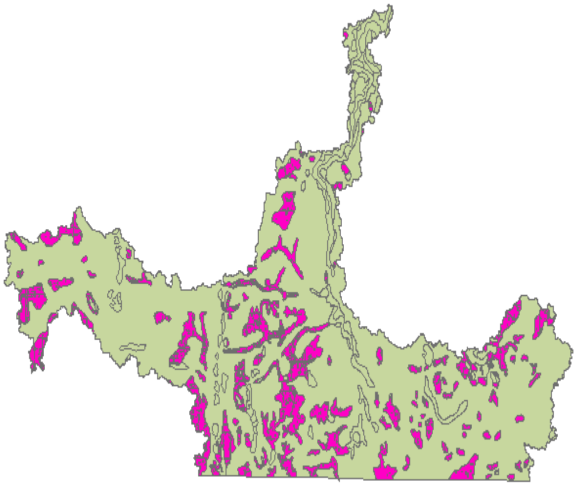


Figure 2.3– Map of Wet Prairie Lands Prior to European Settlement Rasmussen (2012). Wet Prairies are indicated in purple and clipped to the Minnesota portion of the watershed.

the total acres available within the watershed in Minnesota. Historically the Blue Earth River Watershed was comprised of mainly small grains, hay, and grasslands. Pre-settlement land cover was predominately prairie and wet prairie.

Today, there is a great departure from the historical land cover and land use. Of the 557,376 acres of historical prairie cover, 510,260 acres are now cropland. Of the 147,738 acres of original wet prairie land cover, 138,727 acres now exist as cropland (Rassmussen 2012). Thus, for the entire watershed, the utilization of the land surface has changed by 92 percent relative to its pre-settlement disposition.

2.4 Significant Previous Research in the Blue Earth River Watershed and Surrounding Areas

Substantial research results regarding the Blue Earth River watershed were formulated throughout the past fifty years. Steil (2005) for example, quantified contaminants within the discharge of the Blue Earth River and found it to be among the most polluted rivers in Minnesota. The source of the pollutants was identified as the modern farming practices that have led to the loss of over 90 percent of the watershed's original wetlands. A second significant research focus on the Blue Earth River was conducted by the Minnesota River Board during the 1990's. They directed multiple local, state, and federal investigators to quantify watershed parameters contributing to runoff and water quality. Their results also show that changes in land use and land cover created changes in runoff and streamflow. These changes dramatically reduced water quality in the Blue Earth River following most precipitation events. In one of the Board's efforts, The Minnesota River Assessment Project (WRC 2000) found that the Minnesota River is impaired by excessive nutrient and sediment concentrations (MRBDC 2002). Subsequent streamflow monitoring indicated that the Blue Earth River delivers approximately 46 percent of the flow to the Minnesota River at Mankato (MPCA 2005). Along with the flow, the Blue Earth River delivers approximately 55 percent of the suspended sediment load and 69 percent of the nitrate nitrogen load (MPCA 2005).

Magdalene (2004) discusses the impacts of intense agriculture tile drainage systems on water quality and how the presence of these systems greatly enhances the amount of non-point source pollution that is transported directly into the stream channel. Her research monitored the surface-subsurface drainage discharge within the Minnesota River watershed basin and provided valuable information on where the non-point source pollution was coming from. She found that surface run-off within the watershed contributed 40 percent of the sediment, 45 percent of the phosphorus and 10 percent of the nitrogen while only accounting for 10 percent of the total runoff. The sub-surface run-off contributed 60 percent of the sediment, 55 percent of the phosphorus and 90 percent of the nitrogen while accounting for 90 percent of the total runoff. Almost all of the farms within the watershed have some sort of drain tile and this has generally increased over time (WRC 2000).

Land use change in the upper Midwest region is contributing to the development of the hypoxia zone in the Gulf of Mexico. As mentioned previously the land use within the Blue Earth River watershed has experienced a 92 percent land cover change from the historical land cover. Magner et al. (2004) states that the nitrate concentrations within the

Blue Earth River are elevated because of channel incision that does not allow for the river to reach the flood plains and the riparian corridor, a process which would allow for nitrate to filter out before continuing downstream. The channel incision comes from the increased discharge resulting from the 'modern tiling' era. Subsurface drainage systems have a considerable effect on the hydrology and pollutant transport (Carlier et al. 2008).

Thoma et al. (2005) studied sediment and phosphorus contributions from stream bank sloughing using LiDAR. His study was mainly focused on the stretch of Blue Earth River between Amboy, MN and the confluence of the Blue Earth River and Wantonwan River. They found that stream bank sloughing contributed up to 56 percent of the total sediment load and 20 percent of the phosphorus load to the Blue Earth River (Thoma et al., 2005).

Knickpoint migration is discussed in Gran et al. (2004) as a possibility for the source of sediment present in the Le Sueur River. The Le Sueur River is a tributary to the Blue Earth River. Gran et al. (2009) found that the average knickpoint migration rate was 3.0 meters to 3.5 meters per year and have migrated 30 – 35 river kilometers upstream from the confluence of the Blue Earth River. The tills and glaciolacustrine sediments at the surface contribute to the high knickpoint migration rates (Gran et al 2009). Furthermore Gran et al. (2009) discusses the significant increase in sediment load in the lower portion, below the knickpoint, of the Le Sueur Watershed signifying the importance of bluffs and ravines and their contributions of sediment.

The Minnesota River Assessment Project (MRAP) stated that sediment is the major pollutant and recommended a 40 percent reduction in sediment loading (WRC

2000). The Diagnostic Study of the Blue Earth River Major Watershed discussed the monitoring program which was implemented and watershed assessment as a result of the MRAP which focused in the concentration and loading of sediment (WRC 2000). The physical characteristics of the greater Blue Earth River watershed basin and sub basin are detailed in Lorenz and Payne (1992).

CHAPTER III

METHODOLOGY

This chapter discusses the methodology used to collect data and develop the necessary data needed to develop a hydrologic model for the Blue Earth River watershed. A brief introduction into the hydrologic software that was used to create the model is followed by a description of the data that are necessary to develop and operate the model.

3.1 Introduction to the Physics-based Vflo™ Model

Vflo™ is a distributed physics-based hydrologic model that has been applied to the Blue Earth River Watershed of northern Iowa and southern Minnesota. *Vflo*™ can simulate stream flows in continuous mode or can be tuned to singular events. In either mode, the model utilizes spatially distributed radar or multisensor data (Vieux et al. 2004). This distributed physics-based simulation combines NEXRAD level II radar rainfall data, digital elevation model data (DEM), and the comprehensive spatial distribution of soil type. Models that utilize distributed parameters, including *Vflo*™, allow better hydrologic analyses because they accurately portray the spatial variability of sensitive hydrologic factors (Reed et al., 2004). The model also offers the advantage because it allows hydrograph analysis at any location within the watershed without the need to survey channel cross-sections.

The *Vflo*™ model has two basic components: Basin Overland Properties (BOP) files and rain rate property (RRP) files. The BOP file contains all the land surface information including flow direction, infiltration parameters, and calibration factors. The rainfall files contain the spatially distributed rainfall rate across the watershed. There are three procedures that are used to develop these files; (1) create theoretical or idealized storms, (2) interpolate existing rain gauge data, or (3) develop new rainfall files from an alternate source, e.g., radar data. These files are saved in *Vflo*™ as *.rrp files which can be used at anytime (*Vflo*™ User Guide v4.0 2008).

The model takes input data in the form of American Standard Code Information Interchange, ASCII, which can be obtained from raster grid data within ArcGIS. The following files related to the land surface must be provided: Flow direction, roughness, slope, channel width, and channel side slope. Other necessary data are related to composition and texture of the surface and include - hydrologic conductivity, wetting front, effective porosity, soil depth, initial saturation, abstraction, and percent impervious. All of the files must be converted into ASCII before they are imported to V*flo*™. The properties of each cell can be entered manually although for a large watershed, such as the Blue Earth River Watershed, this would be very time consuming. The data for the Blue Earth River Watershed were imported for the entire area, and individual cells were changed only as necessary. For example, all properties, e.g., channel width, soil depth, hydrologic conductivity, etc., of the rated channel cells (those containing actual gauging stations) within the model were modified per field observations.

All data used in the V*flo*™ model must have the similar geospatial projections. For this work, all data were projected in ArcGIS to North American Datum (NAD) 1983 Universal Transverse Mercator (UTM) zone 15 north.

All input files must also have the same grid cell size. The grid cell size of 300 meters was determined through a number of statistical tests of different cell size. The optimized grid cell size was chosen for accuracy, file size, and processing time. Cohen's Kappa analyses were performed on soils classification, slope aspect, and land cover GIS layers. Acceptable misclassification, i.e., error < 3 percent, exist in the data with resolution of less than or equal to 300 meters; Figure 3.1 illustrates the results of the test conducted on the Hydrologic Soil Group (HSG). The x-axis represents the various resolutions that were tested while the y-axis expresses the percent of error/misclassification. After the 300-meter threshold is crossed, the percent of error/misclassification becomes greater than 3 percent.

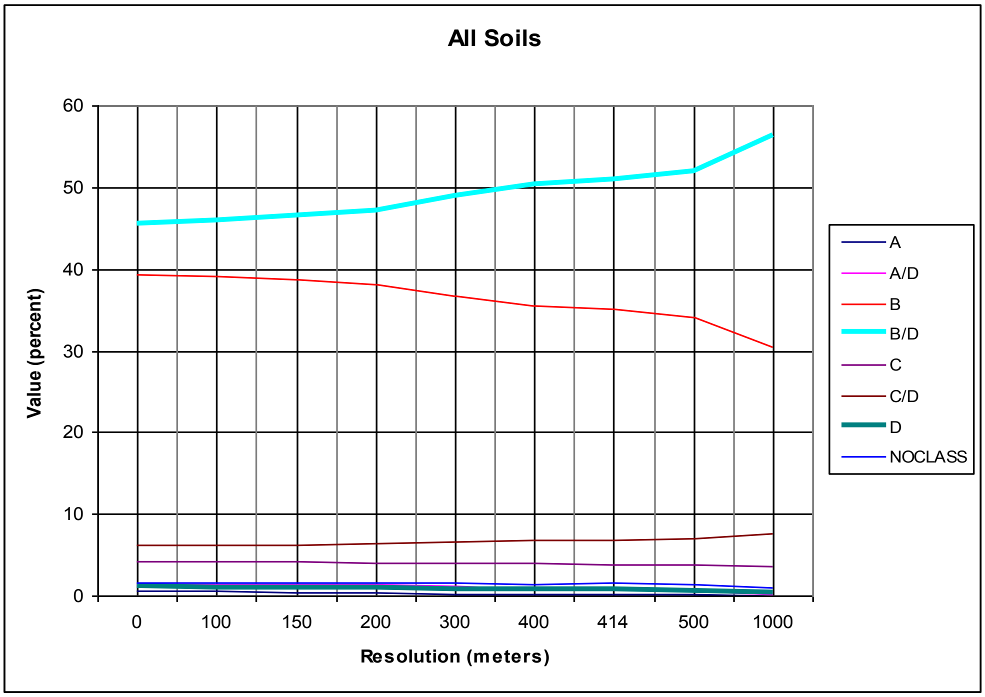


Figure 3.1 Blue Earth River Hydrologic Soil Group Classification at Different Resolution Values. Analysis indicated no significant (3%) misclassification at resolutions less than 300 meters.

Applying the 300-meter cell size to the entire 4014.617 square kilometers, or 1552 square miles, of the watershed yielded 44239 cells over the domain. A diagram of the distributed model over the northern most section of the Blue Earth River Watershed is provided in Figure 3.2 and shows the finite element scheme utilized by the distributed model.

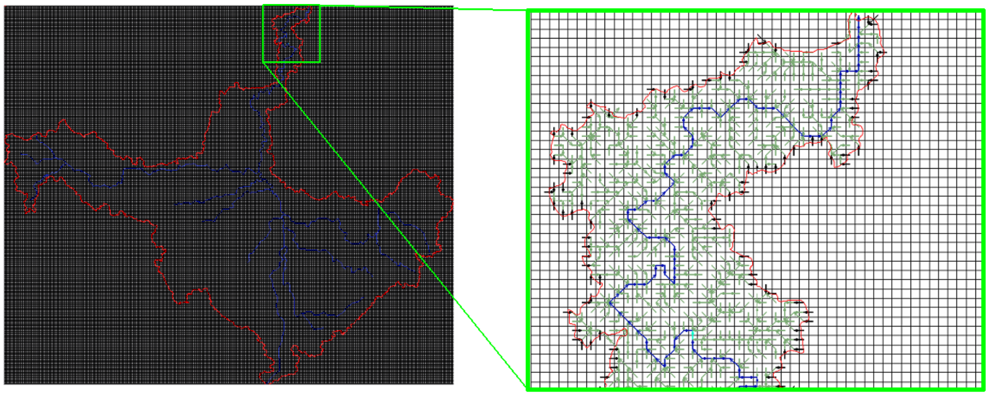


Figure 3.2: Vflo™ distributed model domain for northern most Blue Earth River watershed. The darken apperance of the image on the left is caused by the compression of the lines used represent the boundaries of the grid cells. To illistrate the high resolution grid cells in the model distributed a clipped portion of the model is expanded and displayed on the right. The red line respresents the boundary of the watershed, the blue arrows respresent in the model the main stem of the Blue Earth River, the green cells represent the overland cells in the model, and the black arrows represent the edge of the watershed.

It is important to note that geospatial parameters such as elevation, soil infiltration parameters, and land use classifications are considered homogeneous within individual cells.

3.2 Development Shapefiles and Grids

ArcGIS shapefiles can be used within V*flo*™ in order to reference cell locations within the watershed. This offered the advantage of being able to correctly identify the rated cross section cell within the watershed at Blue Earth County Road 34 (BEC 34), Faribault County Road 8 (FTC 8), and Faribault County Road 12 (FTC 12). The border shapefile that shows the extent of the Blue Earth River Watershed was obtained from the Minnesota River Basin Data Center (MRBDC). Figure 3.3 shows the locations of the rated cross section cells (where stream discharge and channel properties were physically measured) within the watershed.

Multiple Digital Elevation Models (DEM's) were obtained from the United States Geological Survey (USGS) seamless website. The DEM's where then clipped using the ArcMAP clip tool to the boundary shapefile. The clipped DEM grids where combined using the mosaic tool within ArcMAP to create a single 30-meter DEM for the entire watershed. The DEM was subsequently resampled using the ArcMAP resample tool to extract values in accord with the model's grid cell size of 300 meters. Figure 3.4 shows the initial DEM's that were downloaded and reprojected (before the DEM's were clipped to the watershed border and combined together to form the DEM that was resampled). The blue outlines represent the three DEM tiles needed for complete elevation coverage of the entire watershed.

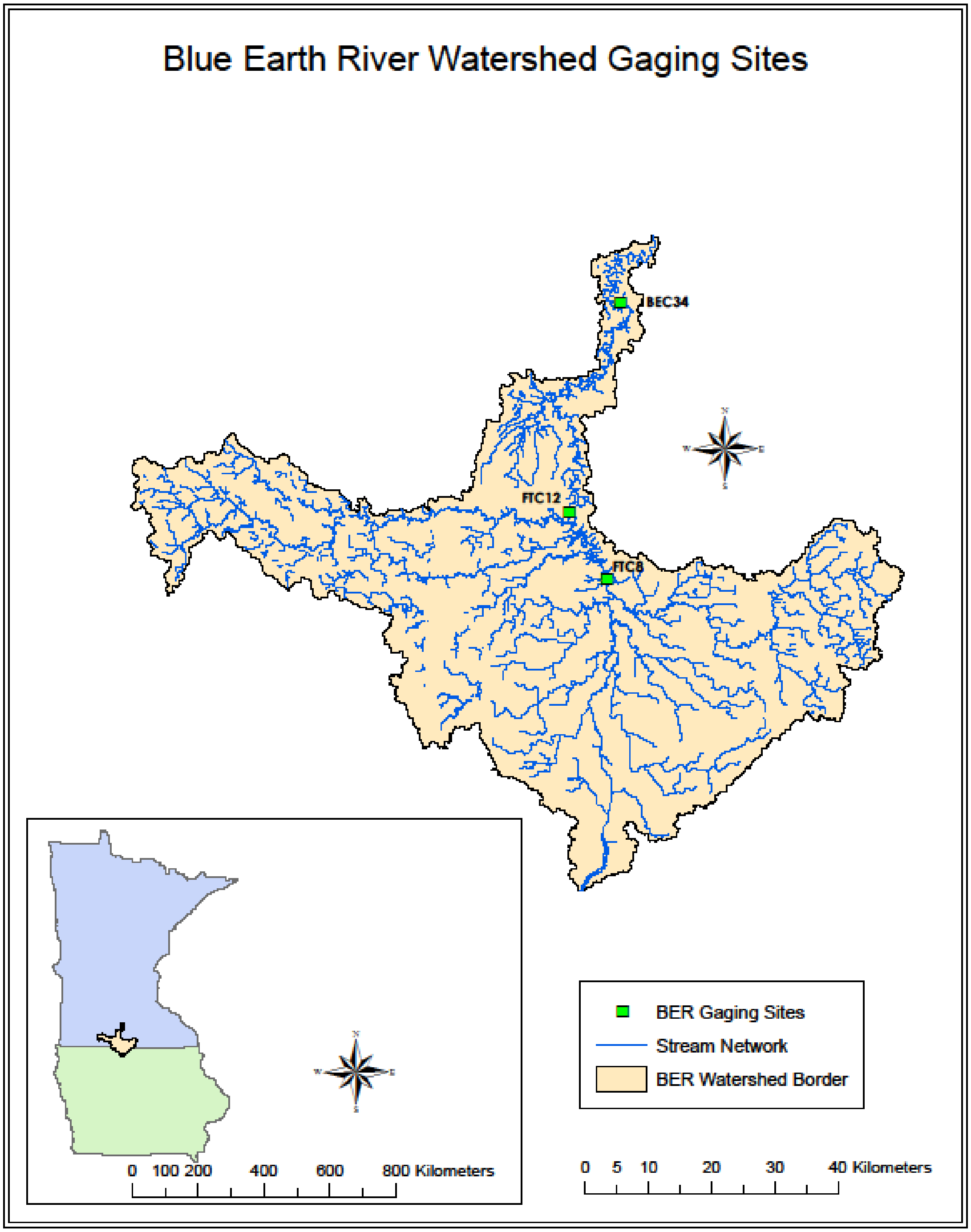


Figure 3.3 Blue Earth River Watershed Gaging Sites. Gaging sites are located along the mainstem of the Blue Earth River allowing for monitoring of contributions by the major tributaries to the Blue Earth River including the East Branch Blue Earth and Elm Creek systems.

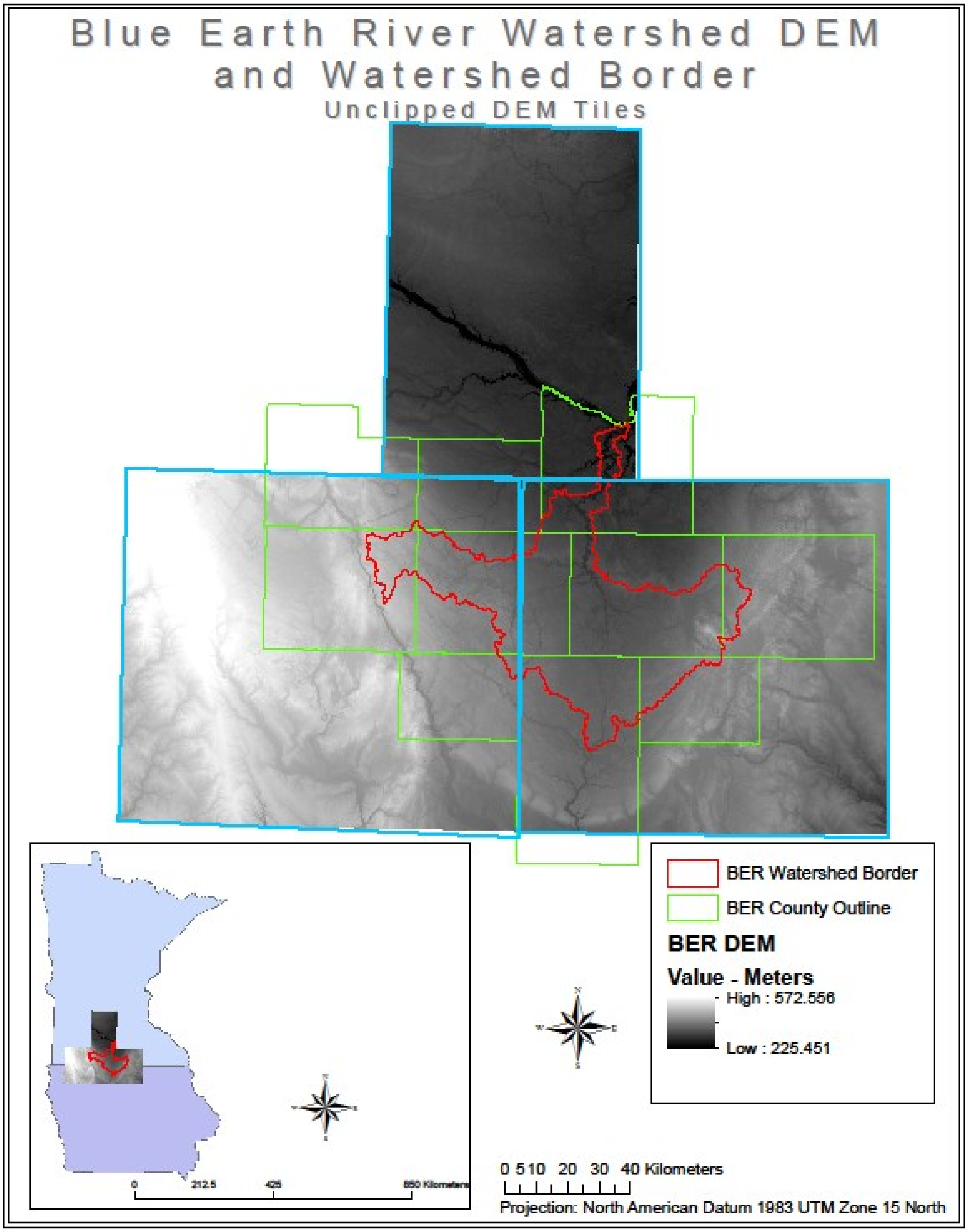


Figure 3.4 - Unclipped DEM Tiles downloaded from the USGS Seamless Data Warehouse Website. Figure also include watershed boundary from the MRBDC. The DEM displays the drainage of the basin that is toward the central axis and to the north.

The stream shapefile and tributaries was obtained from the MRBDC for the streams and tributaries located within Minnesota. The shapefile for the streams and tributaries located in Iowa was obtained from the Natural Resources Geographic Information Systems (NRGIS) library maintained by the Iowa Department of Natural Resources (www.igsb.uiowa.edu/nrgislibx/). These two shapefiles where merged using ArcMAP's merge tool to create a single file. The results were checked for accuracy by visually comparing the shapefile to aerial photography. Careful editing of the position of the streams was performed to ensure that the images of the watershed's aerial photographs and the streams in the final shapefile were matched to within the spatial accuracy of the model, i.e., 300 meters. .

Soil shapefiles were obtained from the NRCS, Soil Data Mart (http://soildatamart.nrcs.usda.gov), for each of the counties within the watershed. The shapefiles where merged using the merge tool in ArcMAP and clipped to the watershed boundary using the clip tool in ArcMAP to create a single shapefile of all soil types for the entire watershed.

