Fall 2020

Assessing Grassed Waterway Implementation Using ACPF and SWAT Models

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ASSESSING GRASSED WATERWAY IMPLEMENTATION USING ACPF AND SWAT MODELS

A Master's Thesis

Presented to

The Graduate College of

Missouri State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science, Geospatial Sciences in Geography and Geology

By

Kirsten Schaefer

December 2020

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Geography, Geology and Planning

Missouri State University, December 2020

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ABSTRACT

Agriculture is the most significant contributor of nonpoint source pollutants in US waterways, with sediment being the most prevalent cause of impairments. Sediment loss mitigation occurs through Best Management Practices (BMPs), such as grassed waterways. Federal and state agencies incentivize the implementation of BMPs through cost-share programs for farmers. The investment of public funds has increased pressure to demonstrate the effectiveness and value of individual projects, necessitating the development of strategies for prioritizing projects based on the sensitivity of sites to sediment erosion and optimal locations for implementation. This study has three primary objectives: (i) document existing locations of grassed waterways, (ii) identify appropriate potential locations for grassed waterways, and (iii) locate critical source areas of sediment erosion in Bridge Creek watershed in southeastern Minnesota. This study uses the Agricultural Conservation Planning Framework (ACPF) toolset to model appropriate locations for grassed waterways and the Soil and Water Assessment Tool (SWAT) to calculate sediment yield throughout the watersheds. The results show that over 80% of erosion occurring in the Bridge Creek watershed is attributed to seventeen critical source areas. The outputs assist in prioritization based on sensitivity to sediment erosion and undeveloped locations for grassed waterways in eleven locations. Results from this study aid in assessing whether the combination of the two models produces a viable prioritization framework and if the process is applicable for watershed management decisions in other locations.

KEYWORDS: grassed waterway, best management practice, ACPF, SWAT, sediment erosion, critical source area, soil conservation

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ACKNOWLEDGMENTS

I have to express my deepest gratitude to all of the people whose assistance was essential in completing this thesis. First, my sincere appreciation towards my advisor, Dr. Toby Dogwiler, who not only encouraged me to tackle this project but never doubted my ability to do so. Without his guidance, the goal of this work would not have been realized. I am also indebted to my committee members, Dr. Mélida Gutiérrez and Dr. Matthew Pierson, both of whom shared their expertise to help strengthen the multidisciplinary foundation of this work. Thanks to Dr. Srinivasan from Texas A&M University for leading the SWAT Workshop and offering continuing advice and guidance as I taught myself the program. In addition to the academic and technical support, I cannot fail to mention the advice, encouragement, and assistance I received from my colleagues at the Missouri Geological Survey, but I must express my gratitude specifically to Jeremiah Jackson and John Corley. As my manager and mentor, Jeremiah consistently empowered me to work with confidence, persistence, and tenacity. When life's distractions would derail my progress-he consistently steered me back to this goal, and for that, I will be forever grateful. My colleague, John Corley, offered help through rounds of edits, constructive criticism, and his continued confidence. His perspective, time, and encouragement is deeply appreciated. A special thank you to my undergraduate advisor, Dr. David Malone, without whom I would have never dreamed of going on to graduate school. And most of all, the support, love, and encouragement of my family and friends, who have always believed in me.

I dedicate this thesis to the 2020 novel coronavirus pandemic, without which I may have never found the time to finish this project.

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INTRODUCTION

Due to the rise in the global population, agricultural demands are increasing worldwide. This increase is apparent in both industrial and traditional farming practices. While agricultural innovation is necessary to feed the growing population, it is often detrimental to water quality. In the US, the agriculture industry is the most significant nonpoint source contributor to surface water contamination (Carpenter et al. 1998; Dressing 2003; Hardy and Koontz 2007). Pesticides, fertilizers, increased soil erosion, and higher stream sediment loads frequently accompany an increase in crop yield. Mitigation of these agricultural impairments is crucial to meet water quality standards.

One of the most abundant water impairments is sediment. Sediment is unique, considering it is both a physical and chemical pollutant. According to the Food and Agriculture Organization of the United Nations (FAO), sediment as a physical pollutant affects receiving waters through both turbidity and sedimentation (Ongley 2005). Turbidity is the measure of the clarity of a fluid primarily as a function of the amount of suspended solids within the fluid. High turbidity limits the ability of sunlight to penetrate the water column, thus negatively affecting aquatic ecosystems.Sediment is credited as a significant cause in the decline and degradation of coral reefs (Richmond 1993; Rogers 1990). Consequently, agricultural sediment has been identified as a critical contaminant of concern affecting the decline in the health of the Great Barrier Reef (Bramley and Roth 2002; Harris 2001; Lewis et al. 2009). In addition, high levels of sedimentation affect open channel flow and geomorphology.

Sediment is also considered a chemical pollutant, due to the adsorption of atoms, ions, or molecules to the sediment's surface (Winterwerp and Van Kesteren 2004). Sediment's ability to

adsorb makes it a preferred medium to which chemical contaminants can bond. Common agricultural contaminants that adsorb to sediment are ammonium, phosphate, and heavy metals from fertilizer applications (Bechmann and Stålnacke, 2019). These same contaminants are attributed to growing eutrification in local lakes and other surface waters (Burkart and James, 1999; Bohlke 2002; Turner and Rabalais 2003). Studies continue to demonstrate that agricultural sediment negatively affects water quality on a global scale.

The leading cause of agricultural soil erosion is surface runoff. Runoff factors include the intensity of precipitation, soil characterristics, vegetation, land use, slope length, and steepness (Schoonover and Crim 2015). The most common category of erosion in agricultural areas is sheet, rill, and wind; defined as "detachment and transportation of soil particles caused by rainfall runoff/splash, irrigation runoff, or wind that degrades soil quality" (NRCS 2012a, p. 1). This erosion is evident in fields as small rills and channels in the soil, excess soil at the base of slopes, and sedimentation in nearby surface waters (NRCS 2012a; Schoonover and Crim 2015).