V*flo*™ model allows the user to specify an unlimited number of watch points, designated cells where modeled discharge and river height (stage) results can be extracted from the model (Vieux Inc. 2007). For the purpose of this study, three watch points were used. The watch points shapefile was created from GPS waypoints collected in the field. The waypoints were collected using a sub-meter DGPS unit, MicroTrakker T100, and an iPAQ. The watch points were then transferred using Microsoft ActiveSync™ before being added to the V*flo*™ model. The locations of all the watch points are listed in Table 3.3.

The flow direction grid is composed of cells that are connected together according to the principal drainage direction and provided the basis for solving the kinematic wave equations in physics based V*flo*™ model. The flow direction grid file was created with the assistance of the ArcMAP Flow Direction tool. ArcMap input requires DEM's that are obtained from the USGS seamless website, and for this study, DEM's with resolution of 1 arc-second or 30 meters were used. The DEM's were clipped to the watershed boundary using the ArcMAP Clip tool. The clipped DEM's were merged using the ArcMAP Mosaic tool.

Because a coarse DEM was used to produce the flow direction grid, a process of stream burning was used in order to obtain the most accurate flow direction grid as possible. Stream burning is the process of taking the stream shapefile which contains the lowest elevation points and the watershed boundary shapefile which has the highest elevation points and fixes their locations into the DEM. This process reduces the misplacement of the stream within the model resulting from the low resolution of the DEM (Vieux Inc.2007). Stream burning is explained in further detail in the following paragraph.

The stream burning process is provided in the V*flo*™ User Guide v4.0. The resampled DEM was raised by 500 meters, this was an elevation higher than the highest elevation value on the resampled DEM, and has a file name DEM_500m. The stream shapefile was prepared for this process by adding a *unit* field with a value of '1'. The shapefile was converted into a grid using the Feature to Raster tool in ArcMAP selecting *unit* as the field and 300 as the output cell size with a file name of str_unit. The raster calculator was then used to multiply the str_unit by the resampled DEM. This creates a new DEM where the only values that were present were where the stream grid cells existed with a file name str_dem. The same process is followed for the watershed boundary shapefile.

The watershed boundary shapefile was prepared for this process by adding a *unit* field with a value of '1'. The shapefile was then converted into a grid using the Feature to Raster tool in ArcMAP selecting *unit* as the field and 300 as the out cell size with a file name of basin_unit. A 600 meter wall, the value must be higher than the highest value of the raised DEM, was then created with a file name basin_600m. The basin_600m and DEM_500m were merged together using the raster calculator to form one DEM with a file name dem_merge1. The str_dem file was then merged with the dem_merge1 file using the raster calculator to create the final DEM with a file name of final_dem. By merging the str_dem and dem_merge1 the drainage direction is forced along the stream cells ensuring that all the overland cells will flow towards a stream cell. The final DEM is shown in Figure 3.5.

A principal control of runoff and variable of runoff equations is topographic slope (US Soil Conservation Service, 1986). V*flo*™ code incorporates slope as the percentage change in slope between adjacent grid cells along a similar aspect. The slopes created for the watershed were the result of using the 30-meter DEM and the Slope tool in ArcMAP. Within ArcMAP, the percent of rise or percent of slope was selected for the output measurement. The resulting grid was then resampled using the resample tool in ArcMAP to the 300-meter cell size. Once the grid was resampled, it was exported as an ASCII file and then loaded into V*flo*™.

Similarly to surface slope, land cover and use are primary contributions to the volume and rate of runoff (US Soil Conservation Service 1986). Land use data were obtained from the Multi-Resolution Land Characteristics Consortium (www.mrlc.gov). The National Land Cover Dataset (NLCD) 2006 was downloaded, clipped to the watershed boundary and then resampled to the 300-meter cell size.

Surface roughness, the friction produced by land surfaces that inhibits water flow, is a unitless parameter that is named in honor of was Robert Manning and is known as Manning's n coefficient. Manning's n is determined empirically and values for various types of land cover were collated by Chow (1959). Table 3.1 shows values of Manning's n from Chow's (1959) table that apply to the land uses found in the Blue Earth River Watershed.

Table 3.1 Manning's n Values Chow (1959)

Description	Roughness (n)
Cultivated Area – no crop	0.030
Cultivated Area – mature row crop	0.035
Cultivated Area – mature field crop	0.040
Trees – dense willows, summer, straight	0.15
Trees – heavy stand of timber, a few down trees, little undergrowth	0.10
Pasture – short grass	0.030
Pasture – high grass	0.035
Main Channels – clean, straight, full stage, no rifts or deep pools	0.030
Main Channels – same as above but with more stones and pools	0.035
Main Channels – clean, winding, some pools and shoals	0.040
Main Channels – sluggish reaches, weedy deep pools	0.070

The texture and composition of watershed soils influence both infiltration and runoff (Horton, 1933). The soil data for the Blue Earth River Watershed were obtained from the USDA Natural Resources Conservation Services (USDA-NRCS) soil data mart. Each county within the watershed was downloaded and the shapefiles were then merged using the merge tool in ArcMAP. The shapefile was clipped to the watershed boundary using the clip tool in ArcMAP. The V*flo*™ model uses a time-based physical basis equation, the Green-Ampt equation for infiltration. The Green-Ampt equation provides the total porosity, effective porosity, wetting front suction, and hydraulic conductivity based on the United States Department of Agriculture (USDA) soil classification: sand, loamy sand, sand loamy, loam, silt loam, sand clay loam, clay loam, silty clay loam, sandy clay, silty clay, clay (Green and Ampt, 1911). The values needed to complete the Green-Ampt equation were provided by Rawls et al. 1983.

Table 3.2 Green-Ampt Infiltration Parameters from Soils Data, Rawls et al. 1983

Soil Texture Class	Total Porosity, in cubic centimeters per cubic centimeter	Effective Porosity, in cubic centimeters per cubic centimeters	Wetting Front capillary pressure, in centimeters	Hydraulic conductivity, in centimeters per hour
Sand	0.437 (0.374 – 0.500)	0.417 (0.354 – 0.480)	4.95 (0.97 – 25.36)	11.78
Loamy sand	0.437 (0.363 – 0.506)	0.401 (0.329 – 0.473)	6.13 (1.35 – 27.94)	2.99
Sand loamy	0.453 (0.351 – 0.555)	0.412 (0.238 – 0.541)	11.01 (2.67 – 45.47)	1.09
Loam	0.463 (0.375 – 0.551)	0.434 (0.334 – 0.534)	8.89 (1.33 – 59.38)	0.34
Silt Loam	0.501 (0.420 – 0.582)	0.486 (0.394 – 0.578)	16.68 (2.92 – 95.39)	0.65
Sandy clay loam	0.398 (0.322 – 0.464)	0.330 (0.235 – 0.425)	21.85 (4.42 – 108.0)	0.15
Clay loam	0.464 (0.409 – 0.519)	0.309 (0.279 – 0.501)	20.88 (4.79 – 91.10)	0.10
Silty clay loam	0.471 (0.418 – 0.524)	0.432 (0.347 – 0.517)	27.30 (5.67 – 131.50)	0.10
Sandy clay	0.430 (0.370 – 0.490)	0.321 (0.207 – 0.435)	23.90 (4.08 – 140.2)	0.06
Slity clay	0.479 (0.425 – 0.533)	0.423 (0.334 – 0.512)	29.22 (6.13 – 139.4)	0.05
Clay	0.475 (0.427 – 0.523)	0.385 (0.269 – 0.501)	31.63 (6.39 – 156.5)	0.03

V*flo*™ also requires initial abstraction, percent impervious, and soil depth. The initial abstraction is the measure of water (rain) that falls to the ground surface before runoff occurs. For each grid cell, initial abstraction was calculated using the following formula:

Equation 3.1 Initial Abstraction Equation

$$\text{Initial Abstraction } (I_a) = 0.2*S$$

Where:

$S = (1000/CN) - 10$

CN = Curve Number

Impervious surfaces contribute directly to runoff. The percent of the watershed that consists of impervious surfaces was downloaded from the Multi-Resolution Land Characteristics Consortium (www.mrlc.gov). The file was then projected into the correct projection, North American Datum (NAD) 1983, Universal Transverse Mercator (UTM) zone 15 north using the project tool in ArcMAP. As with the other V*flo*™ input files, the projected file was clipped to the watershed boundary using the clip tool in ArcMAP and resampled to a 300-meter resolution using the resample tool in ArcMAP, and then converted to an ASCII file.

V*flo*™ numerically estimating watershed runoff using gridded rainfall data produced by radar, rain gauge data from known gauging locations, and user-designed storms. For this study NEXRAD level II data was downloaded from the NOAA website for the seven significant precipitation events that occurred during the 2008 monitoring season. The dates of those events included April 10 – 12; April 17 -19; April 21 -22; April 24 – 26; May 1 – 3; May 29 – 30; June 6 - 9. Each file was a 360 degree scan of the NEXRAD Radar service area KMSP (Chanhassen, Minnesota) that was completed every five minutes. "Precipitation mode" NEXRAD results, equaling a total of 288 files per day, were loaded into V*flo*™ for each selected event. These files were sorted by the precipitation events listed above then saved as rain rate property (RRP) files.

3.3 Stream Gauging Methods

Total stream discharge was evaluated at three sites along the river to calibrate the V*flo*™ model and verify modeled runoff results. The discharge points are listed below in Table 3.3.

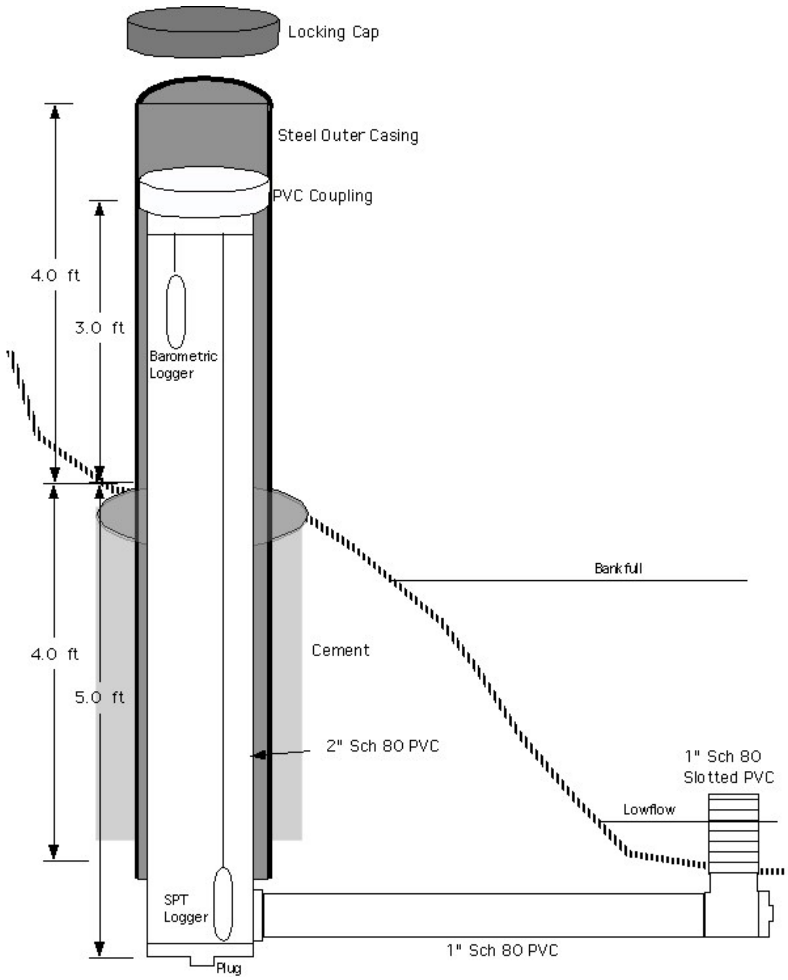
Table 3.3 Total Stream Discharge collection points

Site Name	Longitude UTM Coordinate	Latitude UTM Coordinates	Datum
Faribault County Road 8 (FTC 8)	409808.3387 meters Easting	4836237.2623 meters Northing	NAD 83, UTM Zone 15 North
Faribault County Road 12 (FTC 12)	403815.9052 meters Easting	4846969.5185 meters Northing	NAD 83, UTM Zone 15 North
Blue Earth County Road 34 (BEC 34)	411885.3524 meters Easting	4880036.2006 meters Northing	NAD 83, UTM Zone 15 North

To produce the most accurate record of discharge along the entire length of the river, continuous discharge records for the 2008 monitoring season were collected for the southern, central, and northern sections of the watershed. To determine continuous discharge, standard USGS techniques (outlined below) were employed.

1. Using basic US Geological Survey recommendations (see Rantz, 1982a), stilling wells with continuous stream stage recorders were constructed and installed at monitoring sites FTC8, FTC12, and BEC34. Each stilling well consisted of a vertical section of 2-inch (diameter) Schedule 80 PVC pipe that was fitted with inward facing eye-bolts, a locking cap, and lower fitting that allowed a horizontally-mounted 1-inch Schedule 80 PVC pipe to be attached. These wells

were attached to piers or abutments on the downstream sides of bridges crossing the BER at each monitoring site. In order to eliminate turbulence or other false water level readings cause by the bridge structures, the bottom of each well was fitted with a horizontal, 1-inch Schedule 80 PVC pipe (a "lateral arm") that was buried in the river bottom at depths between 6 in. and 2 ft. and run-out for the length necessary to place its end beneath a location of non-turbulent water. Depending on the site, these lengths varied between 6 and 25 ft. To allow water to enter the well while minimizing the inflow of sediment, 2 ft. tall vertical pipes with ¼ in. holes were attached to the ends of each lateral arm. These "intake pipes" were made of capped 1-inch Schedule 80 PVC pipe and positioned so that the each intake port faced downstream.



2.

Figure 3.5 Typical stilling well construction. Actual dimensions vary individual installation site. (Bryce Hoppie personal communication)

The exact elevation of each well, referenced to the position of the inward-facing eye-bolt, was determined by surveying methods. Exact elevations of boundary monuments on each bridge were obtained from the Blue Earth County and Faribault County public works departments. Surveying equipment was borrowed from the MSU Mankato Department of Civil and Mechanical Engineering.

Within each stilling well, Solinst Levelogger Gold datalogging submersible pressure transducers (SPT) were used to measure and record all stream gages. The SPT was hung from the eye-bolt in each well using stainless steel wire so that the lower tip of the SPT rested less than 2 in. above the bottom of the well. Each SPT was programmed to record water elevation changes to 0.001 ft. every 5 minutes throughout the period of study. Corrections for changing atmospheric pressure were performed with the aid of two Solinst Barologger Gold datalogging atmospheric pressure transducers mounted at the FTC8 and BEC34 sites, and software provided by Solinst Canada Ltd.

3. Each site was physically gaged every 3-5 weeks throughout the monitoring season. Depending on water depth and location, current velocities were determined by the wading rod method or by the weighted current meter and sounding reel method using a bridge-board apparatus (Dingman 2002, Rantz 1982a). Regardless of the method, water depth and velocity were recorded at no fewer than 13 individual locations spanning the width of the river. When water depth exceeded 1.5 ft., average vertical water velocity was determined by averaging values of velocity determined at 0.2 and 0.8 times the total water depth. In shallower water, a single water velocity was procured at a depth of 0.6 times the water depth. Each survey began and ended by recording time and river stage relative to the site's permanent datum, i.e., the eye-bolt on each stilling well.

Stage (relative to each site's permanent datum) and discharge results from each gaging event were combined and used to develop rating curves for each site (Rantz 1982b). Rating curves were then adjusted to allow corrected SPT data to be used directly and thus produce a continuous record of discharge for each site throughout the entire monitoring season.

CHAPTER IV

RESULTS

Chapter 4 discusses all the required parameters needed to complete the development of the model using the *Vflo*™ hydrologic model software which will include land use, Manning's n, wetting front, initial abstraction, effective porosity, hydraulic conductivity, flow direction, flow accumulation, slope, soil classification, and the stream network. This will be followed by the hydrologic data section which will include the observed stage, gauging results, and results of determining the discharge at each of the monitoring stations, and precipitation.

4.1 Overview Vflo™ Model Calibration

Calibration of the *Vflo*™ model for the Blue Earth River Watershed was done by simulating seven precipitation events that occurred during the 2008 monitoring season. The calibration was matched to actual Blue Earth River hydrographs which were the result from stream gauging measurements at the Faribault county road 8, Faribault county road 12, and Blue Earth county road 34 sites during the 2008 monitoring season. Calibration of the *Vflo*™ model to the observed hydrographs at the three sites listed above resulted in a final, calibrated model of hydrology for the entire Blue Earth River Watershed.

The model was calibrated by adjusting the weighting of the infiltration parameters in accordance with the weather conditions in order to attain the correct volume for the simulated hydrographs. The roughness values for both overland and channel along with channel width were adjusted to correctly calibrate the models timing of the peak.

4.2 Description of Vflo™ Model Parameters

Vflo™ utilizes parameters that vary in both space and time to predict hydrologic responses to weather events. The model uses a time-based physical equation for infiltration along with GIS data and radar inputs that offer a scalable prediction model. *Vflo™* hydrologic model requires 18 datasets to solve the infiltration, runoff, and channel flow equations. The datasets needed are listed in Table 4.0 and will be discussed in further detail later in this chapter.

Table 4.0 Vflo™ Parameters Required for Model

Vflo™ Parameters			
Slope	Soil Classification	Roughness (manning's n values)	Flow Direction
Elevation	Abstraction	Wetting Front (WF)	Flow Accumulation
Stream Network	Effective Porosity (EP)	Hydraulic Conductivity	Channel Width
Channel Side Slope	Hydrologic Soil Group (HSG)	National Land Cover Dataset	Initial Saturation
Spatial Distributed Rainfall	Baseflow (CFS)		

Using multiple USGS DEM's that were clipped to the watershed boundary, a mosaic raster file of the land surface elevation was created for the entire watershed. These results are shown in Figure 4.1. The maximum elevation found within the boundary of watershed was in the western part and was 448 meter or nearly 1470 feet above sea level. The lowest elevation is approximately 232 meters or roughly 761 feet above sea level. This elevation marks the northern most point in the watershed where the Blue Earth River discharges into the Minnesota River in Mankato, Minnesota. Although the range of elevation may look large, the watershed is relativity flat with an average decrease in elevation of two feet per mile traveling downstream towards the mouth of the river.

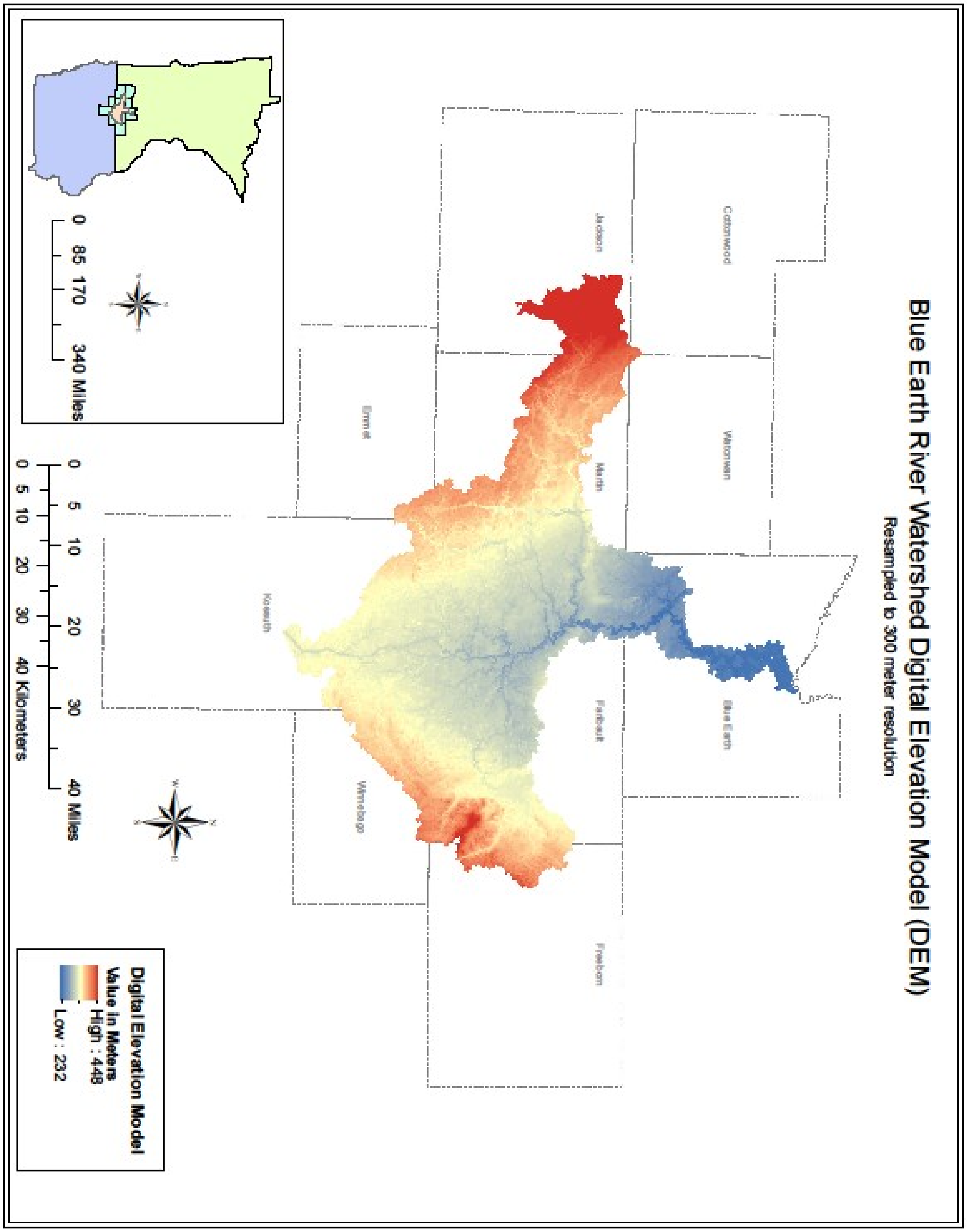


Figure 4.1 - Blue Earth River Watershed Elevations. The watershed has significant drainage towards the west and east towards a central axis and then northward towards the point of discharge.

In conjunction with ArcMap slope tool the same clipped DEM's were used to generate the percent of slope across the entire watershed. These results are shown in Figure 4.2. Broadly speaking the Blue Earth Watershed has relatively low percent slopes. Over 95 percent of the watershed area has a slope of less than 3.5 percent. Outside of the riparian areas are very flat, the average slope of 0.64 percent. Within the incised river valleys and eroded gullies the percent of slope was observed up to 55 percent; however, these step surfaces represent less than one percent.