Regions within a watershed that contribute a disproportionate amount of contamination are known as critical source areas (Maas 1985; Berry et al. 2005). These locations are both hydrologically sensitive and prone to pollutant-loading, thus contributing more contamination than neighboring vicinities. Mitigation of critical source areas is essential for more effective conservation.Preventing and managing critical source areas for sediment erosion is a priority for watershed managers, government entities, and the agricultural community. Management is achieved by identifying the source of contamination and remediating the cause. In the US, the implementation of Best Management Practices (BMPs) helps protect water quality and promote soil conservation. Different BMPs are suited for different locations, sources, and contaminants. One popular BMP used for reducing agricultural rill, sheet, and wind erosion is the grassed

waterway. According to the Natural Resources Conservation Service (NRCS), a grassed waterway is "a shaped or graded channel that is established with suitable vegetation to convey surface water at a non-erosive velocity using a broad and shallow cross-section to a stable outlet" (2000, p. 412-1). Traditionally, soil conservationists choose BMP locations from an in-field interpretation of the agricultural landscape. Field assessments evaluate potential locations for practices. Soil, land use, and slope data is collected to develop site-specific conservation plans. Geospatial technology can refine this process.

With new advances in remote sensing comes the ability to model optimal locations for BMPs and better identify sources of contamination. Physical models assessing nonpoint pollution problems have been used to better understand water quality for over thirty years (Gassman et al. 2007). The purpose of this study is to model ideal locations for grassed waterways as well as identify critical source areas for sediment erosion. Two models, the Agricultural Conservation Planning Framework (ACPF) and the Soil and Water Assessment Tool (SWAT), will be employed to bridge the gap between where grassed waterways could be and where they need to be. The results will be used to assess if the combination of the models can produce a viable prioritization scenario. The data will be valuable in pinpointing potential locations for grassed waterways, identifying critical source areas for sediment erosion, and prioritizing the most cost-effective areas to allocate funds.

This study aims to complete three objectives in the Bridge Creek watershed:

1. Create an inventory of existing grassed waterway locations.
2. Identify potential locations for grassed waterways.
3. Locate critical source areas for sediment erosion.

BACKGROUND

History

Soil conservation practices rose in popularity during the nineteenth and twentieth centuries. However, government funds were not appropriated until the devastation of the Dust Bowl, caused by a combination of poor soil management practices and drought in the 1930s. The destruction of agriculture across the US during the Dust Bowl provided the motivation necessary for Congress to fund erosion research and conservation practices.

Government funding helped drive soil conservation projects in the following years. Zingg (1940) correlated the effects of slope steepness and length on soil erosion. This study produced the first equation used to predict soil erosion rates. The following year, Smith (1941) further developed these ideas through the addition of a conservation practice factor. The Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA) was created in 1953. The ARS was housed within the Agricultural Engineering building at Purdue University, where ARS scientists worked in conjunction with university faculty on experiments. Erosion research stations were created across the Corn Belt to establish a diverse study area. Data was collected from 47 research stations in 24 states to compile a framework for an empirical model (Laflen and Flanagan 2013). Over 10,000 plot years of runoff and soil loss data were measured (Wischmeier and Smith 1965). Soil scientists conducted experiments to test different variables that affect erosion rates, including those documented in Zingg (1940) and Smith's (1941) studies.

Universal Soil Loss Equation. Over more than 20 years, and multiple contributors, the Universal Soil Loss Equation (USLE) was established (Wischmeier and Smith 1965). This empirical model allowed for more precise calculations and avoided the climatic and geographic

restraints inherent in earlier models (Wischmeier and Smith 1965). Due to the model's appropriateness across different geographic and climatic locations, it was named the universal equation. The first version of the equation was published in the USDA's Agriculture Handbook No. 282 (Wischmeier and Smith 1965):

$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$

Where:

A= the computed soil loss per unit area

R= the rainfall factor is the number of erosion-index units in a normal year's rain. The erosion index is a measure of the erosive force of specific rainfall

K= the soil erodability factor is the erosion rate per unit of erosion index for a specific soil in cultivated continuous fallow, on a 9-percent slope 72.6 feet long

L= the slope-length factor is the ratio of soil loss from the field slope length to that from a 72.6-foot length on the same soil type and gradient

S= the slope-gradient factor is the ratio of soil loss from the field gradient to that from a 9-percent slope

C= the cropping-management factor is the ratio of soil loss from a field with specified cropping and management to that from the fallow condition on which the factor K is evaluated

P= the erosion-control practice factor is the ratio of soil loss with contouring, stripcropping, or terracing to that with straight-row farming, up-and-down slope (Wischmeier and Smith 1965, p. 3)

The creation of USLE remains one of the most important contributions to conservation science in the last century, assisting in the estimation and understanding of soil loss from croplands across

the US (USDA ARS 2016). It also helped predict the physical results of different conservation, tilling management, and crop rotation practices, such as use of terracing, contour farming, no-till, or cover crops.

While USLE was instrumental in understanding long-term erodibility, Laflen and Flanagan (2013) describe several shortcomings. The original equation depends on rainfall as the sole source of erosive energy, neglecting both seasonality and runoff. It only considers sheet and rill style erosion, and it ignores deposition. The equation does not account for the physical characteristics of soil and sediment. It is also limited in which conservation practices it acknowledges. These shortcomings were addressed in more recent versions of USLE, the Modified Universal Soil Loss Equation (MUSLE), and the Revised Universal Soil Loss Equation (RUSLE).

Modified Universal Soil Loss Equation. The Modified equation improved on several aspects of the original:

- Uses a runoff factor instead of a rainfall factor
- Able to predict erosion for individual storm events
- Specifies more conservation practices
- Eliminates the need for a delivery ratio (Williams 1975, p. 245-246).

The MUSLE is experimentally proven to be more accurate than the USLE (Williams 1975). This version is specifically for sheet and rill erosion, and it is not appropriate for ephemeral or gully erosion.