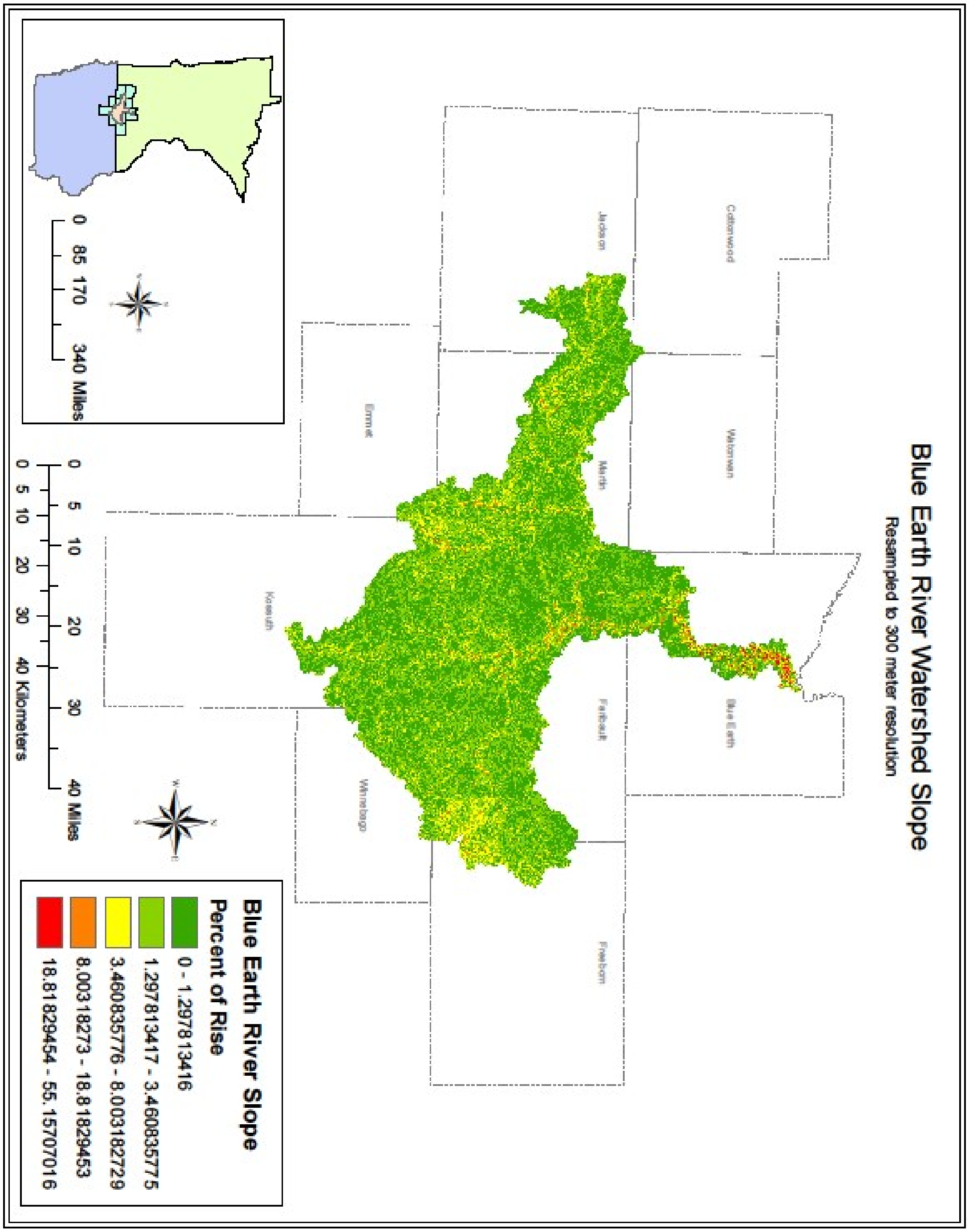


Figure 4.2 Blue Earth River Watershed Percent of Slope. Percent of slope is shown in five classes to illustrate the dominance of low sloping areas, with slopes from 0 to 3.4 percent. With a 300-meter resolution areas of significant slope, 8 to 55 percent exist almost exclusively in the main stem riparian corridor.

The stream network for the Blue Earth River Watershed encompasses ten counties and two states. Due to the vastness of the watershed two stream network files were needed, one file from each of the two states in which the Blue Earth River watershed resides within, Minnesota and Iowa. These two shapefiles where then merged together using the merge tool in ArcMAP to create one file. The resulting shapefile was then checked for accuracy by comparing the shapefile to aerial photography. Errors were found when compared to the current aerial photography. Editing of the streams shapefile was then performed to match the aerial photography ensuring that the most accurate stream shapefile was used for the model. The shapefile was then converted to a raster grid using the conversion tools - feature to raster tool within ArcMAP. The grid was then resampled using the resample tool within ArcMAP to 300 meters.

Figure 4.3 depicts the results of the processes listed above. The results in the northern portions are not the most desired results as when the grid was resampled some information was lost. The lost of information can be attributed to the resampled grid cell size which allowed for generalization of the cell value. The generalization error can be attributed to the river channel in the northern portion of the watershed becomes very incised and narrower than in the southern portion of the watershed. The stream grid was extensively edited in V*flo*™ using the corrected stream shapefile as justification to resolve these errors and ensuring the correct drainage network was established.

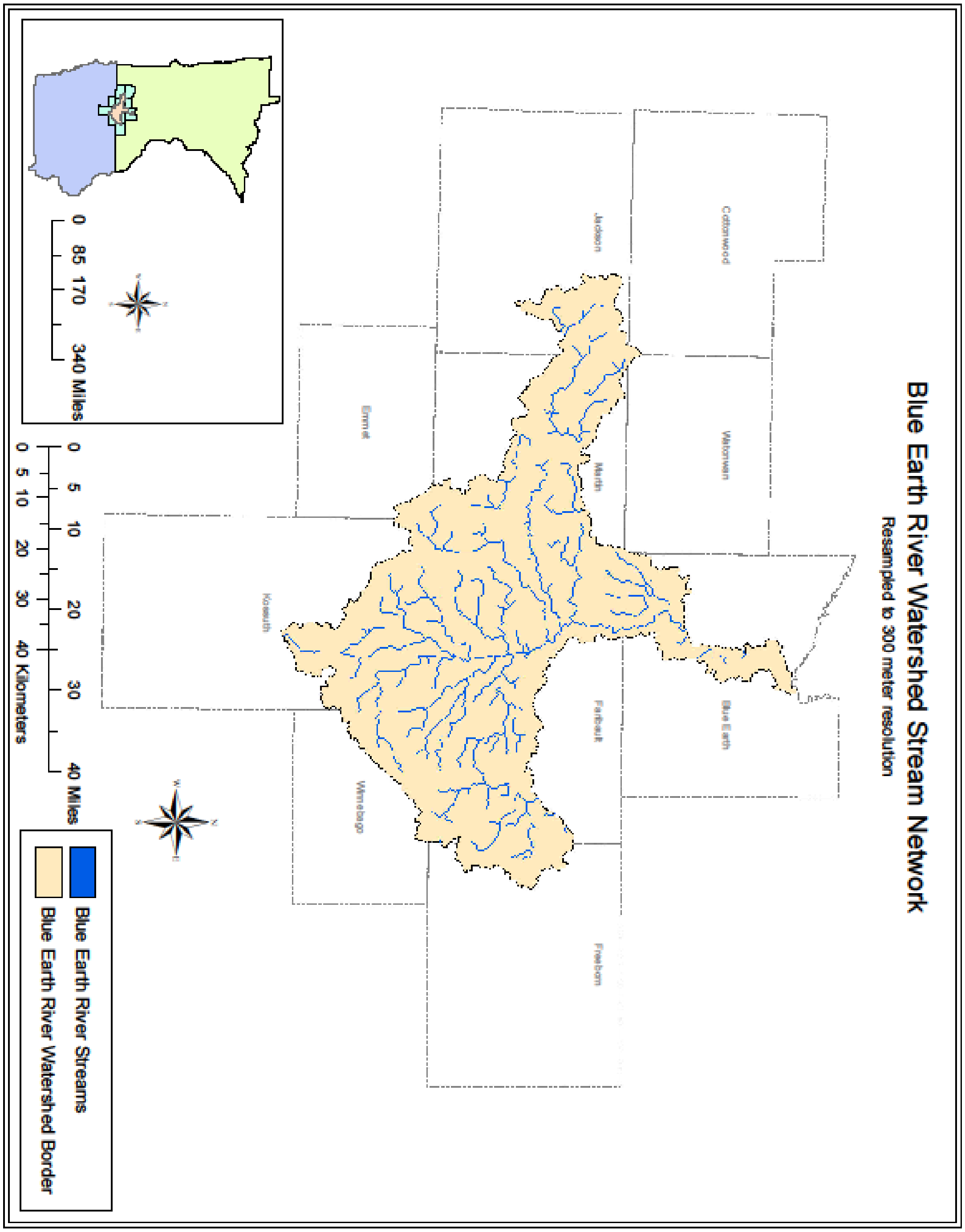


Figure 4.3 Blue Earth River Stream Network. The channels shown in this figure were converted to a raster grid to be used in the V*flo*™ model. The resulting raster grid was edited to ensure conductivity of channel cells.

The soil data for the Blue Earth River Watershed was obtained from the United States Department of Agriculture Natural Resources Conservation Services (USDA-NRCS) soil data mart. Files for the each of the ten counties within the watershed were merged, resampled (to a 300-meter grid cell size) and examined. Figure 4.4 illustrates the results of this process along with the variability of soil classifications throughout the watershed.

The soil classifications along with the Green-Ampt equation for infiltration will be used to derive the other infiltration parameters need for the V*flo*™ model. The dominate soil type of the watershed is fine-loamy soil. This soil is found primary along the western (Elm Creek) and eastern (East Branch Blue Earth River) tributaries. In areas near area main stem fine and silty soils are more common than other types.

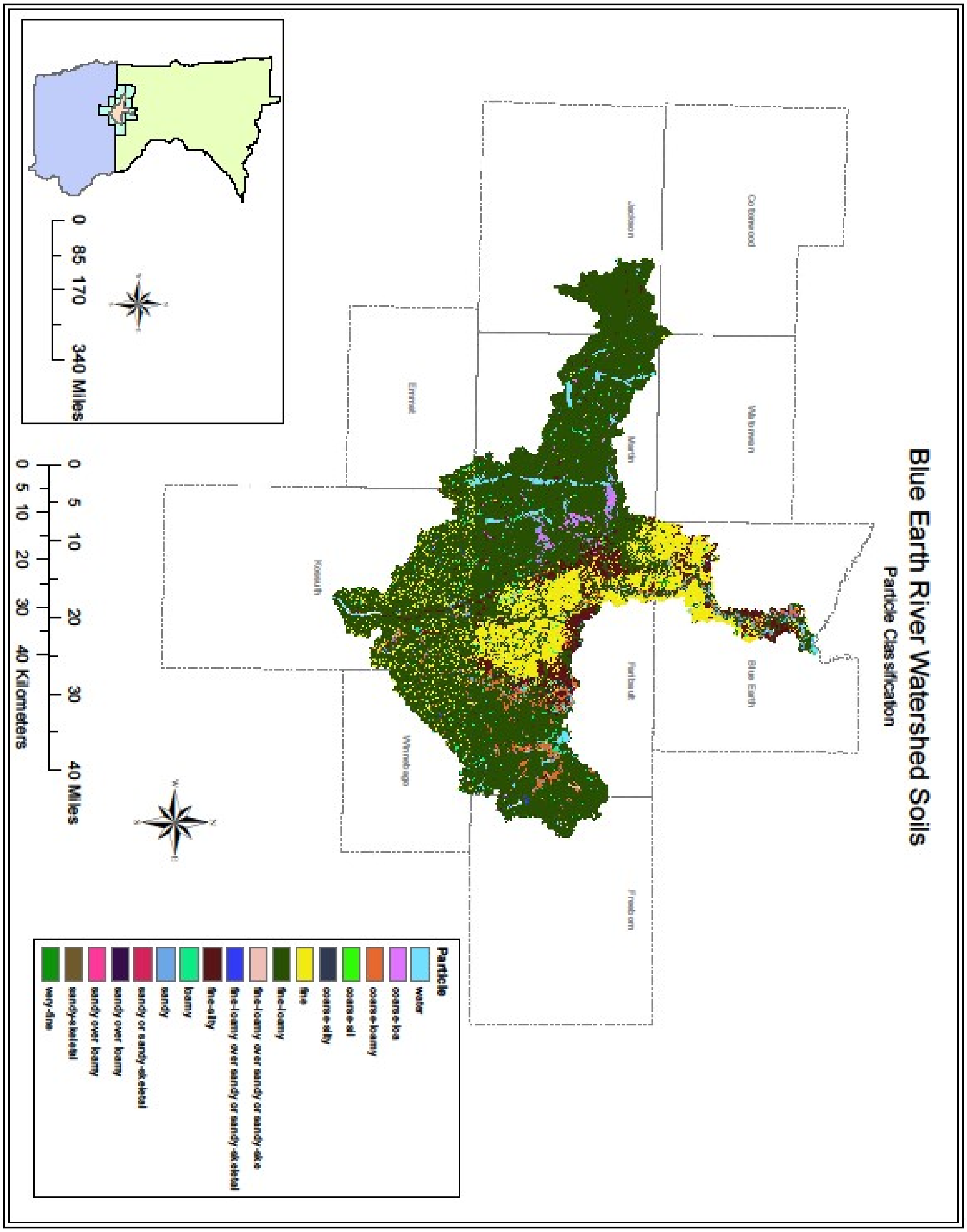


Figure 4.4 Blue Earth River Watershed Soil Classifications. The soil classification shown in seventeen classes to illustrate the variability in soils throughout the watershed and the dominance of fine-loamy evident.

The V*flo*™ model uses a time based physical basis equation, the Green-Ampt equation for infiltration. The Green-Ampt equation provides the total porosity, effective porosity, wetting front suction, and hydraulic conductivity based on soil classification. The soil classification was taken from the soils shapefile described above and entered into a spreadsheet with query statements for each of the soil classifications and their corresponding infiltration values. The infiltration values were then taken from the spreadsheet and added to the shapefile.

Figure 4.5 represents the initial abstraction values for the watershed that were derived from the Green-Ampt equation present in Rawls et al. (1983) and the previously described processes. The watershed has a range of 0.0 to 4.67 inches of initial abstraction with an average initial abstraction value of 0.57 inches. The 0.0 value of initial abstraction can be more than likely related to open water. The higher values of abstraction are present in the northern most portions of the watershed corresponding with the soil classifications fine-slity and very fine.

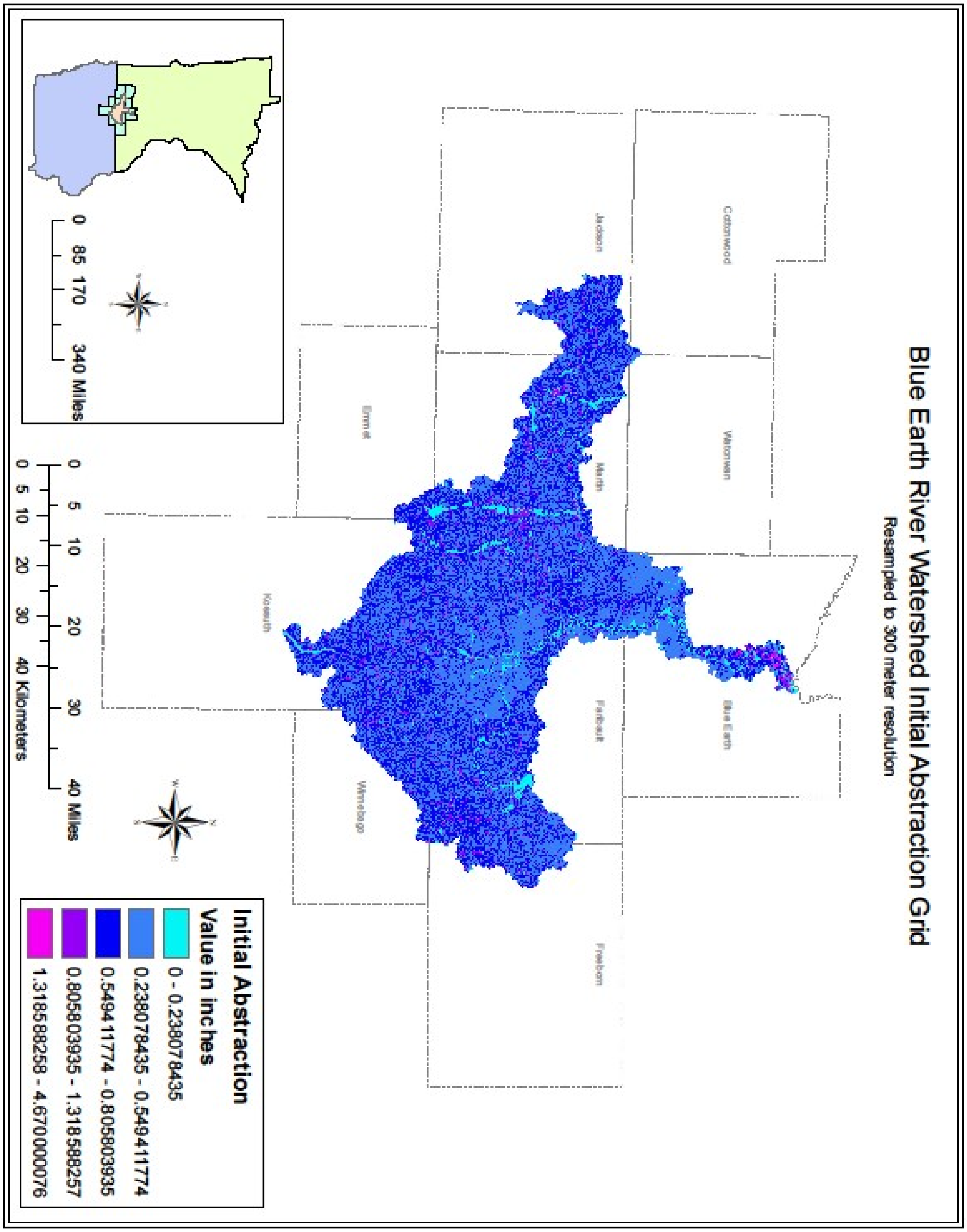


Figure 4.5 Blue Earth River Watershed Abstraction Values. Abstraction values are generally homogenous and show very little spatial variation. No significant trends are observed in these results.

The V*flo*™ model uses a dynamic physical basis equation, the Green-Ampt equation for infiltration. The Green-Ampt equation provides effective porosity for all different types of soil classifications. Described in V*flo*™ help effective porosity is the difference between total porosity and the soil moisture content based on soil classification and is independent of soil moisture at any time. Effective porosity is entered into the V*flo*™ model as a unitless decimal fraction where a value of one is completely porosity and a value of zero is absolutely no porosity (V*flo*™ Inc. 2007).

The soil classification was taken from the soils shapefile described above and entered into a spreadsheet with query statements for each of the soil classifications and their corresponding infiltration values. The infiltration values were then taken from the spreadsheet and added to the soil shapefile as an attribute.

Figure 4.6 represents the effective porosity values for the watershed that were derived from the Green-Ampt equation using values from Rawls et al. (1983). The watershed has an average effective porosity of 0.497, a relativity large number that corresponds to the clay rich content of the soils that are found throughout the watershed (Paulson et al., 1978). The overall range of the effective porosity was found to be 0.0 to 0.51. The zero values match up very well with the lakes present within the watershed along with other open water areas.

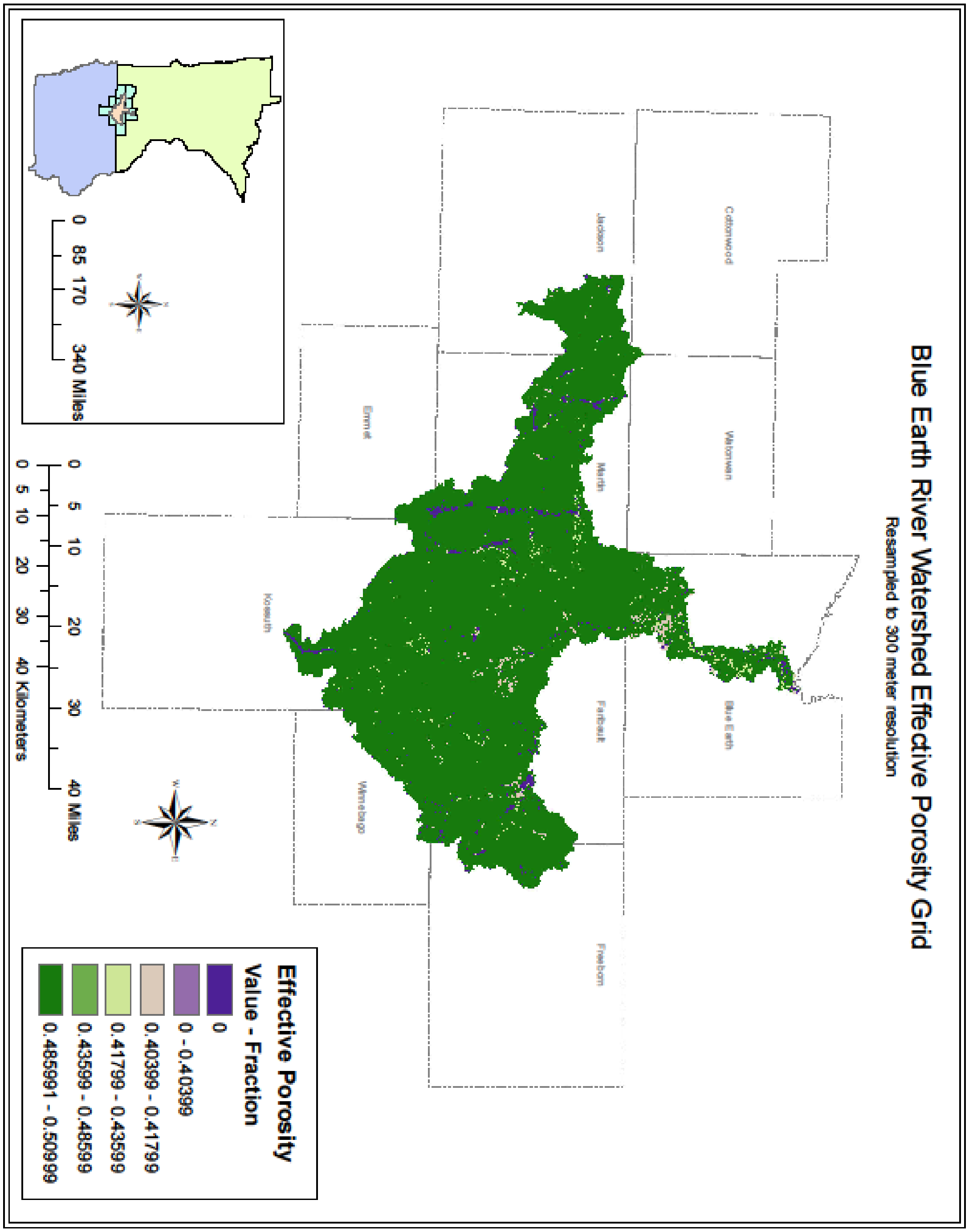


Figure 4.6 Blue Earth River Watershed Effective Porosity Map. The highest values for effective porosity are the most common throughout the watershed. Effective porosity values for the watershed demonstrate very little spatial variation and no significant trends are observed in these results.

Land use data was obtained from the Multi-Resolution Land Characteristics Consortium. The National Land Cover Dataset (NLCD) 2006 was downloaded, clipped to the watershed boundary and then resampled to the 300 meter cell size. The overland roughness, Manning's n values for each land cover type was assigned from the values found in Chow (1959).

Figure 4.7 represents the results of the Manning's n values being added to the NLCD and then classifying the values to display the range of roughness values. The overall average roughness value for the Blue Earth River watershed was 0.039 and has a range of 0.012 to 0.10. The overall average of the watershed corresponds very well with the land cover classification mature row crop and mature field crop. The Blue Earth River watershed is for the most part agricultural land consisting of row crops and field crops. The value of 0.012, pretty smooth, corresponds well to the open water areas along with the impervious areas such as the roads. The maximum values of roughness, 0.10 occur in the riparian areas near the river channels where the land cover is mainly trees and undergrowth.

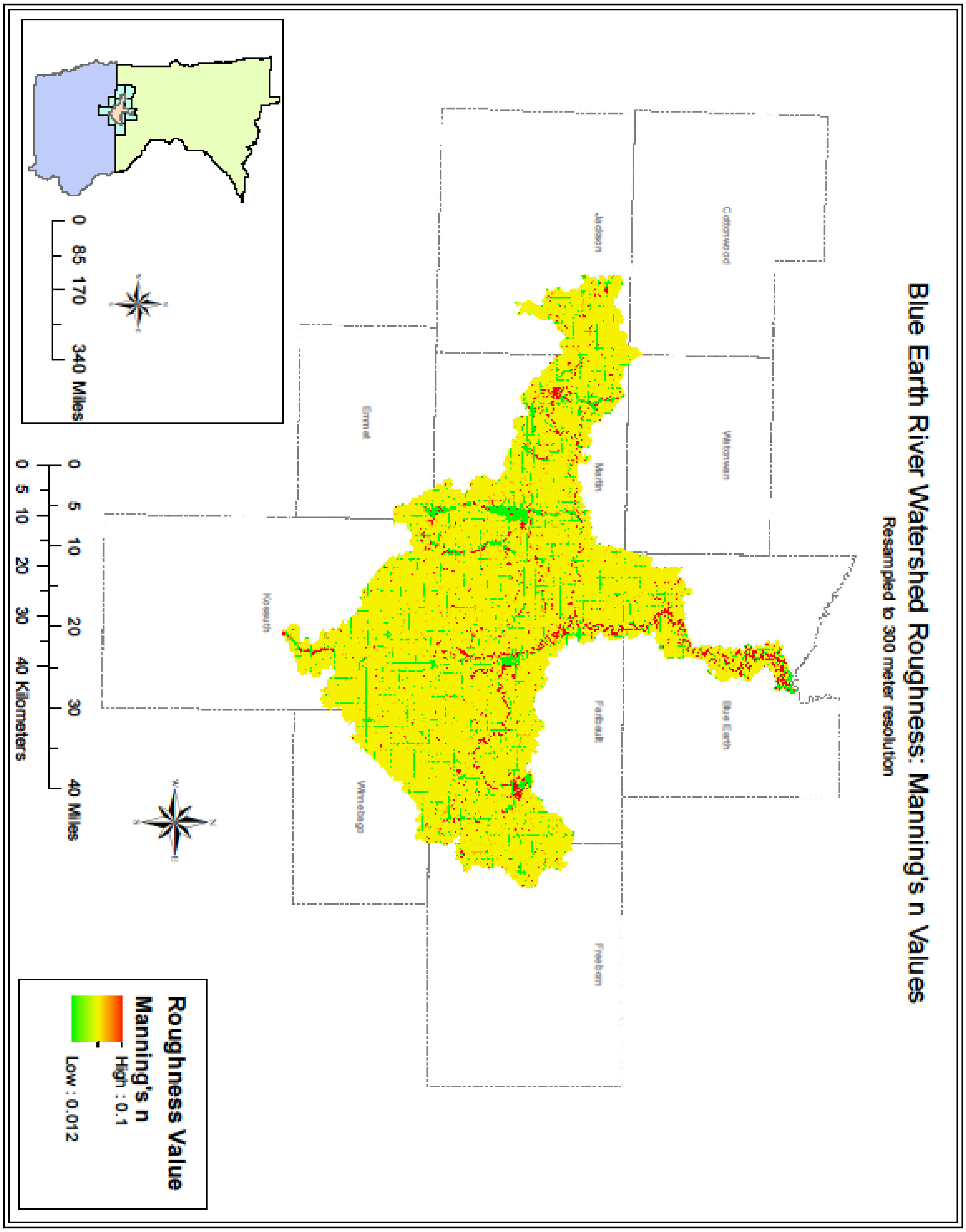


Figure 4.7 Blue Earth River Watershed Manning's n Values. The overall average roughness value for the Blue Earth River watershed was a Manning's n value of 0.039 corresponding well with the dominate land cover throughout the watershed, row crops and pasture.

As mentioned before the V*flo*™ model uses a time based physical basis equation, the Green-Ampt equation for infiltration. The Green-Ampt equation provides values for the wetting front parameter for all different types of soil classifications. Described in V*flo*™ help wetting front is the wetting front suction head and is based on soil classification and is independent of soil moisture at any time. The wetting front is important in deriving the infiltration amounts of unsaturated areas. Wetting Front is entered into the V*flo*™ model as units of centimeters or inches depending on the version of the V*flo*™ model that is begin used, metric or US customary. For the purposes of this study US customary was used and the wetting front units were enter in as inches.

The soil classification was taken from the soils shapefile described above and entered into a spreadsheet with query statements for each of the soil classifications and their corresponding infiltration values. The infiltration values were then taken from the spreadsheet and added to the soil shapefile as attributes.

The wetting front suction head values for the Blue Earth River watershed are presented in figure 4.8. The minimum values tend to be areas of water where the wetting front is expected to be low, open water areas.

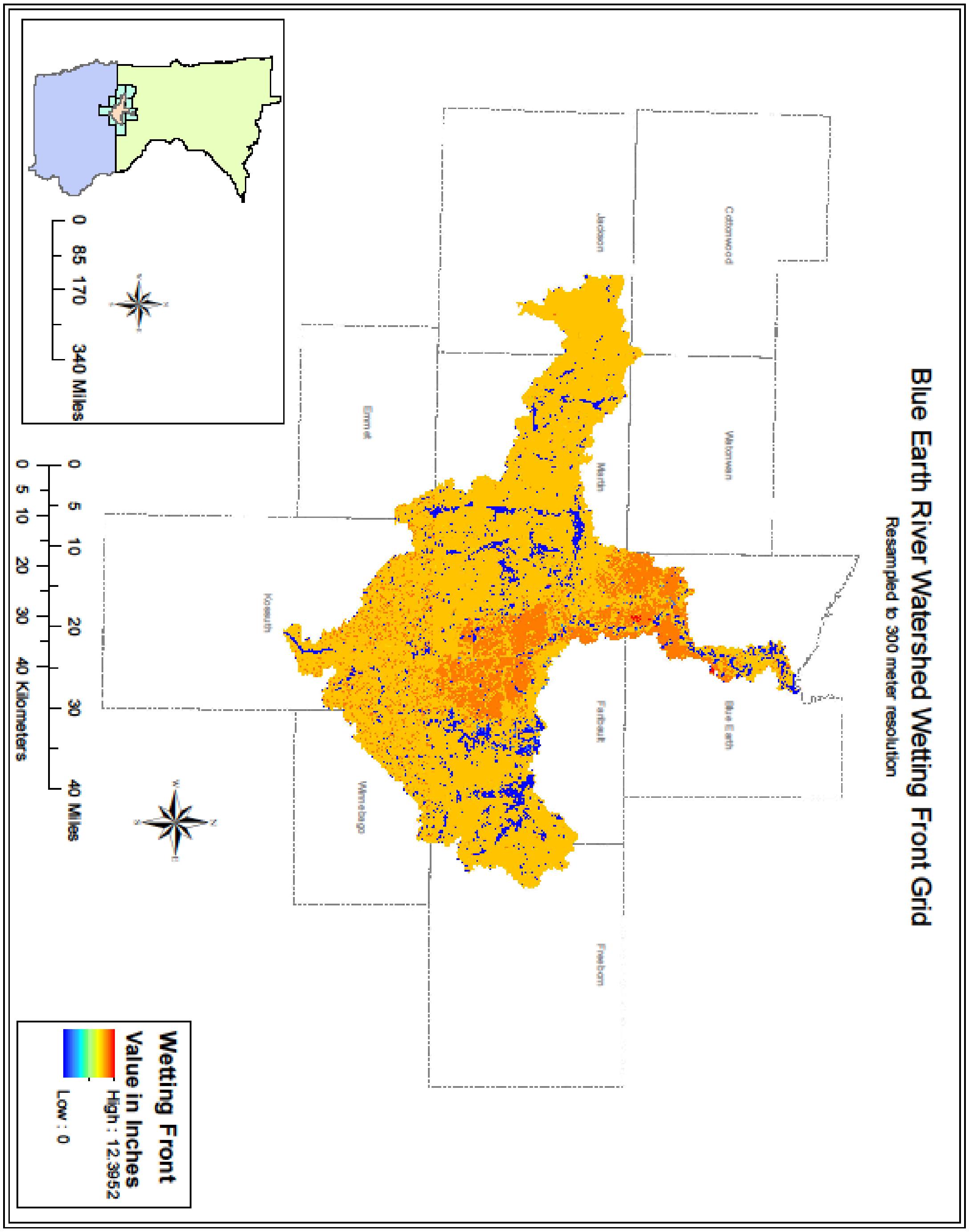


Figure 4.8 Blue Earth River Watershed Wetting Front Values. The moderate wetting front values throughout the watershed are expected with the dominance of fine-loamy soils within the watershed.

As mentioned before the V*flo*™ model uses a time based physical basis equation, the Green-Ampt equation for infiltration. The Green-Ampt equation provides values for the hydraulic conductivity parameter for all different types of soil classifications. Described in V*flo*™ help hydraulic conductivity is the saturated hydraulic conductivity in the Green-Ampt description. The hydraulic conductivity is used to control the infiltration over already saturated soils and is based on soil classification. Like the wetting front parameter, hydraulic conductivity is entered into the V*flo*™ model as units of centimeters or inches depending on the version of the V*flo*™ model that is begin used, metric or US customary. Once again the version used for the purpose of this study the US customary was used and the units used were inches.

The values for the Blue Earth River watershed are presented in figure 4.9. The range of values is from 0.0 to 0.37 inches of hydraulic conductivity. The average value of the watershed is 0.16 inches. The minimum values for the watershed overlay the open water and lakes areas within the watershed. The majority of the watershed is within the range of 0.1189 to 0.3700. Table 4.1 lists the percentages and acres of each the class ranges for hydraulic conductivity within the Blue Earth River watershed.

Table 4.1 Hydraulic Conductivity for Blue Earth River Watershed at 300 meter resolution

Range	Percentage	Acres
0	1.90506	18948.03696
0 - 0.029	1.086689	10808.38728
0.029 - 0.98	6.242873	62092.62816
0.0986 - .1189	4.22	42032.6172
0.1189 - 0.2190	46.84391	465917.106
0.2190 - 0.3700	39.69546	394817.4884

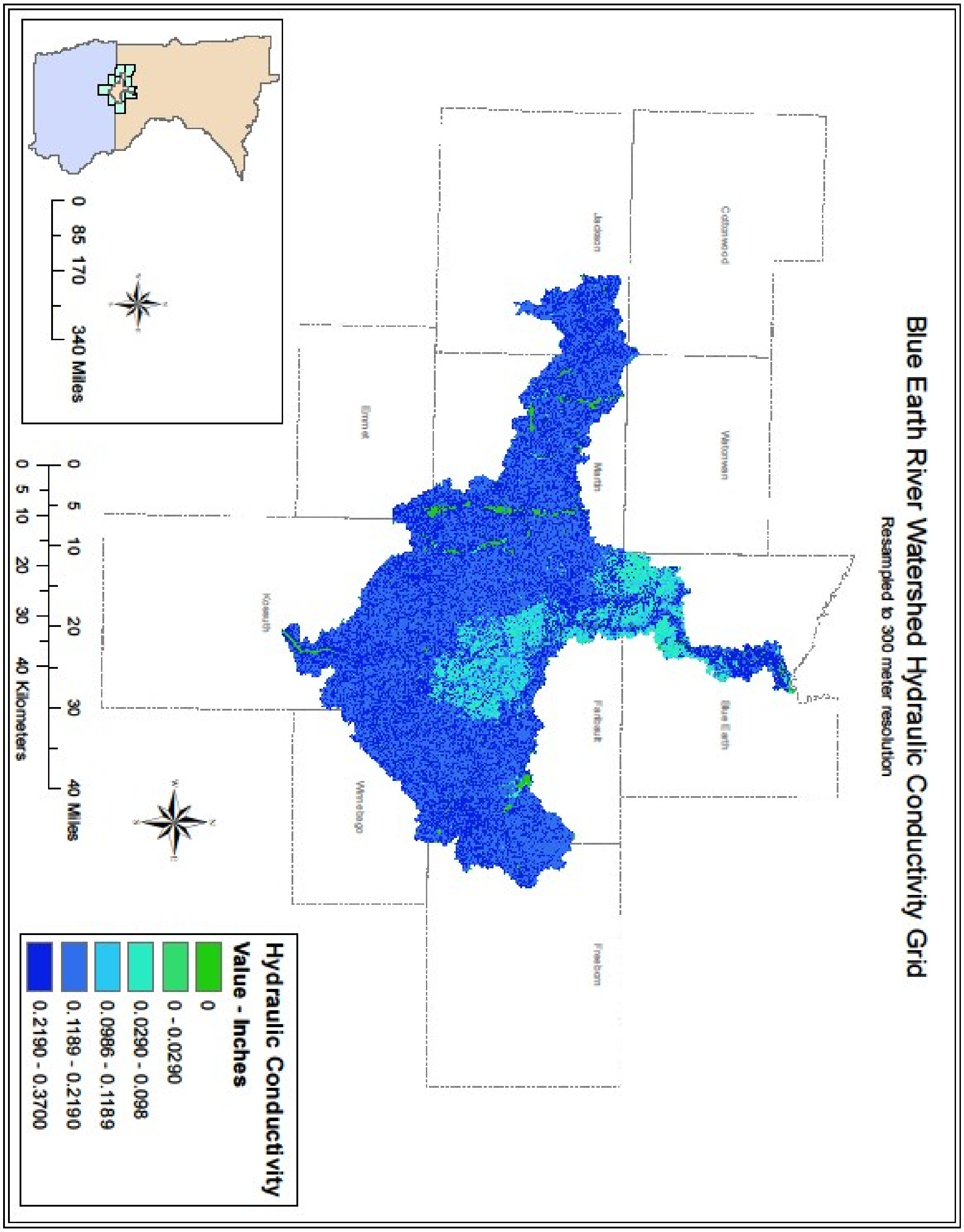


Figure 4.9 Blue Earth River Watershed Hydraulic Conductivity. The highest values for hydraulic conductivity dominate the Blue Earth Watershed. Hydraulic Conductivity values for the watershed demonstrate very little spatial variation.

Land cover data were obtained from the Multi-Resolution Land Characteristics Consortium. The National Land Cover Dataset (NLCD) 2006 was downloaded, clipped to the watershed boundary and then resampled to the 300 meter cell size. The land cover dataset was used with the hydrologic soil group to obtain the curve numbers for the entire watershed. The curve numbers where then used to obtain the abstraction value for each cell within the V*flo*™ model.

The Blue Earth River watershed has an area of 1,002,240 acres in the counties of Blue Earth, Brown, Cottonwood, Faribault, Freeborn, Jackson, Le Sueur, Martin, Steele, Waseca, and Watonwan in Minnesota and Emmet, Kossuth, and Winnebago in northern Iowa. Figure 4.10 displays the 2006 land cover present within the watershed. As one can see the over whelming majority of land cover is agricultural. Table 4.2 is the composition of the resampled 300 meter 2006 NLCD percentages of land cover. Boone (2000) states that the Blue Earth River watershed is comprised of 92 percent agricultural land.

Table 4.2 2006 National Land Cover Dataset percentages

VALUE	CLASS_NAME	PERCENT
11	Open Water	1.44
21	Developed, Open Space	5.78
22	Developed, Low Intensity	0.80
23	Developed, Medium Intensity	0.17
24	Developed, High Intensity	0.07
31	Barren Land	0.06
41	Deciduous Forest	0.76
43	Mixed Forest	0.16
71	Grassland/Herbaceous	2.16
81	Pasture/Hay	0.61
82	Cultivated Crops	85.39
90	Woody Wetland	1.55
95	Emergent Herbaceous Wetland	1.05

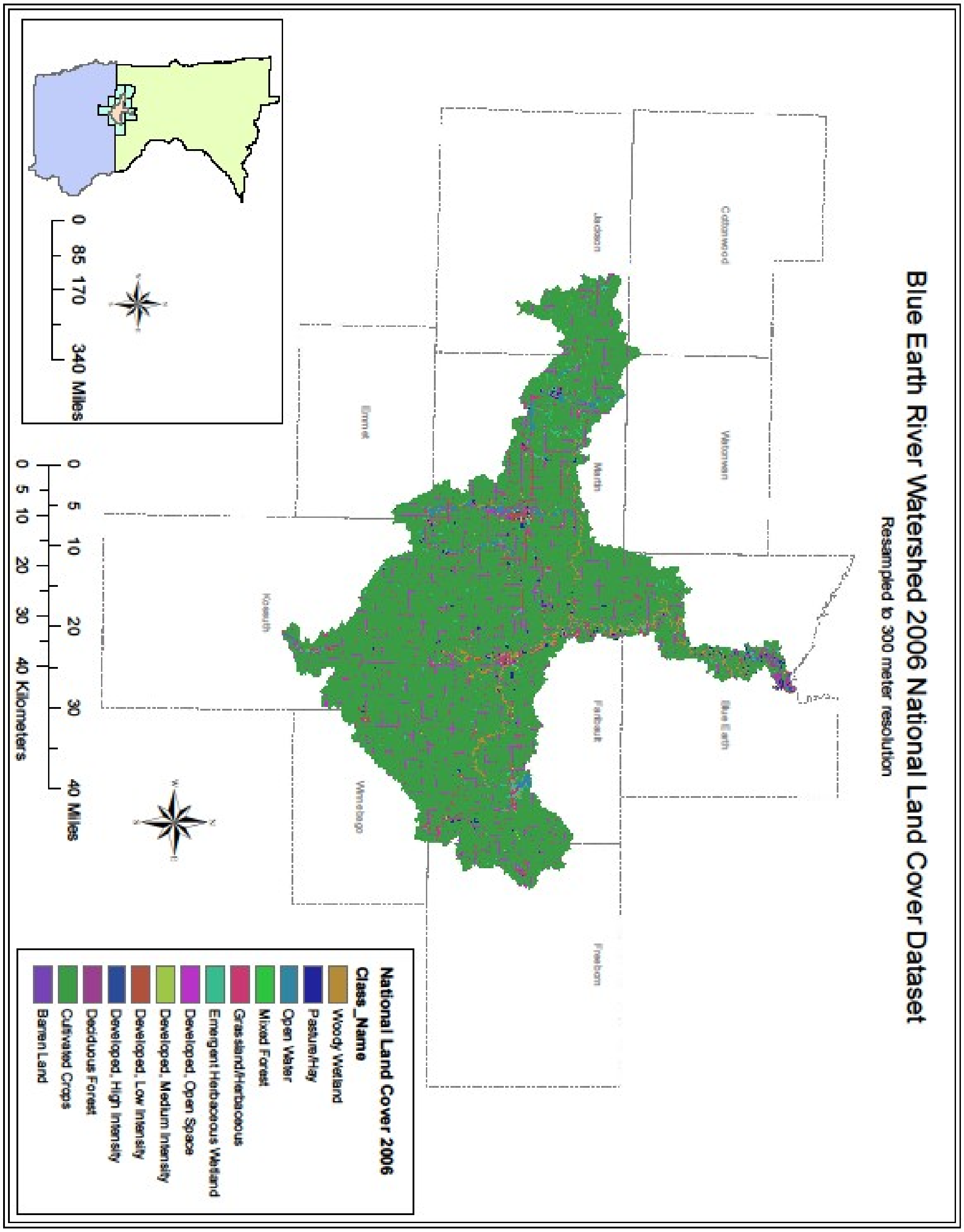


Figure 4.10 Blue Earth River Watershed National Land Cover Dataset (NLCD 2006). The land cover dataset illustrates the homogenous land cover and show almost no spatial variation. Cultivated crops is the dominate land cover throughout the Blue Earth Watershed.

The soil data for the Blue Earth River watershed was obtained from the United States Department of Agriculture Natural Resources Conservation Services (USDA-NRCS) soil data mart. Each county within the watershed was downloaded and the shapefiles were then merged together using the merge tool in ArcMAP. The shapefile was clipped to the watershed boundary using the clip tool in ArcMAP. The symbology was changed to represent the hydrologic soil group. The shapefile was then converted to a raster grid using conversion tools – to raster – feature to raster tool in ArcMAP selecting the hydrologic group as the field and a cell size of 300 meters. Figure 4.11 represents the results of this process and displays the hydrologic soil groupings for the entire Blue Earth River watershed.

As mentioned previously the hydrologic soil group along with the national land cover dataset is used to obtain the curve numbers for the entire watershed. The curve number is then used to extract the initial abstraction value which is used in the infiltration solving process of the model. Table 4.3 lists the composition of the hydrologic soil groups within the watershed.

Table 4.3 Blue Earth River Watershed Hydrologic Soil Group Composition at 300 meter resolution

COUNT	HYDGRP	Percentage	Soil Textures	Infiltration Rate
695		1.556272	N/A	N/A
20258	B/D	45.36253		
510	D	1.142013	Clay loam, silty clay loam, sandy clay, silty clay, or clay	Low
271	A	0.606834	Sand, loamy sand, or sandy loam	High
17534	B	39.26284	Silt loam or loam	Moderate
1858	C	4.160509	Sandy clay loam	Low
704	A/D	1.576425		
2828	C/D	6.332572		

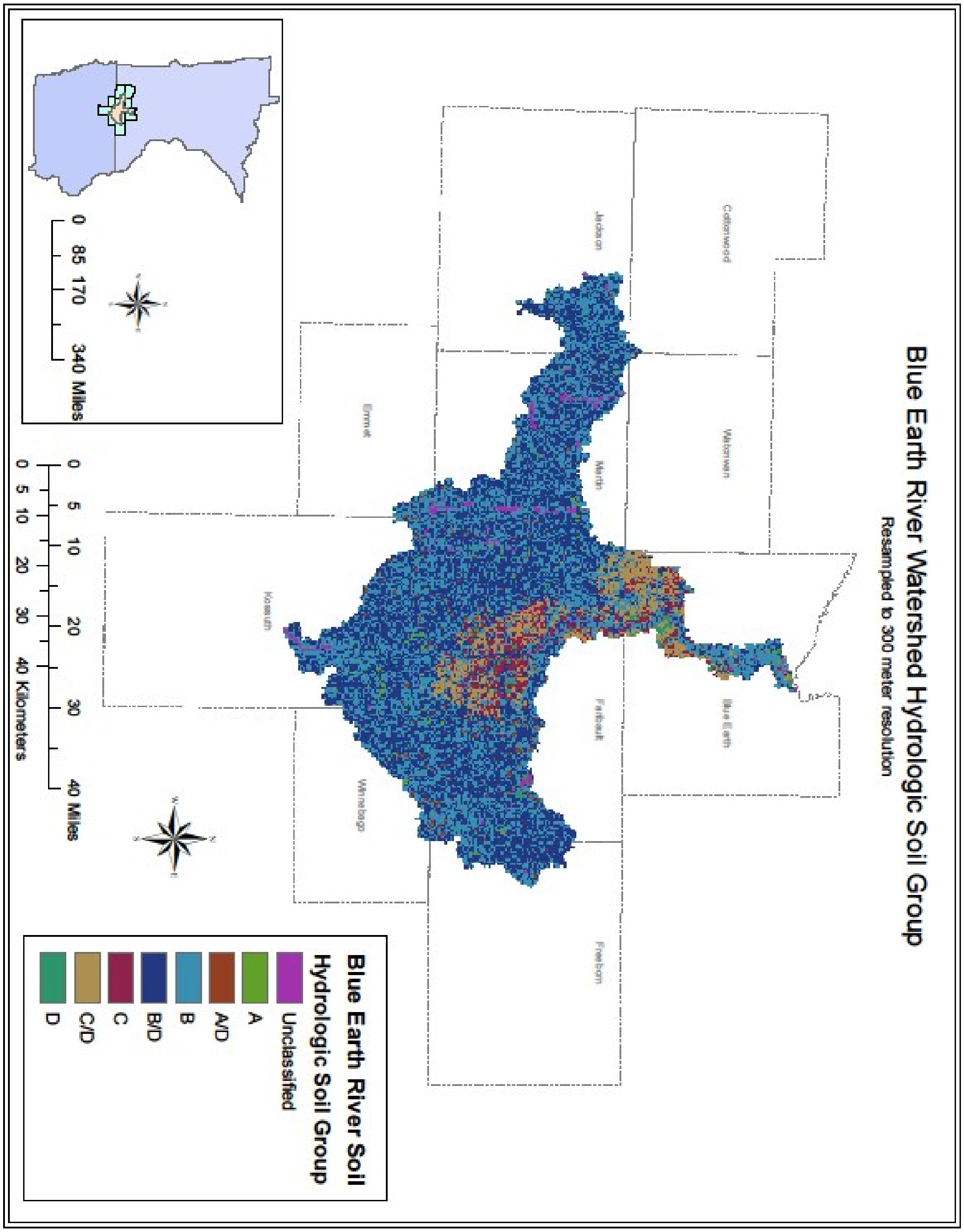


Figure 4.11 Blue Earth River Watershed Hydrologic Soil Groups Grid. Hydrologic Soil Group B/D and B with slow to moderate infiltration rates dominate the watershed. The resampled 300 meter grid illustrates the potential of moderate to high run off rates throughout the watershed.