Revised Universal Soil Loss Equation. The most recent adaptation of USLE, which was published in the USDA's Agriculture Handbook Number 703 in 1997, is the Revised Universal

Soil Loss Equation, or RUSLE (Renard 1997). The revised version programmed the equation into software for computation. The RUSLE also improved on several aspects of the original:

- Erosivity factor database was expanded, refining the accuracy of R
- The addition of a seasonal variable improved the soil erodibility factor, K
- Added subsectors representing prior land use, surface cover, crop canopy, surface roughness, and soil moisture
- A new equation for slope length and steepness
- Additional conservation practices (Laflen and Flanagan 2013; Renard 1997).

While USLE was created for agricultural land, RUSLE was adjusted to include construction plots; however, it also only considers sheet and rill erosion.

Both MUSLE and RUSLE are further developments of the original equation; however, they have one considerable difference, the R factor. MUSLE uses the runoff factor, whereas RUSLE uses the rainfall factor. Although both variables are appropriate in erosion calculations, the suitable equation is chosen based on the scope and characteristics of a project.

While the MUSLE and RUSLE updates provided significant improvements over the original equation, they are not without flaws. Both the RUSLE and MUSLE models are weaker in predicting erosion in the western US, due to the combination of climate and land use (Laflen and Flanagan 2013). Rangeland is a significant land use category in the west, which USLE is not as effective at predicting. Western soils are also drier than the conditions at the eastern research stations used to create the original database. Additionally, the equations remain limited to sheet and rill erosion.

Soil and Water Assessment Tool

The limitations of MUSLE and RUSLE led to the development of physically-based hydrologic models to estimate erosion rates and nonpoint source pollution. The USDA's ARS developed field and watershed scale models, such as *Chemicals, Runoff, and Erosion From Agricultural Management Systems* (CREAMS), (Knisel 1980); Erosion Productivity Impact Calculator (EPIC), (Sharpley and Williams 1990); Water Erosion Prediction Project (WEPP), (Flanagan et al. 1995); and the Soil and Water Assessment Tool (SWAT), (Arnold et al. 1998). Each of these tools contributed to further development of soil erosion modeling capabilities using portions of the USLE (Laflen and Flanagan 2013; Gassman et al. 2007). Physically based models require large amounts of input data and use GIS software for computation. Statistical calibration techniques are required to ensure the goodness-of-fit for each study. Consideration of each tool's strengths and weaknesses is essential before determining which model is best suited for a project.

The SWAT model assesses water supplies and nonpoint source pollution in watersheds and large river basins (Arnold et al. 1998). It is a physically-based continuous time-step model that requires input for soil, land use, hydrology, precipitation, temperature, sediment, solar radiation, and relative humidity (Gassman et al. 2007). The model is applicable for a variety of hydrologic processes, including estimating critical source areas for sediment erosion. The output from the SWAT model produces estimates using both MUSLE and USLE. This project used the SWAT model due to its free, open-source software, continuous time-step capabilities, and the ability to simulate watershed processes in a user-friendly ArcMap interface.

Many case studies have been published using SWAT to model runoff and assess sediment erosion. This application has gained popularity in recent years. Research focuses range

from climate change to phosphorous loading and hydrologic assessment (Nerantzaki et al. 2016; Oeurng and Sanchez-Perez 2011; Yuan et al. 2016). The literature reiterates the importance of understanding erosion risk for planning natural resource management.

In the US, SWAT is used by government agencies for a wide variety of applications. The NRCS uses SWAT to estimate point and nonpoint source pollution and evaluate conservation practices in agricultural watersheds (Mausbach and Dedrick 2004). It is also useful in supporting the Environmental Protection Agency's (EPA) 303(d) Impaired Waters and Total Maximum Daily Load (TMDL) analysis (Amatya et al. 2011; Borah et al. 2006). New updates of SWAT have produced ArcSWAT an ArcMap-based interface of the toolset. Both the SWAT and ArcSWAT interfaces are effective at estimating erosion rates within a watershed and are utilized by government agencies across the US.

Agricultural Conservation Planning Framework

Agencies work to improve site-specific conservation efforts through physical models. High-resolution datasets of topography, soil, water, and land use data are readily available for many locations across the US. These datasets are combined to determine optimal locations for contaminant-reducing BMPs at a site-specific level. In conjunction with the ARS, Tomer et al. (2013) published the first outline for the Agricultural Conservation Planning Framework (ACPF) toolset. These tools use modern datasets to better assist agricultural communities in conservation practice selections.

The ACPF incorporates land use, 3-meter LiDAR elevation, hydrology, and soil data to assess agricultural terrain (Porter et al. 2016). The toolset calculates potentially suitbable locations for grassed waterways, contour buffer strips, nutrient removal wetlands, surface-intake

filters, drainage water management, saturated buffers, water and sediment control basins, and denitrifying bioreactors (Porter et al. 2016). Regulations and engineering standards developed by the NRCS are taken into account to ensure the BMPs recommend by the model output comply with the established engineering standards for each practice (table 1).

To facilitate the usage of ACPF, USDA-ARS created databases of the required land use information for northern Arkansas, Illinois, northern Indiana, Iowa, eastern Kansas, Minnesota, northern Missouri, Nebraska, western Ohio, and Wisconsin. This list is comprehensive as of September, 2020; however, the USDA is consistenty expanding the scope of the database. The rest of the data required to run ACPF is readily available on many state and federal agency websites.

The ACPF toolset uses the calculated Stream Power Index (SPI), a measure of sediment erodibility based on slope, soil type, and catchment area (Porter et al. 2016). The model limits locations of grassed waterways to agricultural fields from the land use data and uses the stream network to avoid riparian areas. The result is an ArcMap polyline layer that represents optimal locations for grassed waterways.

Critical Source Area Identification

To summarize, the SWAT model can estimate erosion rates using the USLE and MUSLE, while the ACPF model produces ideal locations for BMPs across a watershed. By combining these two models, BMPs are prioritized based on sensitivity to erosion. Soil loss tolerance (*T*) is the maximum amount of soil erosion that can occur while maintaining a soil's productivity. *T* values are commonly used as target erosion rates in conservation management. Fragile soils have a lower soil loss tolerance, generally about 1 t/ac/year or 2.5 t/ha/year, while

deeper soils have a higher tolerance for erosion, up to 5 t/ac/year or 12.4 t/ha/year. This study will focus on areas that exceed the maximum soil loss tolerance a critical source area. Outputs for both models in ArcMap layers allow for a seamless transition from modeling to spatial analysis. This study focuses on the targeted implementation of one practice: the grassed waterway. Watershed managers will have the ability to use the results to address the most critical source areas of sediment erosion. No previous studies using the models in tandem have been published.