The process for obtaining the DEM for this parameter is similar to the processes that have been described in previously for the other needed parameters. In order to create the flow direction for the watershed the spatial analyst – hydrology – flow direction tool was used in ArcMAP. The resampled 300 meter DEM was used to create the 300 meter flow direction grid. The resampled flow direction grid was then converted to an ASCII file using the raster to ASCII tool in ArcMAP. Figure 4.12, shows the resulting grid from these processes.

Analysis of the flow direction grid shows the overall flow tendencies of the watershed. The western portion of the watershed has an overall flow direction of east and the eastern portion of the watershed has an overall flow direction of west meeting in what can be considered the middle of the watershed. The analysis does match the overall drainage network of the watershed.

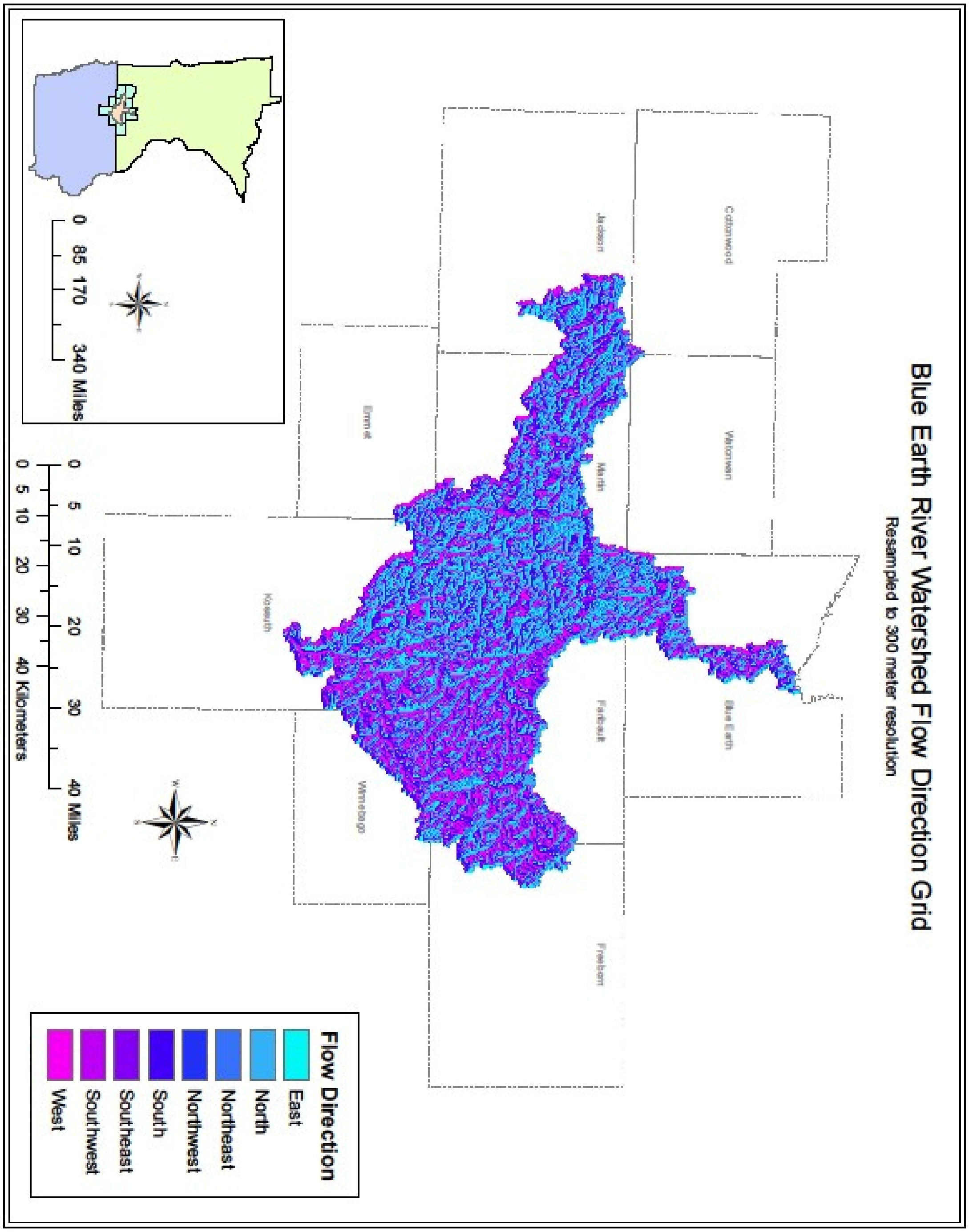


Figure 4.12 Blue Earth River Watershed Flow Direction Grid. The watershed has significant drainage towards the west and east towards a central axis

The watershed 300 meter DEM was used to create the flow direction grid in a process described previously. The resulting flow direction grid was used to create the 300 meter flow accumulation for the watershed using the spatial analyst – hydrology – flow accumulation tool in ArcMAP. The flow accumulation grid was then converted to ASCII using the raster to ASCII tool in ArcMAP.

Figure 4.13 displays the flow accumulation of the watershed. Analysis of the flow accumulation grid reveals that the number of cells that flow into the next cell continues to increase downstream until the river exits the watershed. Minor corrections were performed within the watershed due to the 300 meter resolution. The flow accumulation is the greatest at the mouth of the river and the same is found for the tributaries to the Blue Earth River.

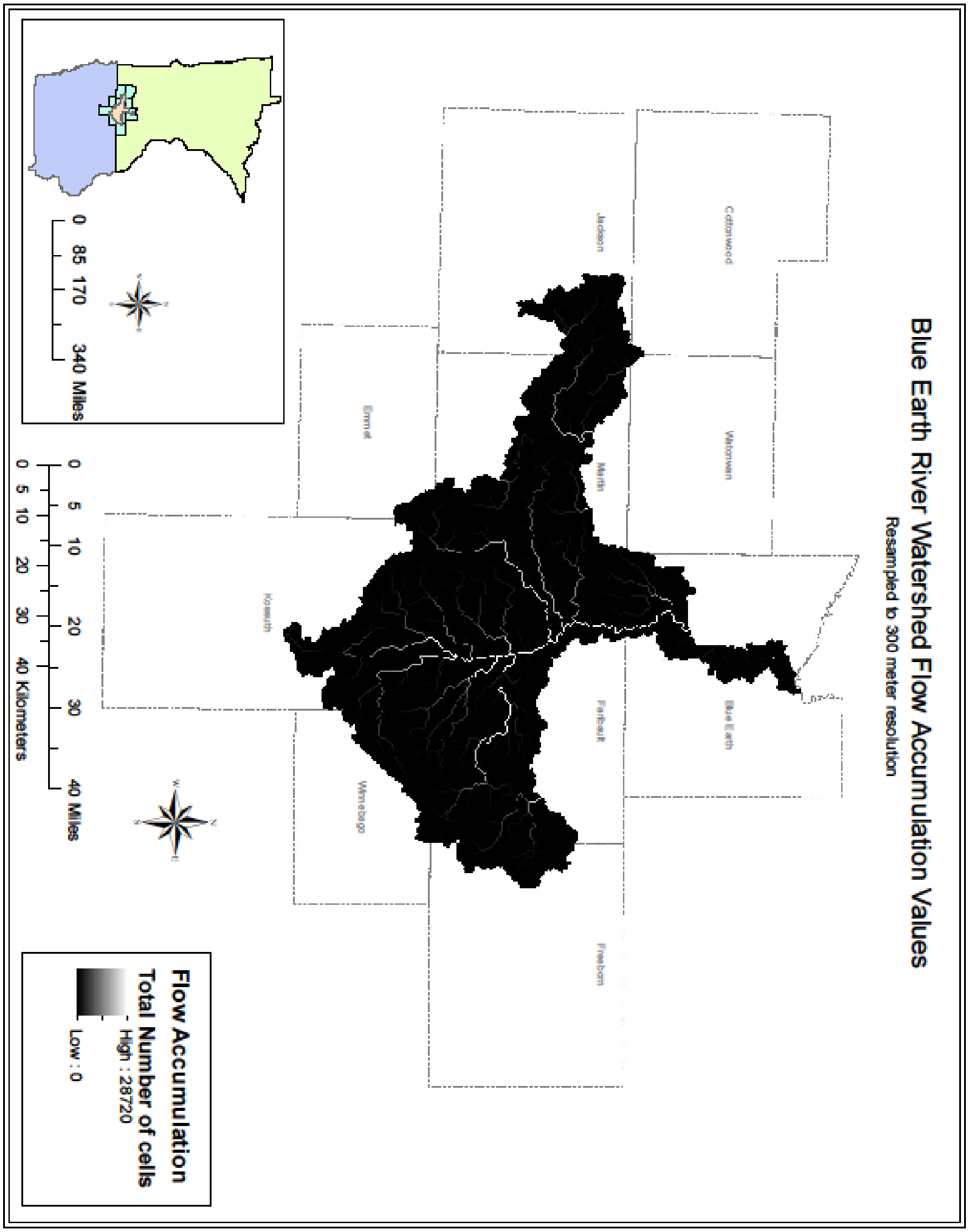


Figure 4.13 Blue Earth River Watershed Flow Accumulation Grid. The flow accumulation trends to be the greatest at the confluence of the Blue Earth River and the Minnesota River. The same is found to be true for the tributaries to the Blue Earth River.

The channel width parameter was developed by using the flow accumulation grid in the following equation:

Equation 4.1 Blue Earth River Watershed Channel Widths Equation

ch_width = 5.77778 *pow({ch_da_sq_km}, 0.1782)/0.3048 for feet
ch_da_sq_km = stream flow accumulation grid * drainage area for each cell

The stream flow grid was multiplied by the drainage area of each cell, 0.09 km^2 or 90,000 m^2 for the Blue Earth River Watershed. The value was then entered into the ch_width equation. The channel width was then converted into an ASCII file using the raster to ASCII tool in ArcMAP. For the cells at Faribault county road 8, Faribault county road 12, and Blue Earth county road 34 the channel characteristics were changed due to the fact that these three sites were the where the monitoring stations were located at and therefore they had more detailed characteristics available. These values were used as rated channel cells at these three locations.

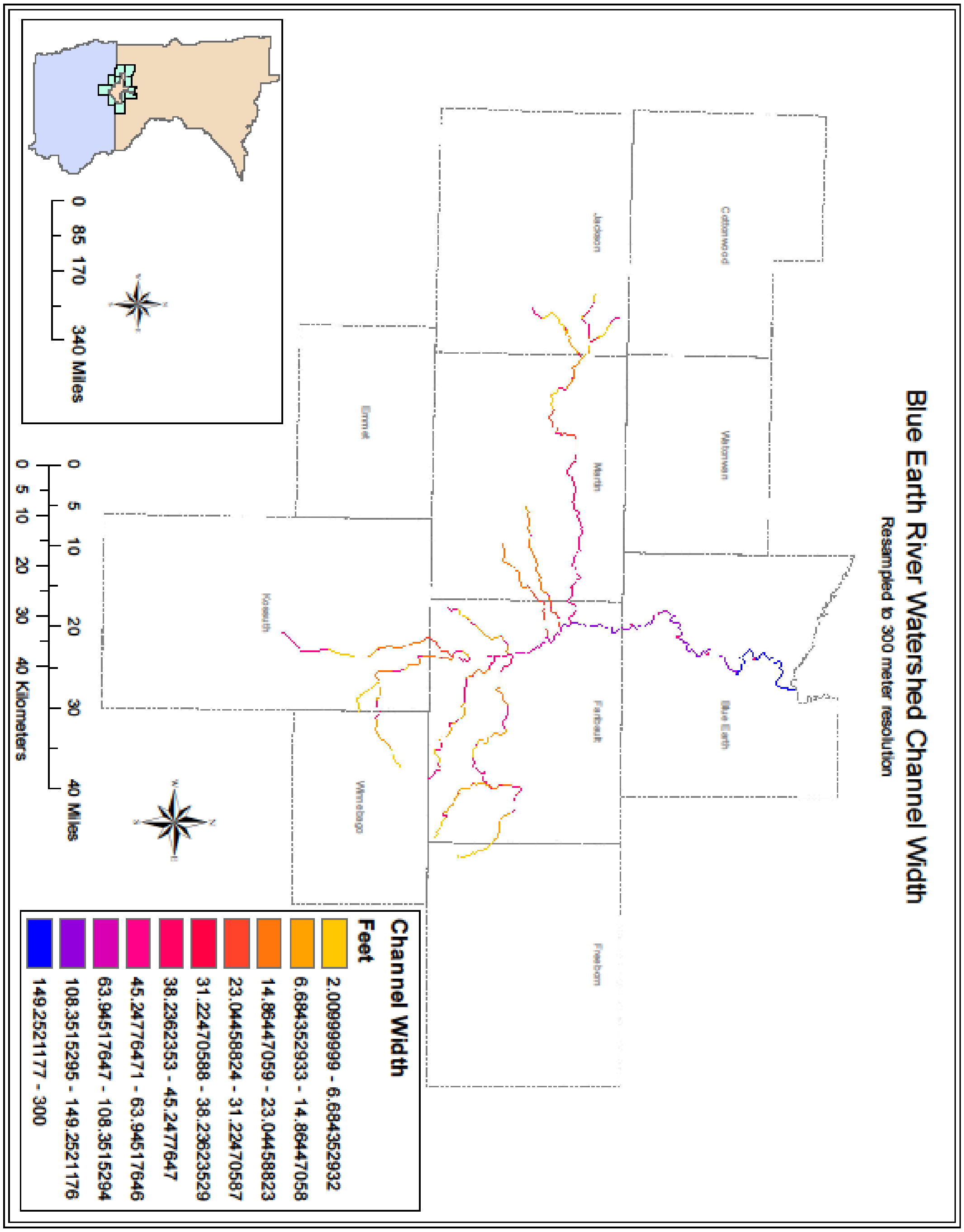


Figure 4.14 Blue Earth River Watershed Channel Widths. The channels shown in this figure were converted to a raster grid to be used in the V*flo*™ model. The resulting raster grid was then checked with field observations to ensure accuracy was within acceptable error of less than 3%.

4.3 Hydrologic Results: Measured Stream Flwo and Observerd Precipitation

The following results include continuous in stream stage monitoring, routine gauging of the Blue Earth River, and the development of discharge hydrographs for the BEC 34, FTC 8, and FTC 12 monitoring stations.

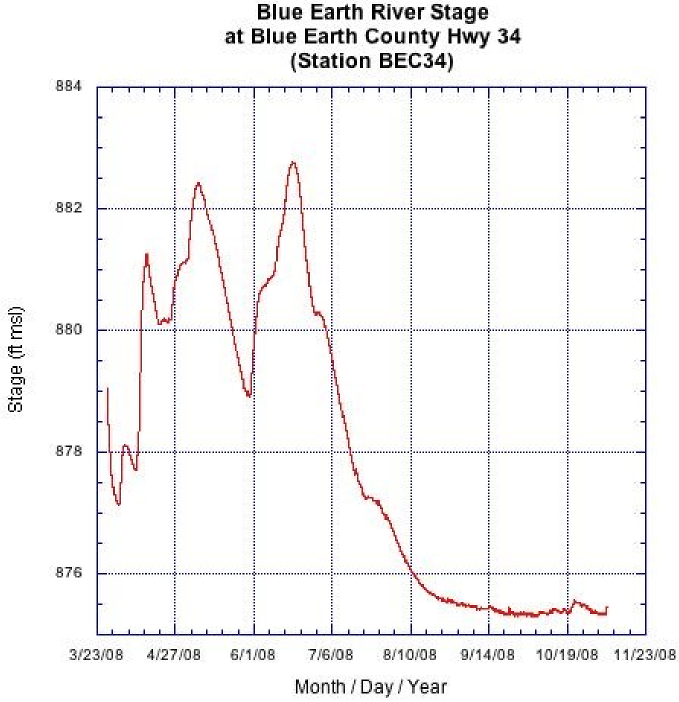


Figure 4.15 Blue Earth River Stage – BEC 34 site. Similar to the monitoring sites upstream (FTC 8 and FTC 12) from BEC 34, seven significant precipitation events led to two major episodes of elevated stage occurring in May and June, followed by a period of extremely dry conditions returning the river to baseflow conditions.

The stage for the Blue Earth River County road 34 site was collected for the entire 2008 monitoring season from complete ice out conditions in late March to mid October. The stage was captured by the methods described above in the gauging methods section.

Analysis of the hydrograph shows that the watershed experienced extremely dry conditions from the end of June until the end of the monitoring season in October.

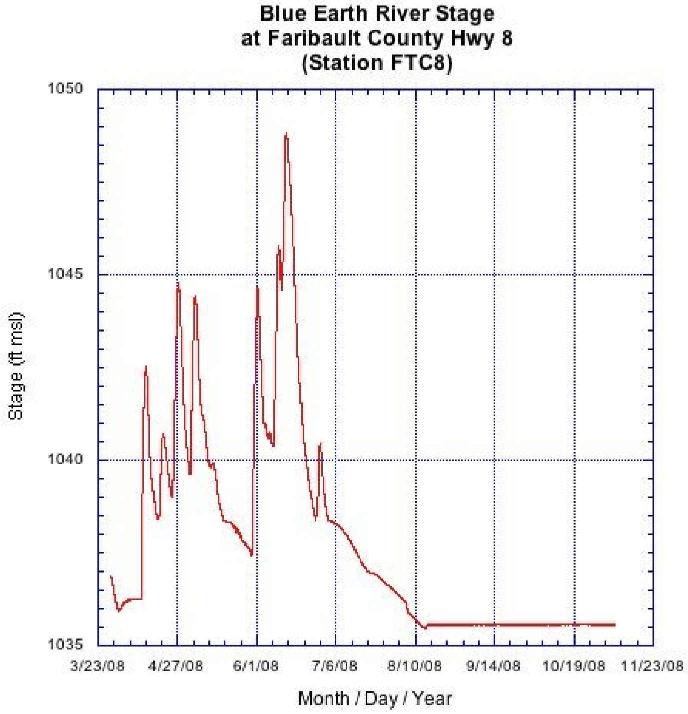


Figure 4.16 Blue Earth River Stage – FTC 8 site. Seven significant precipitation events led to two major episodes of elevated stage occurring in May and June, followed by a period of drought returning the river to baseflow conditions.

The stage for the Faribault County road 8 site, which is the southern most site was collected for the entire 2008 monitoring season. Analysis of the hydrograph shows a high level of sensitivity to precipitation events which occurred within the watershed during this time in part because the location is still downstream of the East Branch of the Blue Earth River and all the of Iowan branches of the river. This site showed responses to eastern and southern rainfalls. The location has extreme high and low flow stages and usually showed responses first to most rainstorms because of its location, being downstream of a fairly large area of the watershed, and the general path of storms in southern Minnesota.

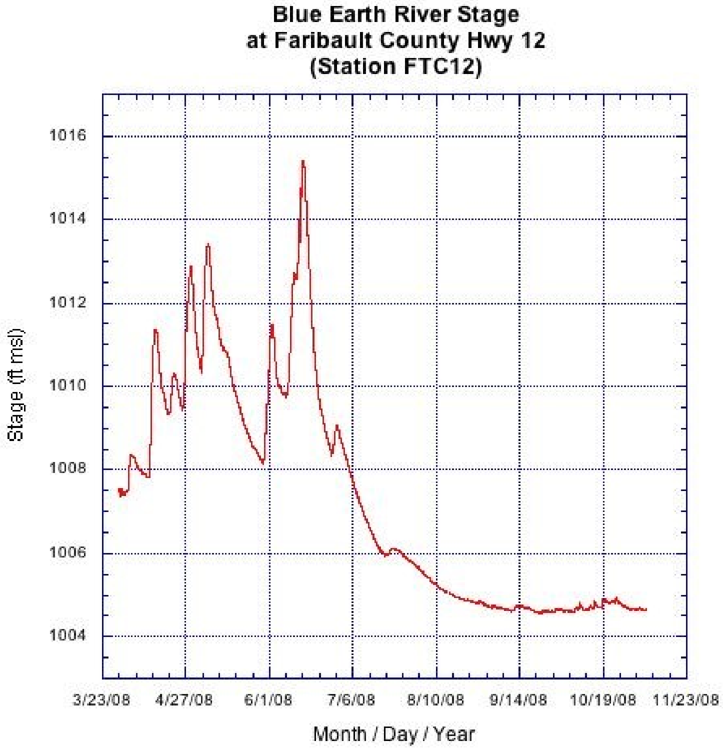


Figure 4.17 Blue Earth River Stage - FTC 12 site. Similar to FTC 8, seven significant precipitation events led to two major episodes of elevated stage occurring in May and June, followed by a period of drought returning the river to baseflow conditions.

The stage for the Faribault County road 12 site located downstream of the FTC 8 site, Elm Creek confluence which also includes Dutch Creek and Center Creek as well was collected for the entire 2008 monitoring season. Western and southwestern precipitation events will be seen preferentially in its stage recordings and will cause the rising limbs first at this location. The stage was captured by the methods described above in the gauging methods section. Analysis of the hydrograph shows more sensitivity to precipitation events at this site. This sensitivity maybe attributed to the Faribault County road 12 site location which is located downstream of Elm Creek and the East Branch of the Blue Earth River confluence. This location accounts for approximately 2/3 of the watershed drainage area.

Tables 4.4, 4.5, and 4.6 represent the date and time, name of persons performing the data collection, channel width, beginning and ending stage of the river, and the measured discharge of the river. This data was then used to calculate to the rating curve for each of the three locations where the stilling wells were installed.

Table 4.4 Blue Earth River Rating Blue Earth County Road 34

Date Time	Names of persons performing rating	Channel Width	Beginning and ending stage of water for each rating	Measured discharge of the river
08/20/2007 12:15 pm start	Mike Merlini Bryce Hoppie	136.4 ft	5.95 feet – start n/a – finish	239 cfs
08/31/2007 2:00 pm start 4:30 pm finish	Mike Merlini, Kathryn Brosch Bryce Hoppie	161 ft	6.97 feet – start n/a – finish	826.20 cfs
10/03/2007 4:48 pm start 6:43 pm finish	Mike Merlini Kathryn Brosch	171 ft	10.08 ft – start 10.14 – finish	2663.13 cfs
06/17/2008	Mike Merlini	171 ft	n/a	2640.99 cfs
08/19/2008 10:12 am start 11:00 am finish	Scott Hommerding, Ryan Beuc	132 ft	4.675 ft –start	95 cfs
11/01/2008 9:00 am start	Mike Merlini	57 ft	875.39 on level logger	16.43 cfs
05/03/2009	Bryce Hoppie	158 ft	n/a – start 6.93 ft – finish	766.61 cfs
06/09/2009 10:30 am start 11:15 am finish	Scott Hommerding, Ryan Beuc	156 ft	5.50 ft – start 5.50 ft – finish	265.34 cfs
06/23/2009 2:00 pm start 4:30 pm finish	Scott Hommerding, Jonathan Stoltman	160 ft	6.99 ft – start	953.85 cfs

Table 4.5 Blue Earth River Rating Faribault County Road 8

Date Time	Names of persons performing rating	Channel Width	Beginning and ending stage of water for each rating	Measured discharge of the river
08/24/2007 10:15 am start 12:30 pm finish	Mike Merlini, Bryce Hoppie	154’ 6” ft	1042.72’ msl – start n/a – finish	1979.72 cfs
09/07/2007 5:00 pm start 5:45 pm finish	Mike Merlini, Bryce Hoppie	114 ft	1036.85’ msl – start n/a – finish	462.61 cfs
10/05/2007 7:45 am start 9:45 am finish	Mike Merlini, Bryce Hoppie	172’ 10” ft	1046.6’ msl– start n/a – finish	3133.72 cfs
05/31/2008 4:45 pm start 7:15 pm finish	Mike Merlini Bryce Hoppie	169 ft	n/a	2870.32 cfs
08/05/2008 12:30 pm start 02:00 pm finish	Scott Hommerding, Bryce Hoppie	80 ft	1036.2’ msl–start n/a – finish	95.46 cfs
10/22/2008 10:22 am start 11:50 am finish	Mike Merlini, Bryce Hoppie	64 ft	n/a	19.38 cfs
05/03/2009 9:15 am start 10:35 am finish	Bryce Hoppie	129 ft	1038.2’ msl – start n/a – finish	512.40 cfs
06/09/2009 12.05 pm start 01:30 pm finish	Scott Hommerding, Jonathan Stoltman	136 ft	1040.12’ msl –start n/a – finish	1149.24 cfs

Table 4.6 Blue Earth River Rating Faribault County Road 12

Date Time	Names of persons performing rating	Channel Width	Beginning and ending stage of water for each rating	Measured discharge of the river
09/30/2007 04:06 pm start 05:45 pm finish	Mike Merlini, Bryce Hoppie	151 ft	26’9” – finish	849.15 cfs
10/05/2007 10:15 am start 11:30 am finish	Mike Merlini, Bryce Hoppie	164 ft	22’ 5.5” – start n/a – finish	3484.54 cfs
04/04/2008 2:40 pm start 4:00 pm finish	Mike Merlini, Bryce Hoppie	151 ft	26’ 5”– start n/a – finish	894.58 cfs
08/05/2008 1:40 pm start 2:55 pm finish	Mike Merlini Bryce Hoppie	115.9 ft	28’ 8” – start n/a – finish	149.21 cfs
05/03/2009 11:35 am start 12:33 pm finish	Bryce Hoppie	150.5 ft	27.75’ – start n/a – finish	767.44 cfs
06/10/2009 11:45 am start 01:00 pm finish	Scott Hommerding, Jonathan Stoltman	151 ft	25’ 5” – start n/a – finish	1099.36 cfs
06/22/2009 11:30 am start 12:30 pm finish	Scott Hommerding, Jonathan Stoltman	151 ft	26’ – start n/a – finish	882.80 cfs

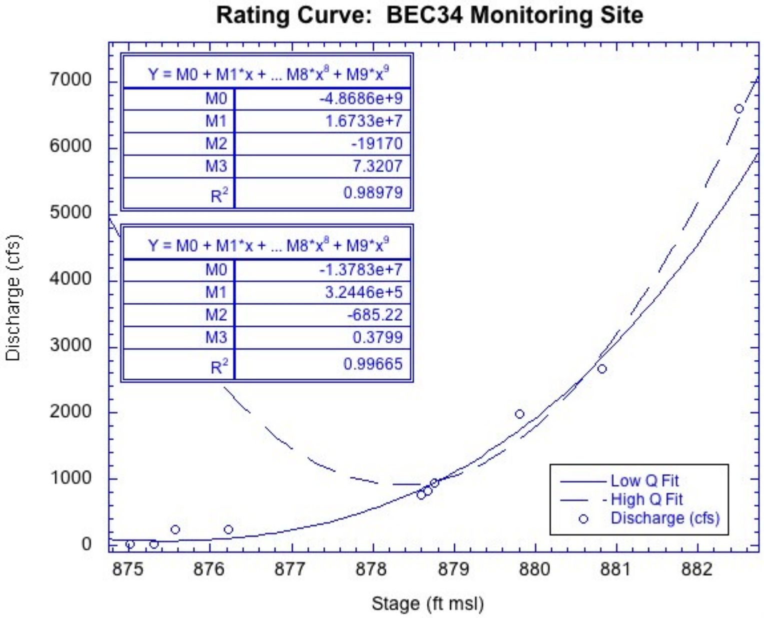


Figure 4.18 Blue Earth River Rating Curve for Blue Earth County Road 34 (BEC34). A two-part fit was needed at this particular site in order to match the results. R-squared values of the single regresion are above .99 for discharge values greater than 878.25 cfs. R-squared values of the single regresion are above .98 for discharge values less than 878.25 cfs demonstrating a extremely strong fit.

The rating curve is for the Blue Earth River County road 34 site, the northern most gauging site on the Blue Earth River. The fits among the existing stage and discharge data are excellent with r-squared values of the single value regression used to fit the stage and discharge results are above 0.99. Differences between the highest rated stage, 2663 cfs and the highest recorded stage, 5455.1 cfs therefore estimates for high flows are subject to errors associated with extrapolating trends. A two-part fit was needed at this particular site in order to match the results corresponding to the low and high flows.

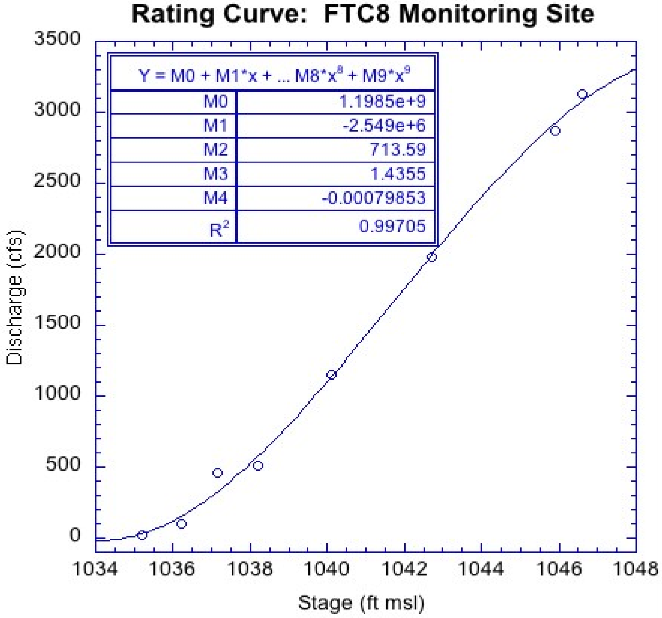


Figure 4.19 Blue Earth River Rating Curve Faribault County Road 8 (FTC8). R-squared values of the single regresion are above .99. A mix of the 3rd and 4th order polynomial equations were used to fit the data.

The rating curve is for the Faibault County road 8 site, the southern most gauging site just downstream of the confluence of the East Branch of the Blue Earth River. The fits among the existing stage and discharge data are again excellent with r-squared values of the single value regression used to fit the stage and discharge results are 0.99705. Differences between the highest rated stage, 3133 cfs and the highest recorded stage, 3711.7 cfs therefore estimates for high flows are subject to errors associated with extrapolating trends. A mix of the 3rd and 4th order polynomial equations were used to fit the data.

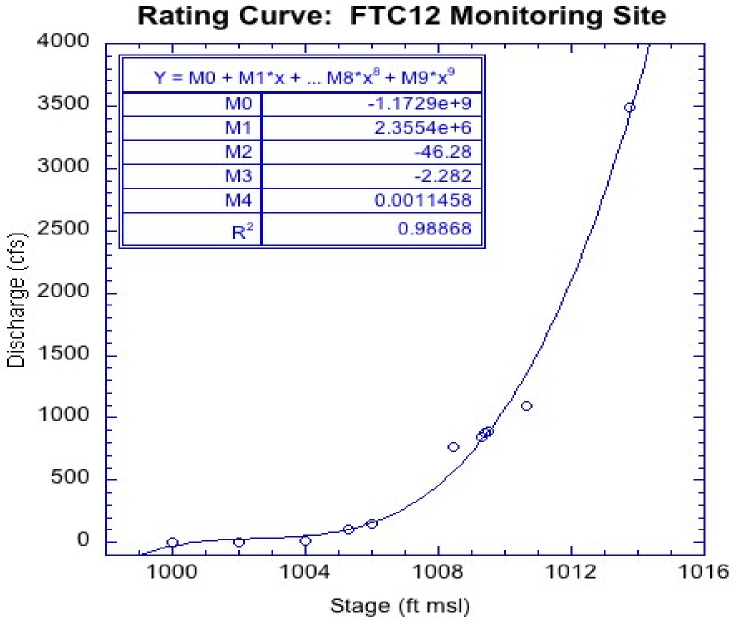


Figure 4.20 Blue Earth River Rating Curve Faribault County Road 12 (FTC12). Single value regression r-squared value of above .98 demonstrates a very strong fit. Although there is a potential of error estimating high flows due to the slope of the fit at the high flow is very steep.

The rating curve is for the Faibault County road 12 site, the gauging site just downstream from the Elm Creek confluence on the Blue Earth River. The r-squared values of the single value regression used to fit the stage and discharge results are 0.98868. Differences between the highest rated stage, 3484.54 cfs and the highest recorded stage, 5115.4 cfs therefore estimates for high flows are subject to errors associated with extrapolating trends. The slope of the fit at the high flow is very steep, the potential errors associated with estimating high flows could be significant.

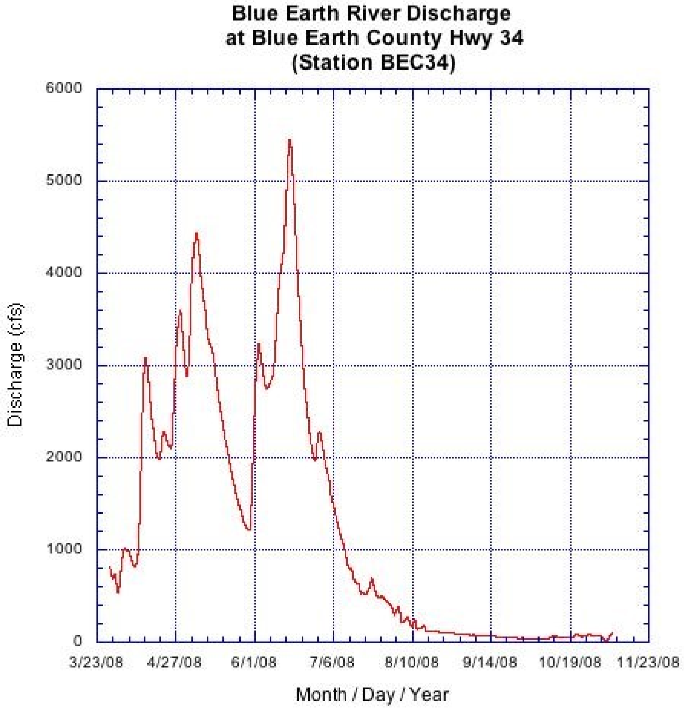


Figure 4.21 Blue Earth River Discharge at Blue Earth County Road 34. Utilizing the two part rating curve along with stage levels to calculate the discharge levels at BEC 34 demonstrate a strong fit. The river returns to baseflow conditions, 300 cfs, from approximately the third week of July.

The discharge and stage record for the BEC 34 site match very well. The rivers' flows are essentially baseflows after the third week of July until the end of the monitoring season. The baseflow at BEC 34 from the third week of July onward is approximately 300 cfs.

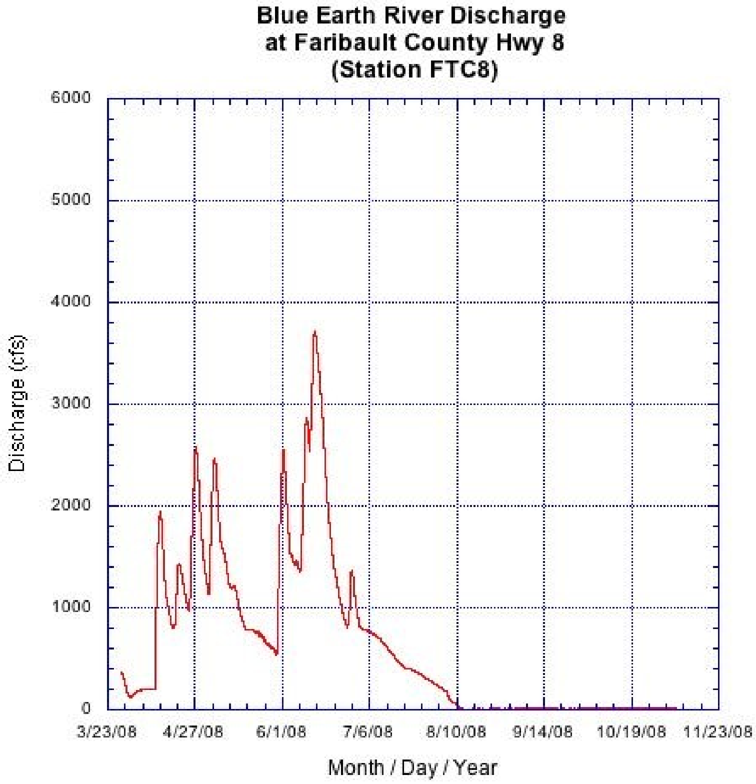


Figure 4.22 Blue Earth River Discharge at Faribault County Road 8. The rating curve and stage levels were used to calculate discharge levels. The resulting hydrograph demonstrates a very strong fit between discharge and stage. The rivers' flow at this site can consider to be baseflow, 270 cfs, after the third week of July.

The discharge hydrograph for FTC 8 matches its stage hydrograph very well. The rivers' flow at this station can also be considered baseflows after the third week of July until the end of monitoring season. The baseflow at FTC 8 after the third week of July is approximately 270 cfs.

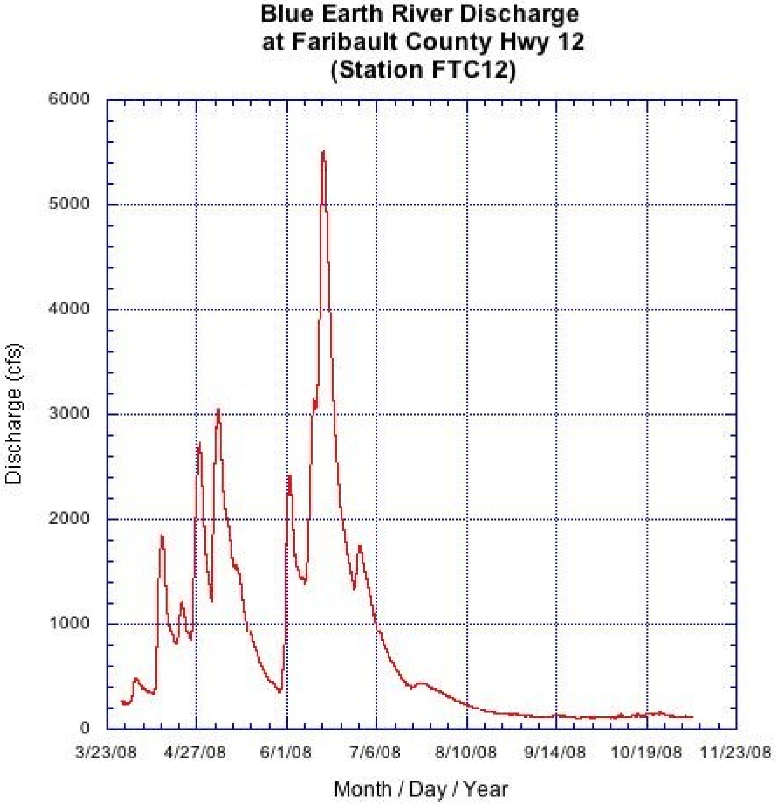


Figure 4.23 Blue Earth River Discharge at Faribault County Road 12. Similar to FTC 8 the rating curve and stage levels were used to calculate discharge levels. The resulting hydrograph demonstrates a very strong fit between discharge and stage. The rivers' flow at this site can consider to be baseflow, 160 cfs, after the third week of July.

Similar to FTC 8 and BEC 34 the discharge and stage hydrographs match very well. The high and low flows at FTC 12 are likely emphasized by the steep relationship between stage and discharge. The rivers' flow at this station also can be considered baseflows after the third week of July until the end of monitoring season. The baseflow at FTC 12 after the third week of July is approximately 160 cfs.

Table 4.7 lists each of the precipitation events modeled and the number of NEXRAD level II file used to create each one of the *.rrp files.

Table 4.7 Number of NEXRAD Level II Files per Storm Event

Rainfall Dates	Number of NEXRAD Files
April 10 – 12	652
April 17 -19	556
April 21 -22	368
April 24 – 26	621
May 1 – 3	580
May 29 – 30	352
June 6 – 9	721

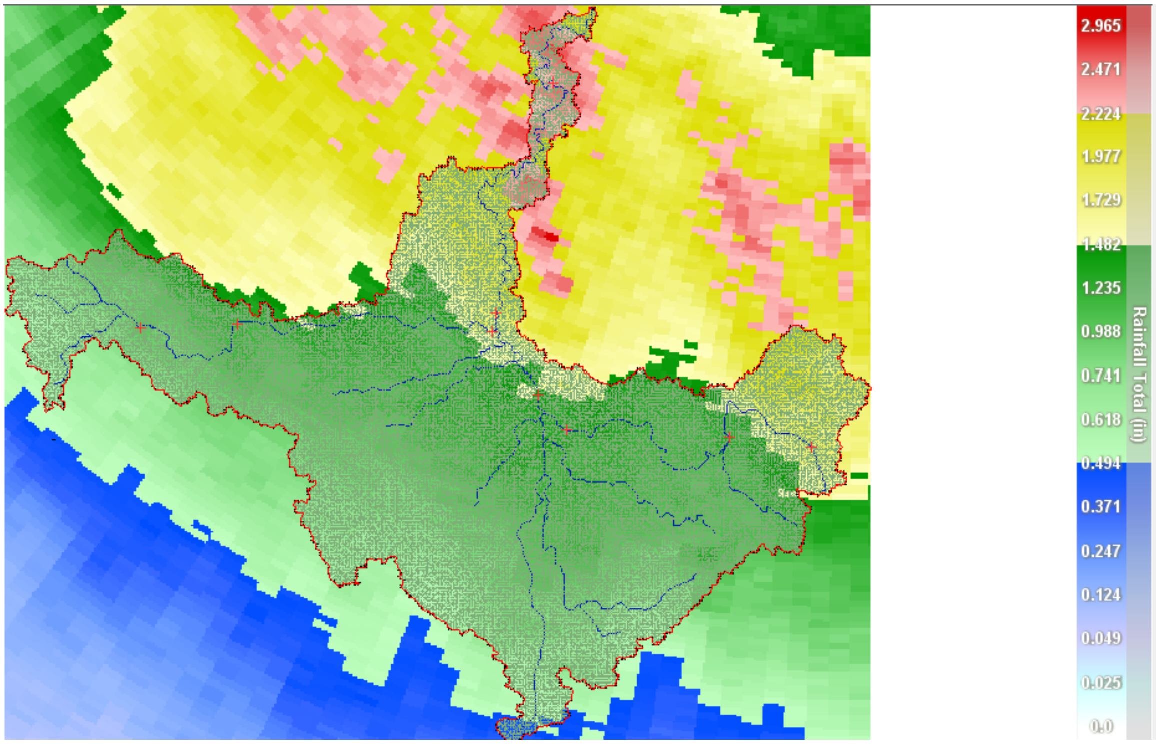


Figure 4.24 Distributed Rainfall for April 10 – 12 Storm. The heaviest precipitation occurred in northern and northeastern portion of the watershed with total accumulations ranging from 1.4 inches to 2.95 inches. Moderate precipitation occurred throughout the remainder of the watershed with total accumulations ranging from .494 inches to 1.4 inches. The headwaters experience the least amount of precipitation with accumulation totals of .124 inches to .493 inches.

The visualization of the NEXRAD level II data distribution of the rainfall for the precipitation event occurring on April 10 – 12, 2008 is displayed in Figure 4.24. The northern and northeastern portion of the watershed received the heaviest rainfall. The majority of the watershed experienced a moderate rainfall. The headwaters of the Blue Earth River experienced minimal rainfall.

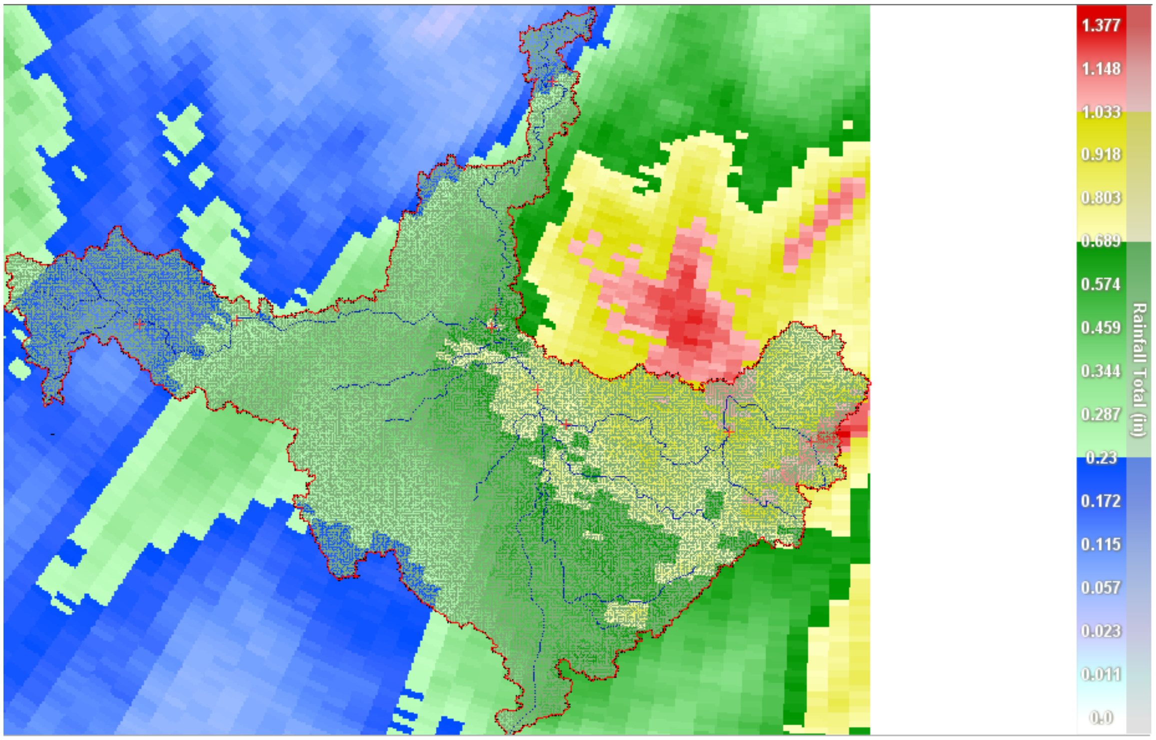


Figure 4.25 Distributed Rainfall Data April 17 – 19. Moderate precipitation occurred throughout the entire watershed with the northeastern portion of the watershed receiving the heaviest precipitation with total accumulations ranging from .689 inches to 1.48 inches. The western portion received the least amount of precipitation with total accumulations ranging from .023 inches to .22 inches.