Table 1: Criteria and descriptions for grassed waterways.

	Conservation Practice Standards[1]
Criteria	Description
Capacity	Convey runoff from 10-year frequency, 24-hour storm
Stability	Select species that have the capacity to achieve adequate density, height, and vigor within an appropriate time frame to stabilize the waterway
Width	Keep the bottom width of trapezoidal waterways less than 100 ft.
Side Slopes	Flatter than a ratio of two horizontal to one vertical
Depth	Must be large enough so that the water surface of the waterway is below the water surface of the tributary channel, terrace, or diversion that flows into the waterway at design flow
Drainage	When needed to establish or maintain vegetation on sites having prolonged flows, high water tables, or seepage problems use… (additional conservation practices)
Outlets	Provide a stable outlet with adequate capacity
Vegetative Establishment	Establish vegetation as soon as conditions permit. Use mulch anchoring, nurse crop… to protect the vegetation until it is established (p.2-3)

[1] USDA NRCS 2000

STUDY AREA

Several factors were considered to select the study area. First, the location needed to be a primarily agricultural watershed. The second was the availability of the required data. Digitization of grassed waterways requires aerial photography, ideally from the most recent spring, whereas models require high-resolution watershed data, including soil, elevation, and land use. Third, a location that has above average rates of sediment yield was also desired. The combination of these criteria made southeastern Minnesota an ideal location for this study.

Regional Location and Physiography

The Root River watershed (figure 1) encompasses 1,064,961 acres within six counties of southeastern Minnesota. The western portion of the watershed is comprised of glaciated uplands associated with the Wisconsinan Des Moines Lobe and adjacent Pre-Illinoisian drift (Hobbs 1999). The eastern portion of the watershed is part of the Driftless Area, which is famous for trout fishing, hunting, water recreation, biking, and hiking (Birr et al. 2012). Therefore, its water resources are a fundamental aspect of the local economy (Gartner 2002). The United States Geological Survey (USGS) divides watersheds into different Hydrologic Unit Codes, or HUCs. These HUCs describe the area of a watershed, with fewer digits for larger HUCs and increasingly more digits for smaller ones (Seaber et al. 1987). An agricultural HUC-14, referred to as a subwatershed, was examined (figure 1).

This subwatershed was one of three selected in a study completed by the Minnesota Department of Agriculture as representative of the region's physiography (Birr et al. 2012). This

study, known as the Root River Field to Stream Partnership, brought together stakeholders throughout the region to assess the health of the Root River and its watershed.

Lower South Fork Root River – Bridge Creek (HUC 070400080806)

Geology and Geography. The Root River drains from west to east into the Mississippi River. Its main tributaries are the South Fork and the North, Middle, and South Branches (Birr et al. 2012). The majority of the Root River watershed falls within the Driftless Area, except the western portion, which is within the Western Corn Belt Plains. The Driftless Area of Minnesota, Wisconsin, Iowa, and Illinois is a karst terrain comprised of dominantly carbonate rocks (Birr et al. 2012). The Driftless Area portion of the watershed was glaciated in the early Quaternary, but the evidence of this glaciation has mostly been eroded, except for very isolated pockets of till that are deeply weathered (Hobbs 1999). Birr et al. (2012) separated the watershed into three regions of topography, from west to east: glacial till, karst, and uplands. The varying parent rock underlying regions of the watershed accounts for the difference in topography. The Bridge Creek subwatershed is representative of the upland region, with relatively rolling-to-flat uplands, steep dissected bluff valleys, and broad alluvial floodplains (Koschak et al. 2012). Bridge Creek is within the Lower South Fork of the Root River watershed in western Fillmore and eastern Houston Counties (figure 1).

Land Use. The watershed is predominantly agricultural, including mixed farm and rangeland. The Minnesota Pollution Control Agency quantifies land use in the Root River watershed as the following: 41.0% cropland, 30.7% rangeland, 22.1% forest/shrubland, 5.3% developed communities, 0.7% wetlands and 0.2% open water. The primary crops grown are corn and soybeans, with rangeland for dairy and hog production. In addition to cropland land use,

water quality problems in the region are also attributed to rangeland practices (Koschak et al. 2012).

Prior to European settlement, the Driftless Area was comprised of diverse ecosystems, including tallgrass prairie, oak savanna, and sugar maple basswood forest (Albert 1995; Shea et al. 2014; Knoot et al. 2015). Post-settlement, forestland decreased due to logging and was replaced with agricultural cropland (Rhemtulla et al. 2007). Land use changes directly impacted the soil's stability, increasing soil erodibility and land degradation.

Soils. Bridge Creek soils are typically alfisols and entisols. The alfisols are suborder udalfs formed in loess, with fluvent entisol soils with alluvial origins. Udalfs are developed under native deciduous forests and grasses, whereas fluvents are developed on alluvial floodplains in this area (Weil and Brady 2017). These soil suborders are all agriculturally productive, hence the historical land use changes from forestland and prairie to cropland in the region (Rhemtulla et al. 2007). The most common agricultural soils in Bridge Creek are Blackhammer-Southridge silt loam, Chaseburg and Judson silt loam, Fayette silt loam, Seaton silt loam, and Tama-Downs complex. These soils are all fine-silty, well drained, have maximum soil loss tolerances, and are commonly used for crops or pasture.

Sediment Erosion. The NRCS has compiled a National Resource Inventory (NRI) that has estimatedaverage rates of sheet, rill, and wind erosion across the US since 1982. Table 2 shows the difference in average water (sheet and rill) and wind erosion rates from 1982 to 2015. Changes in land use and the addition of conservation practices have led to a reduction of national erosion rates by over 30% in both categories (USDA 2018). The current national average cropland soil erosion rate is 5-12 t/ha/year (Montgomery 2007).