The visualization of the NEXRAD level II data distribution of the rainfall for the precipitation event occurring on April 17 – 19, 2008 is displayed in Figure 4.25. The northeastern portion of the watershed received the heaviest rainfall. The majority of the watershed experienced moderate rainfall totals. The western portion of the watershed experienced minimal rainfall.

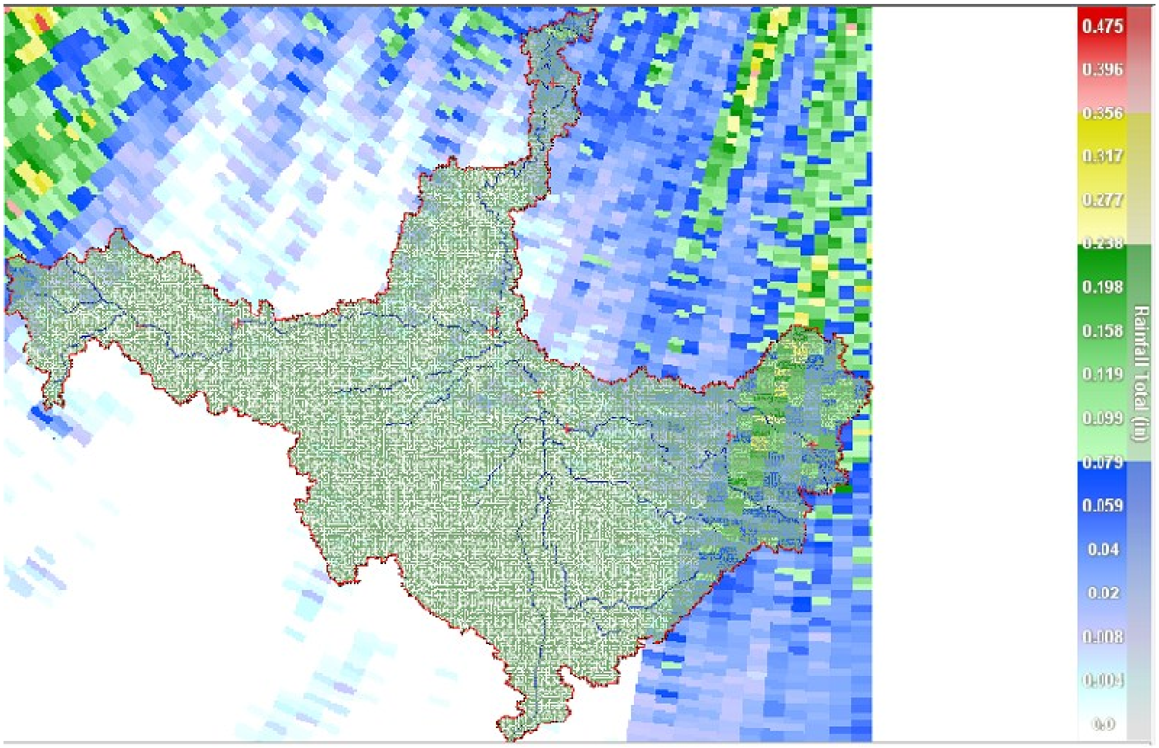


Figure 4.26 Distributed Rainfall Data April 21 - 22 Storm. Little to no precipitation was recorded for most of the watershed with the exception of the northeast portion receiving light or moderate precipitation with total accumulations ranging from .04 inches to .198 inches.

The visualization of the NEXRAD level II data distribution of the rainfall for the precipitation event occurring on April 21 – 22, 2008 is displayed in Figure 4.26. The northeastern portion of the watershed received the heaviest and majority of the rainfall. The majority of the watershed experienced little or no rainfall. The northern portion of the watershed experienced minimal rainfall.

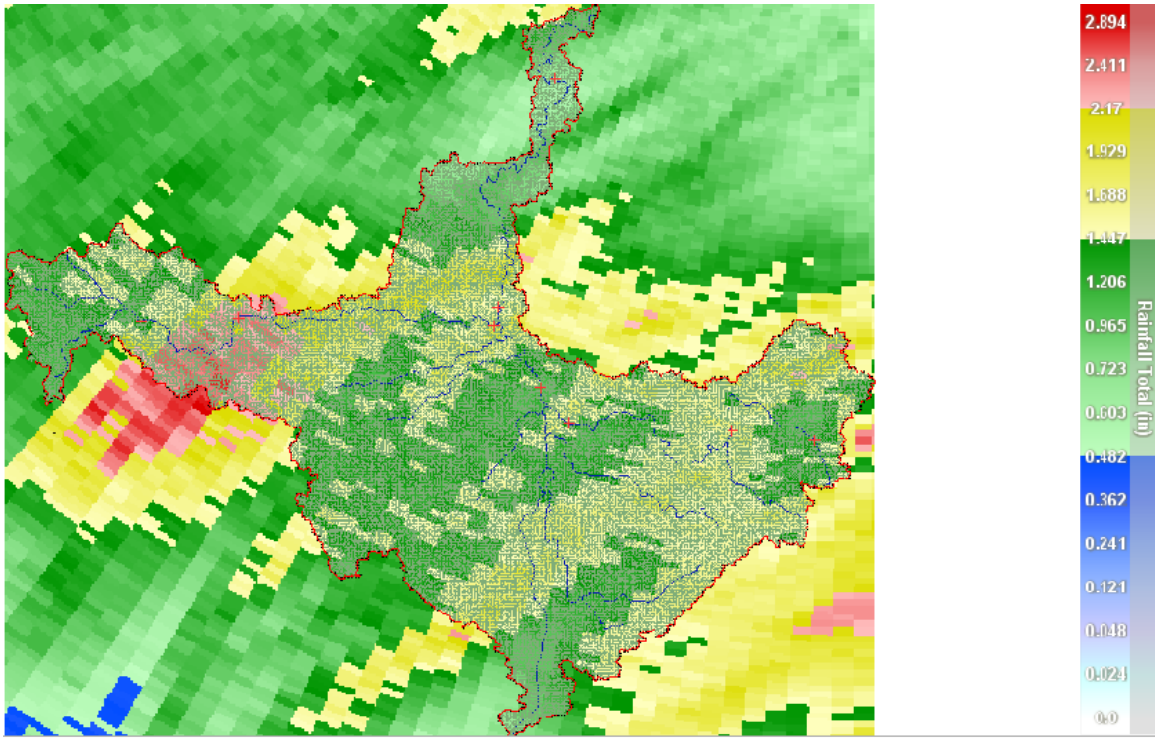


Figure 4.27 Distributed Rainfall Data for April 24 - 27 Storm. Moderate to heavy precipitation encompassed the entire watershed with the heaviest precipitation occurring in the western portion of the watershed with total accumulations ranging from 1.411 inches to 2.895 inches.

The visualization of the NEXRAD level II data distribution of the rainfall for the precipitation event occurring on April 24 – 27, 2008 is displayed in Figure 4.27. The western portion of the watershed, mainly over the Elm Creek sub watershed received the heaviest rainfall. The majority of the watershed experienced moderate to heavy rainfall. The northern portion a long with the headwaters of the watershed experienced the least amount of rainfall.

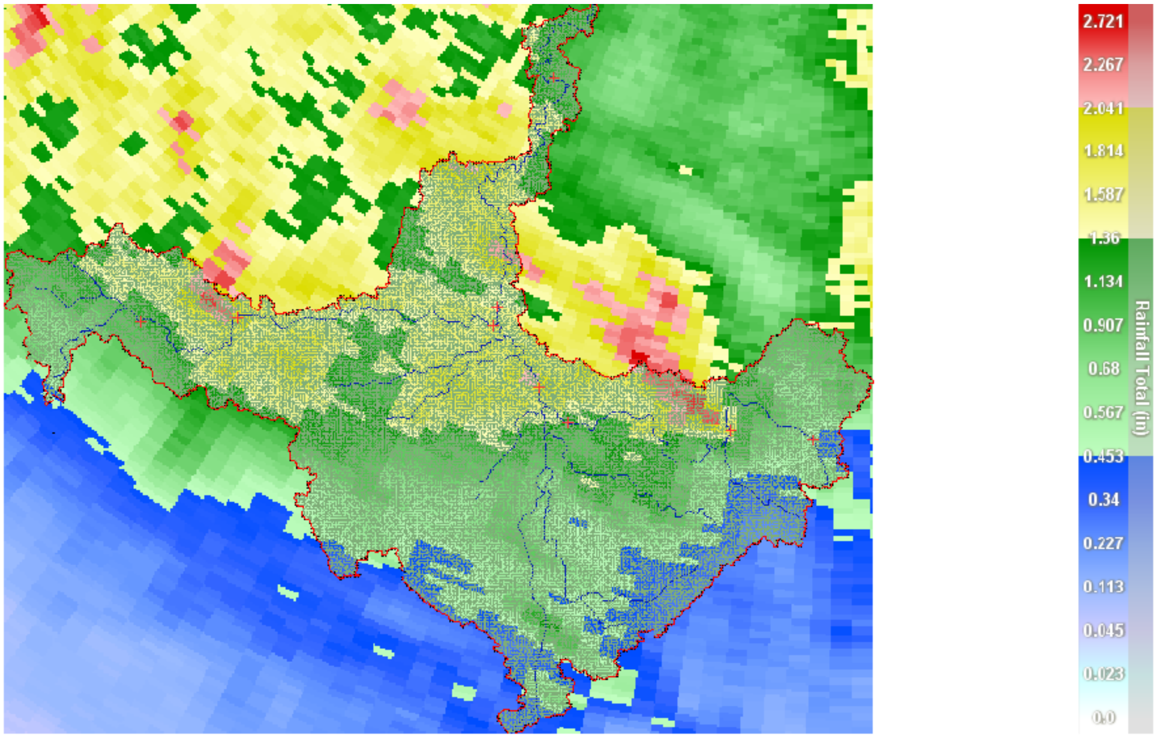


Figure 4.28 Distributed Rainfall Data for May 1 - 3 Storm. Central and northwestern portions of the watershed received moderate to heavy precipitation with total accumulations ranging from 1.36 inches to 2.041 inches. The southern portion and northern portion received moderate precipitation with total accumulations ranging from .453 inches to 1.35 inches.

The visualization of the NEXRAD level II data distribution of the rainfall for the precipitation event occurring on May 1 – 3, 2008 is displayed in Figure 4.28. The northwestern and central portions of the watershed, received the heaviest rainfall. The southern and northern most portion of the watershed experienced a moderate amount of rainfall. The southeastern portion of the watershed experienced the least amount of rainfall during this precipitation event.

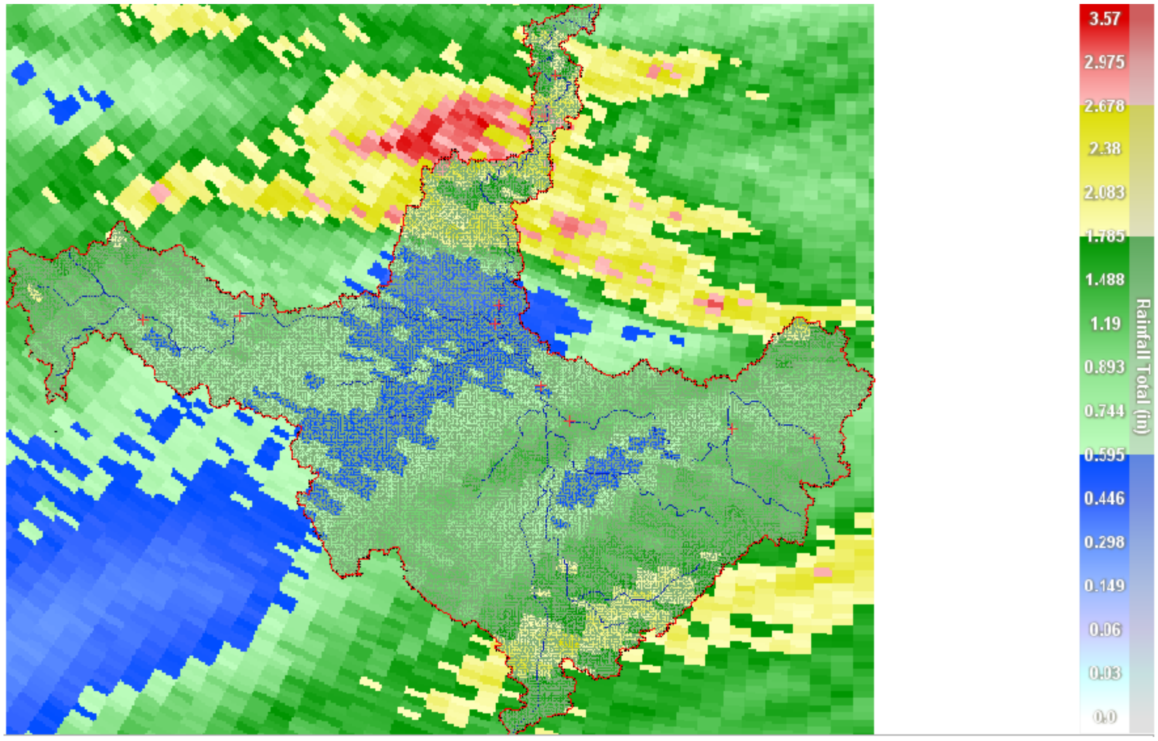


Figure 4.29 Distributed Rainfall Data for May 29 - 30 Storm. Moderate to heavy precipitation occurred throughout the watershed with the heaviest precipitation occurring in the upper northern portion of the watershed near the confluence of the Blue Earth River and Minnesota River with total accumulations ranging from 1.785 inches to 2.975 inches. The majority of the watershed experienced total accumulations ranging from .446 inches to 1.784 inches.

The visualization of the NEXRAD level II data distribution of the rainfall for the precipitation event occurring on May 29 – 30, 2008 is displayed in Figure 4.29. The upper northern portion of the watershed received the heaviest rainfall. The majority of the watershed experienced a moderate amount of rainfall with the exception of the central portion of the watershed. The central portion experienced the least amount of rainfall.

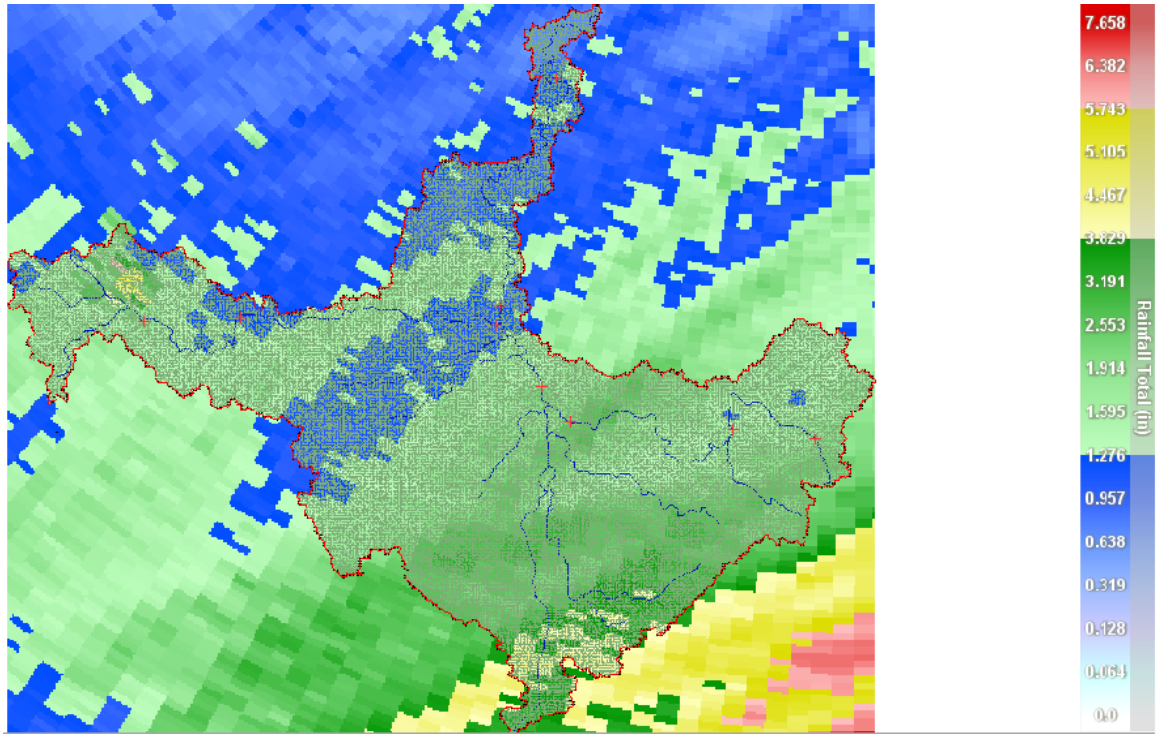


Figure 4.30 Distributed Rainfall for June 6 – 9 Storm. Moderate precipitation occurred for the majority of the watershed with total accumulations ranging from 1.595 inches to 2.553 inches. The eastern and southern portions receiving more precipitation than the western portion had total accumulations ranging from 2.553 inches to 3.829 inches.

The rainfall distribution for the June 6 – 9 is displayed in Figure 4.30. The pattern of the heaviest rainfall follows the general distribution with the eastern portion of the watershed receiving more rain than the western portion of the watershed. The southern and eastern portions of the watershed contributed the most to the observed and simulated flows for this precipitation event.

CHAPTER V

DISCUSSION

One of the twelve major watersheds of the Minnesota River, the Blue Earth River watershed is located in south central Minnesota and north central Iowa. The drainage area of the Blue Earth River watershed is approximately 1,550 square miles. The Blue Earth River watershed occupies a central portion of Minnesota's prairie pothole region where the land use is largely agricultural. Surface sediments consist of clay-rich soils and glacial lake deposits that promote depression storage and slow infiltration rates. The Blue Earth River flows north by northeast and has seven major tributaries: the Middle Branch of the Blue Earth River, the East Branch of the Blue Earth River, the West Branch of the Blue Earth River, Elm Creek, Wantonwan River, Le Sueur River, and Center Creek. As mention previously the Blue Earth River watershed is one of the twelve major watersheds of the Minnesota River basin; Magdalene (2004) suggests that artificial drainage systems such as drainage tile and drainage ditches also contribute significantly to the Blue Earth River flow and expedite the movement of water along with pollutants throughout the watershed.

5.1 Watershed Characteristics and Relationships to Infiltration and Runoff

The overall slope is displayed in Figure 4.1 and has been resampled to the 300 meter resolution that was needed for the model. The Blue Earth River watershed has an average of 0.64 percent of slope with a minimum value of 0.0010 percent of slope and a maximum value of 10.167 percent of slope. The slope values are with the acceptable range for the model as they are in pretty close agreement with the slope presented in Lorenz and Payne (1992). Fairly flat slopes of the Blue Earth River watershed impacts runoff by allowing pooling of rainfall thus delaying runoff along with allowing for a greater amount evaporation to occur. This also tends to lead to erosion being widespread through the watershed. There is a fairly large degree of generalization though due to the fact that the best available resolution of the entire watershed was 30 meters which was resample to 300 meters selecting the bilinear option. Defined in the ArcGIS 10 help, the bilinear resampling method performs a bilinear interpolation to determine the new value of the cell based upon a weighted distance average of the four nearest input cell centers. This method is ideal for continuous data such as elevation data but it will cause some smoothing of the data. This is an undesirable result when performing hydrologic analysis and was taken into consideration when evaluating the grid.

The best elevation data of the entire watershed available was 30 meter resolution and then resampled to 300 meter resolution, the result is shown in Figure 4.2. The resampled watershed dataset has a maximum value of 448 meters above sea level and a minimum of 232 meters above sea level.

The stream network shapefile accuracy is paramount to the model being able to predict the flows accurately. For this reason aerial photos were used to correct and to verify the existence of the stream network. The photos used were National Agriculture Imagery Program (NAIP) 2006. The drainage network was determined by comparing and adjusting the existing shapefile data. Figure 4.3 represents the results of the modified drainage network. The northern portion of the drainage network became disconnected when the resampling process took place. This is a direct result of the coarse 300 meter resolution and the bilinear resampling method used. In order to correct these errors the aerial imagery was then used again in V*flo*™ to ensure an accurate drainage network was in place.

The soil composition of the Blue Earth River watershed is displayed in Figure 4.4. Analysis of the soil composition shows that over 84 percent of the watershed is classified as fine to fine-loamy particle size which has the potential for high run off. This value corresponds very well to the hydraulic conductivity and the hydrologic soil group description of soil groups B/D and B. The cells classified as water make up about 1.7 percent of the composition of the watershed which falls within the acceptable error of less than 3 percent misclassification. Table 5.1 details the acreage and percentage of each soil classification.

Table 5.1 Soil Particle Classification for Blue Earth River Watershed

TAXPARTSIZ	Acres	Percentages
fine-loamy	708616.7	70.72650951
Water	16990.97	1.695855797
Fine	144934.7	14.46582753
coarse-loamy	20393.61	2.035470898
Loamy	14900.45	1.487203382
not used	1934.835	0.193114469
Sandy	10519.28	1.049921194
fine-silty	66384.86	6.625824024
Sandy-skeletal	355.8317	0.035515305
fine-loamy over sandy or sandy-skeletal	1356.609	0.135402099
fine-loamy over sandy or sandy-ske	1312.13	0.130962686
coarse-silty	3847.431	0.384009232
very-fine	578.2266	0.05771237
coarse-silty	889.5794	0.088788262
coarse-loamy	8562.201	0.854587018
Sandy or sandy-skeletal	22.23948	0.002219707
Sandy over loamy	311.3528	0.031075892

The initial abstraction parameter for the Blue Earth River watershed is displayed in Figure 4.5. The initial abstraction of the watershed was calculated using the following equation:

$$\text{Initial Abstraction (Ia)} = 0.2 * S$$

Where:
$S = (1000/CN) - 10$
CN = Curve Number (3.1)

Analysis of the initial abstraction for the watershed further justifies the potential of high run off after a precipitation event. Over 88 percent of the watershed only requires 0.238 to 0.8058 inches of precipitation before run off occurs. Of that percentage, 50.59 percent only needs 0.238 to 0.5494 inches of precipitation before run off occurs. This range of abstraction values is found throughout the entire watershed but it tends to be more prevalent in the areas where the soil particles are fine and the hydrologic soil group is either classified as C or C/D. These soil groups have slow to very slow infiltration rates which also increase the potential for high run off. The initial abstraction for the watershed changes through the season with values being lower in the spring especially when the ground is still partially frozen and higher in the summer when crops are mature and interception is high. Table 5.2 details the ranges and percentages of each range within the watershed.

Table 5.2 Initial Abstraction for the Blue Earth River Watershed

Range	Count	Percentage	Acres
0.0 - 0.238	2072	4.633	46080.21
0.238 - 0.5494	22626	50.59	503190.6
0.5494 - 0.8058	17125	38.29	380851.2
0.8058 - 1.3185	2584	5.778	57466.83
1.3185 - 4.6700	314	0.702	6983.198

The effective porosity for the Blue Earth watershed is displayed in Figure 4.6. Effective porosity is entered in the *Vflo*™ model as a unitless fraction ranging from 0 meaning absolutely no porosity to 1 meaning complete porosity. Effective porosity is the difference between the total porosity and the soil moisture content (*Vflo*™ Help 2010). The watershed has a minimum value of 0.0 and a maximum value of 0.5099 with an average value of 0.497. Table 5.3 details the composition of the watersheds effective porosity values.

Table 5.3 Blue Earth River Watershed Effective Porosity Values

Effective Porosity	Count	Percentage	Acres
0	953	2.135765671	21194.23
0.0 - 0.43599	928	2.07973824	20638.24
0.43599 - 0.5099	42740	95.78449609	950515.5

The roughness values also known as the Manning's n values were assigned by land cover and hydrologic soil groups, Figure 4.7 displays the results of the roughness classification. The range of the values of roughness was 0.012 to 0.10. The minimum value of 0.012 mainly corresponds with open water and impervious surfaces. The maximum roughness value of 0.10 occurs in the riparian areas where the presence of trees and downed trees are prevalent. The average roughness for the entire watershed is 0.035 which relates well to the Manning's n roughness value for mature row crops. As mentioned before the dominate land use within the watershed is agricultural. Table 5.4 details the percentages of each roughness value for the watershed.

Table 5.4 Manning's n Roughness values for Blue Earth River Watershed

Roughness	Count	Acres	Percentage
0.1	380	8451.00392	0.851998834
0.059	692	15389.72293	1.551534719
0.055	729	16212.58384	1.6344925
0.045	5	111.19742	0.011210511
0.03999	950	21127.5098	2.129997085
0.035	38101	847346.5799	85.42633573
0.015	3648	81129.63763	8.179188807
0.012	96	2134.990464	0.215241811

Low intensity, medium intensity, high intensity, and open water make up a mere 8.394 percent of the watersheds' acreage. Mature row crops and pasture comprise to make up 868,474 acres or 87.58 percent of the area in the watershed. The riparian area is relatively small in acreage totaling 8451 acres or 0.85 percent of the watershed.

Figure 4.8 represents the wetting front values in inches for the Blue Earth River watershed. The wetting front parameter in the *Vflo*™ model is the wetting front suction head of the Green-Ampt infiltration (*Vflo*™ Help 2010). The wetting front for the watershed has a minimum value of 0.0 inches to a maximum value of 12.39 inches with an average value of 10.29 inches. The average value for the wetting front coincides with the fine-loamy particle size of the soil which comprises over 70 percent of the watersheds soils. The minimum value of 0.0 inches occurs in areas of open water and impervious surfaces and accounts for 2.05 percent of the total watershed acreage in this grid.

Hydraulic conductivity within the Blue Earth River watershed, Figure 4.9, is the saturated hydraulic conductivity, K_s in the Green-Ampt infiltration routine. Hydraulic conductivity can be simply explained as how water moves through the soil. The hydraulic conductivity for the watershed has a range of 0.0 to 0.37 inches per hour with an average value of 0.16 inches per hour. The range of hydraulic conductivity of 0.1198 to 0.2190 has a percentage of approximately 46 percent which corresponds to the hydrologic soil group B/D. The range of 0.2190 to 0.3700 has a percentage of approximately 39 percent which corresponds very well with the hydrologic soil group B. The hydrologic soil groups and their infiltration characteristics will be discussed later in this section.

The land cover classification for the Blue Earth River watershed, Figure 4.10, can almost be considered homogeneous. The prevailing land cover classification is cultivated crops with a percentage of 85.39 percent and if combined with grassland and pasture/hay classification the percentage increases to 88.16 percent. Boone (2000) states the Blue Earth River watershed is comprised of 92 percent agricultural. The land cover classification used then falls within the acceptable error. According to the Blue Earth River major watershed diagnostic report (2000), lakes and wetlands account for approximately 2 percent of the total acreage of the watershed. The 2006 land cover classification has a little larger percentage of 1.44 percent, which is classifying any areas of open water including sloughs, the rivers, creeks, and tributaries to the Blue Earth River.

The soil classification for the Blue Earth River watershed, Figure 4.11, when resampled does trend towards what soil types are present within the watershed with minimal error. Surface sediments of the Blue Earth River watershed consist of clay-rich soils and glacial lake deposits that promote depression storage and slow infiltration rates. An analysis of the soils hydrologic soil group for the Blue Earth River watershed 45.4 percent of the watershed was classified as B/D which is defined by the Natural Resources Conservation Service (NRCS) as soils with moderate infiltration rate when thoroughly wet with moderately fine texture to coarse texture for drained soils, group B, and soils having very slow infiltration rates with high run off potential when thoroughly wet consisting of clays that have a high shrink-swell potential for undrained area, group D. The next largest classification percentage was hydrologic soil group B consisting 39.3

percent of the soils within the Blue Earth River watershed. As defined previously, these soils have a moderate infiltration rate. The majority of the soils, over 84 percent of the Blue Earth River watershed soil fall into the category of having moderate to very slow infiltration rates with the potential of high run off.

This section of the discussion discusses the infiltration characteristics in relation to geomorphic factors, soil properties, hydrologic parameters and how they influence the watershed's runoff and discharge. The Blue Earth River watershed has soils properties that have moderate to very slow infiltration rates with the potential of high run off. The slope is of the Blue Earth River watershed has fairly flat slopes and impacts runoff by allowing pooling of rainfall thus delaying runoff along with allowing for a greater amount evaporation to occur. These factors coupled together cannot describe the magnitude or rapid onset of the hydrographic crest. The increase runoff from croplands and the increased connectivity of channel systems makes the watershed unnatural and requires the hydrologic model to be calibrated to adjust for these changes within the watershed.

5.2 Summary of Modeled Precipitation Events

Vieux and Bedient (1998) concluded that the WSR-88D or more commonly known as NEXRAD data can accurately estimate rainfall at the catchment scale. The NEXRAD level II data for the precipitation event occurring on April 10 – April 12, 2008, displayed in Figure 4.24, shows the distribution of rainfall and the accumulation totals for the precipitation event. The northern and northeastern portion of the watershed received the heaviest rainfall with total accumulations ranging from 1.4 inches to 2.95 inches of rain. The majority of the watershed experienced a range of 0.494 inches to 1.4 inches. The headwaters of the Blue Earth River experienced minimal rainfall with a range of 0.124 inches to 0.493 inches.

The NEXRAD level II data for the precipitation event occurring on April 17 – April 19, 2008, displayed in Figure 4.25, shows the distribution of rainfall and the accumulation totals for the precipitation event. The northeastern portion of the watershed received the heaviest rainfall with total accumulations ranging from 0.689 inches to 1.48 inches of rain. The majority of the watershed experienced a range of 0.23 inches to 0.688 inches. The western portion of the watershed experienced minimal rainfall with a range of 0.023 inches to 0.22 inches of rainfall.

The NEXRAD level II data for the precipitation event occurring on April 21 and April 22, 2008, displayed in Figure 4.26, shows the distribution of rainfall and the accumulation totals for the precipitation event. The northeastern portion of the watershed received the heaviest and majority of the rainfall with total accumulations ranging from 0.04 inches to 0.198 inches of rain. The majority of the watershed experienced little or no rainfall. The northern portion of the watershed experienced minimal rainfall with a range of 0.004 inches to 0.02 inches of rainfall.

The NEXRAD level II data for the precipitation event occurring on April 24 - April 27, 2008, displayed in Figure 4.27, shows the distribution of rainfall and the accumulation totals for the precipitation event. The western portion of the watershed, mainly over the Elm Creek sub watershed received the heaviest rainfall. The majority of the watershed experienced moderate to heavy rainfall. The northern portion along with the headwaters of the watershed experienced the least amount of rainfall.

The NEXRAD level II data for the precipitation event occurring on May 1 – May 3, 2008, displayed in Figure 4.28, shows the distribution of rainfall and the accumulation totals for the precipitation event. The northwestern and central portions of the watershed, received the heaviest rainfall with total accumulations ranging from 1.36 inches to 2.041 inches of rain. The southern and northern most portion of the watershed experienced a range of 0.453 inches to 1.35 inches. The southeastern portion of the watershed experienced minimal rainfall with a range of 0.113 inches to 0.452 inches of rainfall.

The NEXRAD level II data for the precipitation event occurring on May 29 and May 30, 2008, displayed in Figure 4.29, shows the distribution of rainfall and the accumulation totals for the precipitation event. The upper northern portion of the watershed received the heaviest rainfall with total accumulations ranging from 1.785 inches to 2.975 inches of rain. The majority of the watershed experienced a range of 0.595 inches to 1.784 inches with the exception of the central portion of the watershed. The central portion experienced minimal rainfall with a range of 0.446 inches to 0.594 inches of rainfall.

The NEXRAD level II data for the precipitation event occurring on June 6 – June 9, 2008, displayed in Figure 4.30, shows the distribution of rainfall and the accumulation totals for the precipitation event. The pattern of the heaviest rainfall follows the general distribution with the eastern and southern portions of the watershed receiving more rain than the western portion of the watershed. The total accumulation of the western portion of the watershed ranged from 1.595 inches to 2.553 inches with the exception of one heavy pocket of rain occurring in the elm creek sub watershed which had a range of 5.105 inches to 6.382 inches. The total accumulation of rainfall in the eastern and southern portions ranged from 2.553 inches to 3.829 inches within this area. The southern and eastern portions of the watershed contributed the most to the observed and simulated flows for this precipitation event.

5.3 Simulated Results of 2008 Significant Precipitation Events

The model has been calibrated for each of the selected precipitation events in the 2008 monitoring season. The calibration was performed by matching observed flows during the same time period at the three collection sites: FTC 12, FTC 8, and BEC34. To correctly calibrate the model for the watershed base flows were assigned depending on the time of the year and the observed flow. The early precipitation events, April 10 to April 12, April 17 to April 19, April 21 to April 22 and April 24 to April 27 roughness was decreased throughout the watershed due to the fact that the majority of the land was barren and still was going through a freeze - thaw nightly cycle. Along with the adjustment to the roughness value, soil depth was adjusted in part for the same reason as listed above. The nightly freeze - thaw cycle limited the depth to which infiltration was able to occur thus affecting the total run off during the precipitation events for the watershed. The next precipitation event occurring May 1 to May 3 the roughness was increased throughout the watershed because of the emergence of the row crops. Along with the roughness calibration, the soil depth was calibrated to allow for full infiltration and the initial saturation was calibrated to represent what would be the typical soil saturation at this time of the year. The abstraction value was also calibrated to a higher value due to planted row crops depleting the soil moisture requiring more rainfall to occur before runoff will occur. The base flow was an interesting point for this calibration. The FTC 12 site, just downstream of Elm Creek confluence, had a smaller base flow than the FTC 8 site, the southern most site. This shows the recharge of the underlying aquifer between these two locations. The next set of precipitation events occurring May 29 to May 30 and June 6 to June 9 proved to be the most challenging calibrations. The roughness was again increased. Justification for this increase is that the row crops were in full canopy by this time. Abstraction was slightly increased because of the row crops in full canopy and their demand for water which depleted the antecedent moisture. Initial saturation was also decreased during this time for the same reason. The base flow again at the FTC 12 site was smaller than the base flow at the FTC 8 site still meaning that the underlying aquifer was being recharged. What proved to be most challenging about this calibration for these precipitation events was the fact that the whole watershed was in the same saturation state. More variability of the calibration factors was needed to match observed flows for these two precipitaion events.

Table 5.5 Blue Earth River Watershed Model Baseflows Values

Precipitation Event Dates	Blue Earth County Road 34	Faribault County Road 12	Faribault County Road 8
April 10 – 12	0.0055 cfs/ft	4.1 x E-4 cfs/ft	1.8 x E-4 cfs/ft
April 17 – 19	0.0055 cfs/ft	2.0 x E-4 cfs/ft	8.0 x E-4 cfs/ft
April 21 – 22	0.0055 cfs/ft	2.3 x E-4 cfs/ft	0.0010 cfs/ft
April 24 – 26	0.0055 cfs/ft	3.0 x E-4 cfs/ft	0.0010 cfs/ft
May 1 – 3	0.0071 cfs/ft	9.0 x E-4 cfs/ft	0.0013 cfs/ft
May 29 – 30	0.01 cfs/ft	2.0 x E-4 cfs/ft	0.0013 cfs/ft
June 6 – 9	0.01 cfs/ft	2.0 x E-4 cfs/ft	0.0013 cfs/ft

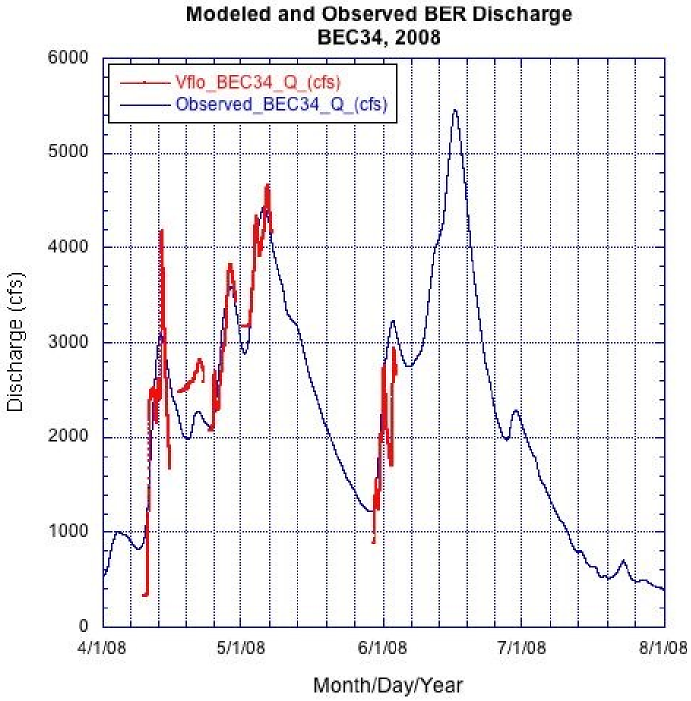


Figure 5.1 BEC 34 Simulated Flows vs. Observed Flows – 2008. An extremely strong match between the simulated flow and observed flow provided justification to the model being correctly calibrated. Overestimation errors fall within acceptable error of less than 3% error.

The 2008 hydrograph for BEC 34, northern most site downstream of the confluence of the Watonwan River but upstream of the Rapidan Dam, site is displayed in Figure 5.1. Analysis of the simulated flow shows an extremely strong match to the observed flows. The calibration of the model at this site was the most complex due to its location within the drainage network. The April 24th through April 26th simulated results match the timing of the peak flow but overestimate the peak flow volume although the overestimation is within the 3 percent margin of error. The May 1st through May 3rd simulated flows peak a little earlier than the observed flow peak but the volume matches along with the slope of the rising and falling limbs. The June 1st through June 3rd simulated results show a double peak resulting in lower flows than what was observed. The double peak is more than likely due to the spatial variability of the infiltration parameters that would not allow for uniform weighting of the parameters. The rising limbs for all the model precipitation events match the slopes of the observed flows along with the simulated volumes being within less than 3 percent of the observed flows.

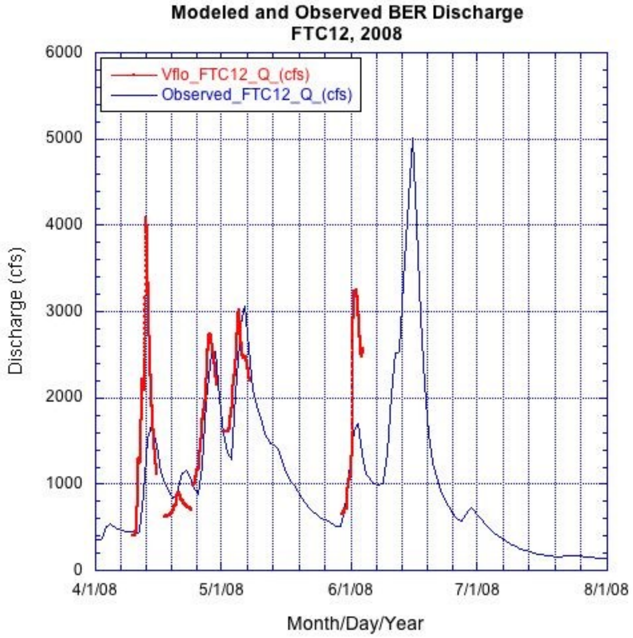


Figure 5.2 FTC 12 Simulated Flows vs. Observed Flows – 2008. An extremely strong match between the simulated flow and observed flow. Overestimations of discharge during the precipitation event April 24th through April 26th and June 6th through June 9th fall within the acceptable error range of less than 3% error.

The 2008 hydrograph for FTC 12 site is displayed in Figure 5.2. Analysis of the simulated flow shows an extremely strong match to the observed flows. The April 24th through April 26th simulated results match the timing of the peak flow but overestimate the peak flow volume although the overestimation is within the 3 percent margin of error. The May 1st through May 3rd simulated flows peak a little earlier than the observed flow peak but the volume matches along with the slope of the rising and falling limbs. The rising limbs for all the model precipitation events match the slopes of the observed flows along with the simulated volumes being within less than 3 percent of the observed flows.

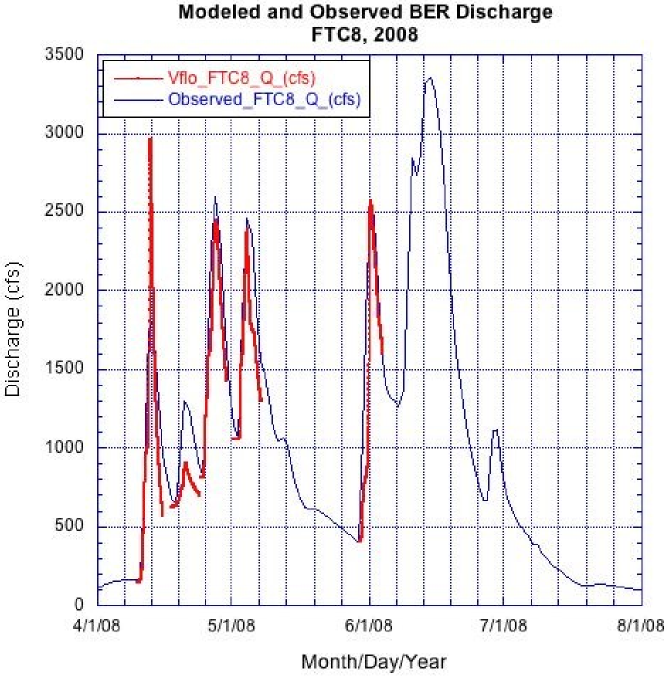


Figure 5.3 FTC 8 Simulated Flows vs. Observed Flows – 2008. Simulated flows show an extremely strong match to the observed flows. Overestimation errors fall within the acceptable error of less than 3% error. The match demonstrates that the calibrated model is capable of predicting flows where flow predictions have never been done in the past.

The 2008 hydrograph for FTC 8 site is displayed in Figure 5.3. Analysis of the simulated flow shows an extremely strong match to the observed flows. This strong match demonstrates that the calibrated physics-based distributed model is more than capable of being capable predict the flow of the Blue Earth River where flow predictions have never been able to in the past. The rising limbs for all the model precipitation events match the slopes of the observed flows along with the simulated volumes being within less than 3 percent of the observed flows.

5.4 Implications of Model BER Watershed Hydrology

The Blue Earth River watershed hydrology is comprised of complex parameters that control the runoff and infiltration. The overland cell roughness parameter is important in attenuating the peak discharge whereas the channel roughness parameter modifies the timing of the peak discharge within the channel. The model provides interesting findings in that the water takes approximately three days to travel from the southern most collection site, FTC 8 to the northern most collection site, BEC 34. This time frame does not seem to change no matter where the precipitation falls within the watershed.

The shape and timing of the simulated hydrograph was affected by the weighting of the roughness values for both overland cells and channel cells. Increasing the roughness of channel cells attenuated the peak timing while increasing overland roughness delayed the arrival timing of water into the channel. This calibration of the simulated hydrologic model is indicative of an unnaturally drained system, a system that has been altered. The land surface utilization of the Blue Earth River watershed has experience a 92 percent change relative to the watershed’s pre-settlement disposition. Boone (2000) states that the Blue Earth River watershed is comprised of 92 percent agricultural land. The change from pre-settlement prairie land and wetland to predominately agricultural land and the agricultural drainage systems associated with the draining and modification of those pre-settlement prairie land and wetland has impacted the hydrologic regime with resulting environmental impacts.

The altered hydrologic regime of the Blue Earth River watershed has increasing flow accumulation with decreasing drainage area (Figure 4.13). Further analysis of the hydrologic model of the Blue Earth River watershed suggests that the increased sediment yield is a result of increase stream flow and velocity. An increase in stream flow and velocity has other implications causing an increase in bluff and bank failures along the river leading to an increase in the Blue Earth River's suspended load. An increased suspended load within the Blue Earth River has more implications that are discussed in Rassmussen (2012). The results of this research indicated that the increased suspended load along with the increased flow and velocity of the Blue Earth River as altered the trap efficiency of the Rapidan Dam and reservoir.

Schottler (2010) found that non-field sediment loads were the greatest in the large, and steeply incised watersheds of the Blue Earth River and Le Sueur River. Field erosion was found to contribute less than 25 percent of the sediment in the Blue Earth River and Le Sueur River meaning that more than 75 percent of the sediment can be attributed to bluff and blank failures within these deeply incised watersheds. As mentioned above, the Blue Earth River watershed has increasing flow accumulation with decreasing drainage area (Figure 4.13) and an increased sediment yield is a result of increase stream flow and velocity. The simulated hydrologic model demonstrates the low-permeability soils of the Blue Earth River watershed covered with row crops are forcing more water into the riparian with greater force causing a greater increase in stream bank and bluff failure. The calibration of the model further enforces these results with having to increase channel roughness in order to get the simulated flows hydrograph to fit the hydrograph of the observed flows.

CHAPTER VI

SUMMARY AND RECOMMENDATIONS

A physics-based distributed model, *Vflo*™, was used to simulate flows of the Blue Earth River where previously flows were never observed. The outcome of this thesis research is the development of a calibrated numerical hydrologic model for the Blue Earth River watershed that is based on existing geographic information system (GIS) layers and collected data for seven NEXRAD level II precipitation events for the 2008 monitoring season. The validation of the calibrated numerical model was derived by matching observed flows of the Blue Earth River collected from installed stilling wells at strategic locations.

Along with a hydrologic model for the Blue Earth River watershed a better understanding of the hydrologic regime within the watershed is achieved. Land surface utilization of the Blue Earth watershed has experienced a ninety-two percent change relative to the pre-settlement deposition. The land use changes within the Blue Earth River watershed explain the runoff total volume however the land cover, soil properties, precipitation characteristics cannot explain the peak discharge magnitude or the rapid onset of the hydrograph crest. The increased runoff rates from croplands and increased connectivity of channel systems within the watershed make the watershed “unnatural”. This better understanding of the hydrologic regime will allow for better best management practices (BMP’s) to be implemented.

The Green – Ampt infiltration method was used to solve for infiltration for the spatially distributed parameters of hydrologic conductivity, wetting front, effective porosity, soil depth, initial saturation, abstraction, and percent impervious. Initial saturation has a direct effect on the simulated volume. Saturation was assumed for the simulated precipitation events during the 2008 season and was based on analysis of previous precipitation events and duration of the events. It should be noted that this parameter proved to be accurate for these seven precipitation events modeled and may not be accurate for other events and seasons.

Hydrologic conductivity may control the infiltration process over already saturated soils (Vieux 2004) and was weighted for each precipitation event. Soil depth was assigned the depth specified in the soil survey for all the grid cells although it should be noted that the model showed no sensitivity over ten inches of soil depth. Another parameter affecting the volume is the wetting front, with increases in the weighting resulting in decreases in runoff and simulated flow.

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Appendix A

NEXRAD Level II Rainfall files used to generate *.rrp files for *Vflo*™ model.

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