Southern Minnesota has significantly higher than average erosion occurring, with Driftless Area critical source area erosion rates above 25 t/ha/year (Lee 1982; Trimble 2000). Several studies have been completed to understand the problem. Gran et al. (2009) completed a sediment budget for the Le Sueur River watershed in south-central Minnesota, north of the Driftless Area. Knickpoint migration causes more substantial sediment erosion in the Le Sueur watershed. The watershed is divided into an upper and lower portion. The upland area is comprised of agricultural glacial deposits, whereas the lower area contains eroding bluffs and ravines, separated by the primary knickpoint. The Le Sueur study attributes 75% of the erosion to non-field sources: "ravines, bluffs, terraces and stored floodplain sediments" (Gran et al. 2009, p. 11). Sediment storage has increased due to changes in land use and hydrology, with current rates of sedimentation an order of magnitude higher than the estimated pre-European settlement rates (Gran et al. 2009).

However, studies in the Driftless Area have shown that cropland erosion rates have been decreasing. Trimble (1999) completed a long term study to analyze the sediment budget for Coon Creek, an agricultural watershed within the Wisconsin portion of the Driftless Area, which is also separated into uplands and lowlands (Hobbs 1999). This study found that the rate of alluvial sediment storage in Coon Creek has been declining since the 1940s, attributed to improvements in land use and conservation practices targeted at decreasing the upland erosion rates (Trimble 1999). The study shows the change in sediment storage from 1853 to 1993, with the most recent storage rates ~6% of the original quantity.

Although there have been drastic improvements, the Driftless Area still has a soil erosion problem. Conservation efforts have reduced the amount of erosion in the region significantly, but the downward trend in soil erosion rates has substantially decreased since 1997 (USDA 2018).

Achieving further reductions in the erosion rate will require a more targeted approach to conservation.

Environmental Values. Minnesota is one of the pioneering states in addressing water quality problems. Water recreation, specifically trout fishing, is one of Minnesota's most important tourism markets. Clean waters are necessary for a thriving trout population, which is a significant contributor to Minnesota's economy. Gartner (2002) estimated that ~$1.8 billion is spent in the state each year on fishing-related recreation.

In 2015, Minnesota passed the Buffer Law, which required buffers on all public waters by 2017 and all public ditches by 2018 (Minn. Stat. § 103F). Buffers are areas or strips of land in between a field and water resource with permanent vegetation that reduce water velocity and trap sediment (USDA NRCS 2016). Here the term buffer refers to vegetative or riparian strips. Vegetative strips are composed of planted or indigenous grasses, while riparian strips can involve both vegetation and trees (USDA NRCS 2016). These buffers help decrease nutrient and sediment pollution rates. The Buffer Law is the first in the nation to mandate BMPs on private lands and is evidence of Minnesota's commitment to water quality.

Table 2: Average rates of sheet, rill and wind erosion.

	Average rates of erosion[1]		
Erosion Type	Year	Quantity (tons/acre/year)	Quantity (t/ha/year)
Sheet and Rill	1982	3.82 tons/acre/year	9.44 t/ha/year
Wind	1982	3.21 tons/acre/year	7.93 t/ha/year
Sheet and Rill	2007	2.59 tons/acre/year	6.40 t/ha/year
Wind	2007	1.99 tons/acre/year	4.92 t/ha/year
Sheet and Rill	2015	2.71 tons/acre/year	6.70 t/ha/year
Wind	2015	1.91 tons/acre/year	4.72 t/ha/year

[1] USDA 2018

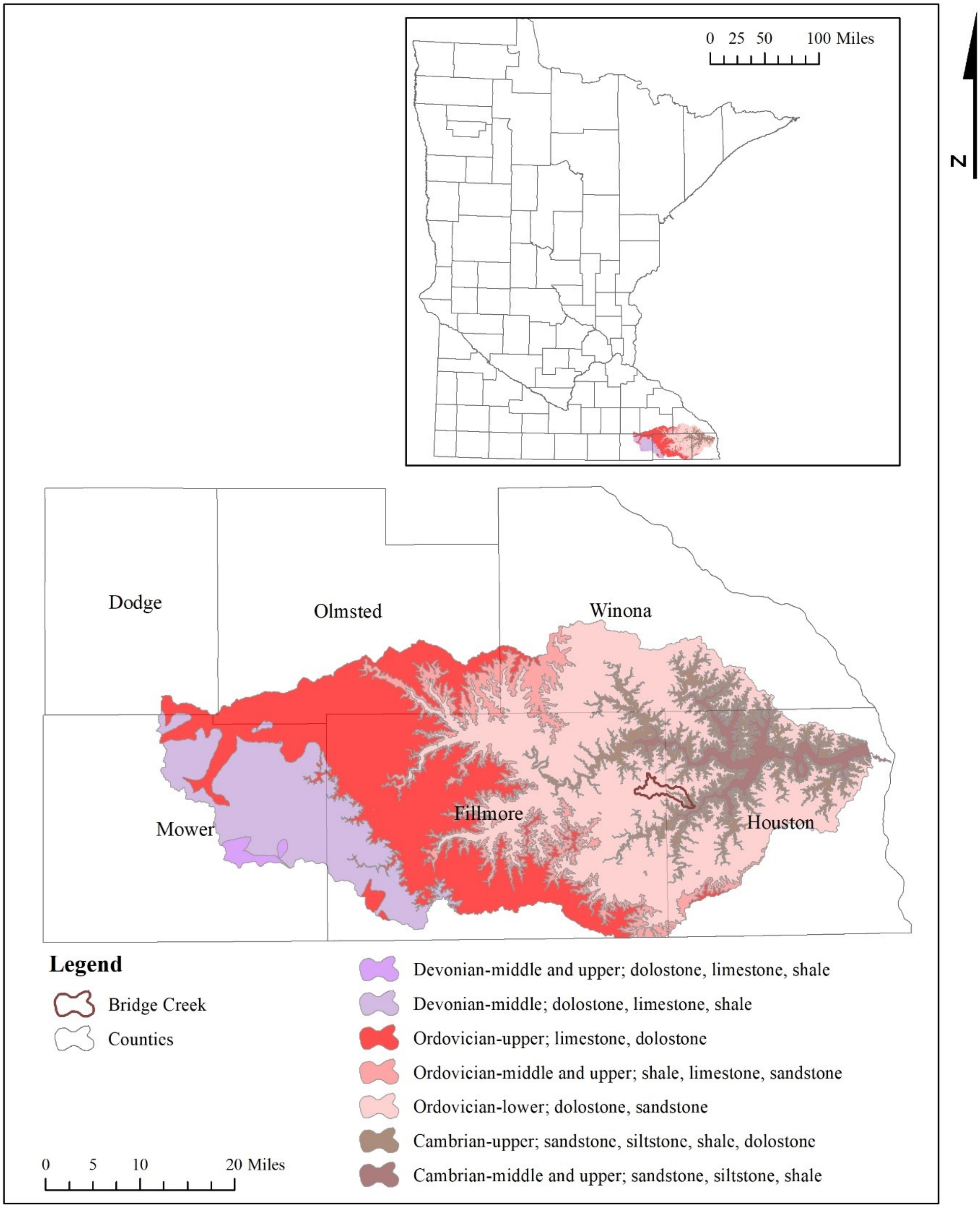

Figure 1: Geology of the Root River Watershed. The study area, Bridge Creek subwatershed, which is located along the Houston and Fillmore County boundary, is outlined.

METHODS

The goal of this research is to use geospatial methodologies to efficiently identify and prioritize critical source areas of sediment erosion. This was completed through three objectives: create an inventory where grassed waterways currently exist, identify locations where grassed waterways would enhance conservation effectiveness, and prioritize those sites for future implementation. Three tools helped complete these objectives: 1.) GIS to identify and inventory existing grassed waterways in Bridge Creek, 2.) the Agricultural Conservation Planning Framework to identify additional suitable sites for grassed waterways, and 3.) the Soil and Water Assessment Tool to quantify the potential benefit of implementing proposed grassed waterways. Last, a combination of these results supported a prioritization scenario of the areas where new grassed waterways would have the most impactful potential soil erosion reduction.

Objective 1: Create an Inventory of Existing Grassed Waterway Locations

Aerial photography from spring 2015 (table 3) was analyzed to identify the location of existing grassed waterways in Bridge Creek. Spring photographs are preferred for the contrast between the green grasses and brown, dormant crops. The NRCS definition and engineering specifications of grassed waterways (table 1) were used to create the following rules for uniform interpretation of the aerial photographs:

- Keep the bottom width less than 100 ft. (NRCS 2002)
- More than one parallel strip is ignored, as they are considered contour strips (NRCS 2002)
- Start the waterway perpendicular to field edge

- If intersecting a riparian zone, stop at first tree
- Ignore field perimeters, must be an intentionally developed waterway
- Cannot run parallel to perennial stream (NRCS 2002)

A polyline feature class was created in ArcMap to represent the existing grassed waterways. Hydrology data from the USGS was used to identify perennial streams and extensive grassed waterways were measured using the ArcMap Ruler tool to ensure they fit within the defined dimensions. These rules allowed for a systematic interpretation of the watershed with an output map of consistently described existing grassed waterways.

Objective 2: Identify Potential Locations for Grassed Waterways

The Agricultural Conservation Planning Framework (ACPF) toolset was designed to help watershed managers better control, trap, and treat agricultural contaminants. Grassed waterways are effective at mitigating soil erosion in areas susceptible to gully formation due to concentrated runoff, steep hillslopes, unstable soils, and/or intense rainfall. The ACPF toolset uses soil, land use, hydrologic, and elevation data to establish where gully erosion is probable, as well as identify potential locations for best management practices— in this case, grassed waterways.

The ACPF toolset is designed to run on HUC-12 watersheds. The data must be formatted correctly for the tools to process as outlined in the ACPF v2 Manual (Porter et al. 2016). Each of the data layers used in the ACPF analysis must be named in the proper format, as seen in figures 2, 3, 5, 6, 7, and 8. The data sources for the Bridge Creek base layers used in this analysis are found in table 3 and were provided by ARS. Appendix A contains a glossary defining each of the tools used in ACPF and SWAT processing, whereas figures of the input layers are found in Appendix B.

After the data layer preparation, the stream networks were developed. Stream network development prepares the Digital Elevation Model (DEM) to accurately represent hydrologic flow across the area (figure 2). During this process, a watershed boundary that encompasses the LIDAR-derived boundary, as well as the USGS National Hydrography Dataset boundary, is created to ensure adequate coverage. The DEM is 'filled,' raising the elevation values within all depressions to create a smooth and continuous flow network. Subsequent layers assume that overland flow from each cell is directed to the neighboring cell with the steepest downward gradient, thus creating flow direction and flow accumulation data.

Before completion of any additional processing, the created layers are reviewed. The created pour point must be in a viable location; that is, the cell lowest in elevation that has the highest accumulated flow, for the subsequent tools to run. Pour point placement was checked using the Identify tool in ArcGIS. By zooming in to the pixel scale, the elevations surrounding the given pour point were examined. This method verified that the generated pour point was the lowest elevation on the perennial stream. Once the lowest elevation was selected, the Flow Network layer was reviewed.

The DEM used to create the flow network was derived from LiDAR data (Light Detection and Ranging). LiDAR measures the distance to the Earth's surface from an airborne sensor creating a digital surface model. However, this method produces "digital dams" where features, such as culverts and bridges, cross streams or ditches. The LiDAR senses the top of the bridge deck or the roadway as the "ground" surface, instead of the bottom of the stream which is hidden underneath. As such, the DEM does not recognize that the hydrologic flow path extends through the culvert or under the bridge, causing the bridge or culvert to effectively act as digital dams that impede the derivation of an integrated hydrologic flow network. Manual identification

of digital dams is necessary during the derivation of the flow network. This process is referred to as "cutting" or "burning in" the stream through the digital obstacle. To diagnose impediments in the flow network, the Identify Impeded Flow tool was used. This tool helps identify where depressions were found within the DEM that cause pooling within the flow network. Pooling signifies either a natural sink or a digital dam in the DEM that needs to be corrected. The areas yielded by the Identify Impeded Flow tool help guide the creation of cut lines. Using a combination of DEM rasters and aerial photography the digital dams in the Bridge Creek watershed were identified. The ACPF toolset was used to correct these imperfections using the DEM burning technique (figure 3). By digitizing cut lines where the flow network was impeded, the user was able to cut the streams through the digital dams. This process is illustrated in figure 4. The cut lines feature classes are used to revise the initial flow network, with all the digital dams cut through to create a coherent, integrated flow network for the watershed. Successfully creating the final flow network may require multiple iterations of the process (see flowchart in figure 3 and Appendix B-5).

A series of cut lines were required to hydrologically condition the Bridge Creek DEM to be representative of the real world flow network, as shown in figure 4. To avoid creating further imperfections, sparse manipulation of the DEM is recommended; therefore, cut lines were used conservatively to correct the digital dams.

Once the hydrologic conditioning of the DEM was completed, the stream network was divided into perennial and intermittent stream orders. This categorization allows for BMPs to be recommended based on proximity to riparian areas adjacent to perennial streams. Using a combination of the DEM and aerial photography, visual interpretation was completed to identify

segments with continuous flow. The accuracy of the stream network definition directly affects BMP outputs; therefore, this step is crucial (Porter et al. 2016).

The last step in creating a stream network was to create the Stream Reaches and Catchments, as outlined in figure 5. These updated layers provided a new watershed boundary according to the hydrologically conditioned input data. The geospatial layer created for the Bridge Creek watershed boundary is found in Appendix B-7.

After the finalization of the stream network, several tables were generated (figure 6). First, the By-Field Slope Statistics tool used the new field boundary and the unfilled DEM to create a slope raster and a slope table (Appendix B-1). The slope data is used to identify fields susceptible to gully erosion and suitable for runoff control practices, like grassed waterways. Next, the Moore Terrain Derivatives were calculated. This tool is also useful in identifying susceptibility to soil erosion by creating the Stream Power Index (SPI), which is used as an indicator of the erosive power of flowing water (Appendix B-8).

Finally, the Grassed Waterways tool was ready to run. The tool used the SPI raster, field boundary, and stream reach layer inputs to generate optimal locations for the BMP, as shown in figure 7 and Appendix B-9. The user identified an SPI threshold for the tool to run, ranging from 97%-99%. The lowest option (97%) was used to identify the greatest number of grassed waterways for conservative calculations later on. The output of the tool created a polyline indicating optimal locations for the grassed waterways.

The ACPF tool created one continuous polyline, instead of a series of individual objects representing each potential grassed waterway location. The Advanced Editing tool Explode Multipart Feature was used to separate the polyline into segments, thus completing Objective 2.

Objective 3: Locate Critical Source Areas for Sediment Erosion

The SWAT Model uses a combination of physical, climate, and hydrological data to compute the impact of land management practices over time. This study used SWAT to locate critical source areas for sediment erosion.

The first step to run the SWAT model is watershed delineation. However, there is an option to input pre-existing data layers. The watershed boundary, stream reach catchments, and flow network previously created and hydrologically conditioned with the ACPF toolset were used as inputs (figure 8). Using the same data for both models provides the ability to compare the outputs upon completion. A raster file of the Bridge Creek watershed polygon was created using the Polygon to Raster tool, which was used as the SWAT watershed boundary mask. Next, the previously created Peuker-Douglas Stream Network was burned into the watershed. The DEM-based area tool was used to calculate the number of cells used in the analysis. No additional outlets or inlets were used in this model, point sources were not modeled, and the HUC-14 had no additional inlets. The main watershed outlet was defined, the watershed was delineated, and the subbasin parameters were calculated. The watershed was further divided into subbasins for calculations (Appendix B-10).

The next step was to define land use, soil, and slope raster layers (figure 9). The NRCS land use and SSURGO soil data from Appendix B-11 and Appendix B-12 were used. It is important to note that the mapping of the SSURGO soil data for Houston and Fillmore counties was completed at different scales and published in different versions. At the time of data acquisition, Fillmore County was published in version 13, while Houston County was published in version 12. This difference in resolution affects the ability to model soils in the watershed uniformly (Appendix B-12); however, both resolutions are acceptable to adequately model the

watershed. Each raster has several pre-defined classes associated with it. Each dataset (land use, soil, slope) is separated into several desired classes that are distinguishable from one another. This step is primarily for international users that do not have national land use or soil databases with predefined classes. In the US, the USDA publishes defined land use and soil classes; however, the slope raster was user classified applying 0-2%, 2-8%, and >8% breaks (Appendix B-13).

After preparation of the layers, the Hydrologic Response Units (HRUs) were delineated, as seen in figure 9 and Appendix B-14. In SWAT, HRUs are regions of a subbasin that possess unique land use, soil, and slope combinations. The HRU is the building block of the model, and size determines the resulting level of precision. The user can assign either the dominant HRU or multiple HRUs for each subbasin. Consequently, selecting multiple HRUs increases the processing time of the model but also the level of precision. A threshold percentage may be utilized to group HRUs together within ranges of similar land use, soil, or slope features. This study did not use a threshold value, thus using all available combinations, resulting in the most elaborate analysis option.

Next, the climate data was defined, following the steps in figure 10. Using physically collected inputs increases the validity of the model. Historical climate data was used for annual rainfall and temperature (table 3). There is an option to use stored first-order weather data, which was used for the sediment yield, solar radiation, and relative humidity averages. First-order stations are primarily maintained under the auspices of the National Weather Service or Federal Aviation Administration (table 3). Utilizing observed data inputs increases the validity of the model and minimizes the amount of calibration necessary.

The SWATCheck function was used to identify potential problems with the model. SWATCheck screens for common problems in calibration and data inputs within the simulation. The output dialog offers help in understanding unrealistic model simulations and ways to troubleshoot the potential causes. SWATCheck feedback did not identify any problems with the parameterized model. The maximum sediment yield modeled for the Bridge Creek watershed, without grassed waterways, was 46.7 t/ha/year. This figure is similar to the rates reported in Trimble and Crosson (2000) and Lee (1982) for the region, further validating the model.

SWAT is a time-step model that can simulate a daily, monthly, or yearly interval. The interval used for the study was a monthly time step from 1/1/1980 to 12/31/2010. The SWAT model was run for a base calculation of sediment yield in Bridge Creek, with no grassed waterways simulated.

Analysis

The SWAT model output consists of water quality data at the HRU level. The HRU SWAT output was merged with the HRU shapefile for geospatial analysis in ArcMap. HRUs that have an erosion rate exceeding the maximum soil loss tolerance of >12t/ha/year are considered critical source areas within the watershed. For analysis, the shapefile was symbolized based on sediment erosion rates (SEDth) using three classes of soil loss tolerance (Schertz 1983; Montgomery 2007):

- Low: <5t/ha/year
- Average: 5-12t/ha/year
- High: >12t/ha/year

The potential locations for grassed waterways identified by the ACPF toolset that intersect a critical source area were analyzed for a prioritization scenario. To calculate the potential erosion reduction for the area, a new layer was created that joined the HRU data with the potential grassed waterway locations. Thus, grassed waterways were analyzed based on the water quality modeled at its physical location. The analysis assumes that erosion is evenly distributed across each HRU, which vary in size from 9 m^2 to 619,659 m^2. For analysis, the area of each grassed waterway was converted to the percentage of the HRU it encompasses (area grassed waterway/area HRU). The result represents the quantity of erosion the grassed waterway could potentially mitigate in its modeled location. For example, if a potential grassed waterway location takes up 10% of an HRU area with an estimated sediment yield of 15.0 t/h/year, the calculated grassed waterway reduction potential is up to 1.5 t/h/year (figure 11). The locations were then ranked based on erosion reduction potential.

The analysis assumes erosion is occurring uniformly across the HRU and that the grassed waterway is effective over its area. Also, the calculations only utilize the sediment yield modeled in the critical source area. Neighboring HRU's are not included in the calculation, and the grassed waterways were not divided into segments for a more thorough analysis.

Table 3: Data layer information for ACPF and SWAT model inputs.

Data	Geospatial Dataset Details			
	Location	Origin	Source	Accessed
2015 Aerial Photography	Fillmore, Houston counties	NRCS	https://gdg.sc.egov.usda.gov/GDGOrder.aspx	October 2016
HUC-14 Watershed Boundary	Bridge	NRCS	https://gisdata.mn.gov/dataset/geos-dnr-watersheds	October 2016
Hydrology	State of Minnesota	MN Geospatial Commons	https://gisdata.mn.gov/dataset/water-dnr-hydrography	October 2016
3-m DEM	Fillmore, Houston counties	MN Geographic Data Clearinghouse	ftp://ftp.lmic.state.mn.us/pub/data/elevation/lidar/county/fillmore/	October 2016
Land Use, Soil, and HUC 12 Watershed	Lower South Fork Root River	USDA ACPF Database	http://www.nrrig.mwa.ars.usda.gov/st40_huc/dwnldACPF.html	October 2016
Rainfall, Temperature	Rushford Station 217184	MN DNR	http://www.dnr.state.mn.us/climate/historical/index.html	July 2017
Sediment Yield, Solar Radiation, Relative Humidity	-	SWAT generated	-	July 2017

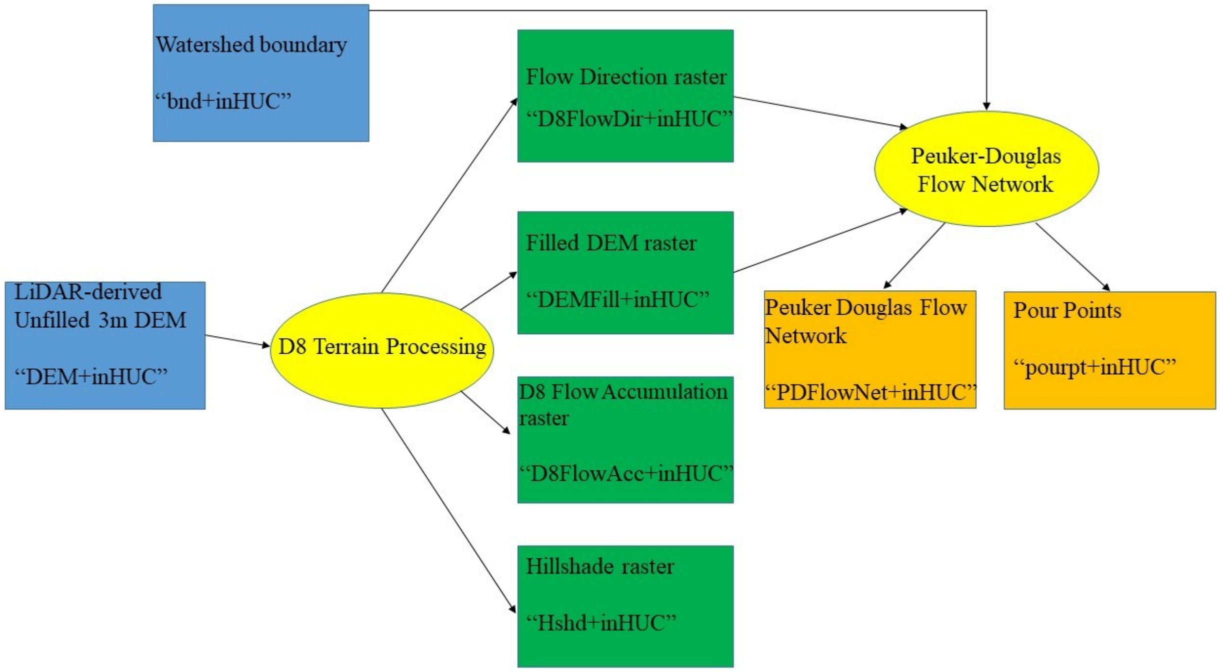

Figure 2: ACPF Stream and Flow Network processing. Square-data layer; Oval-tool; Blue-original data from table 3; Green-data produced from one process; Orange-data produced from a user-generated layer.

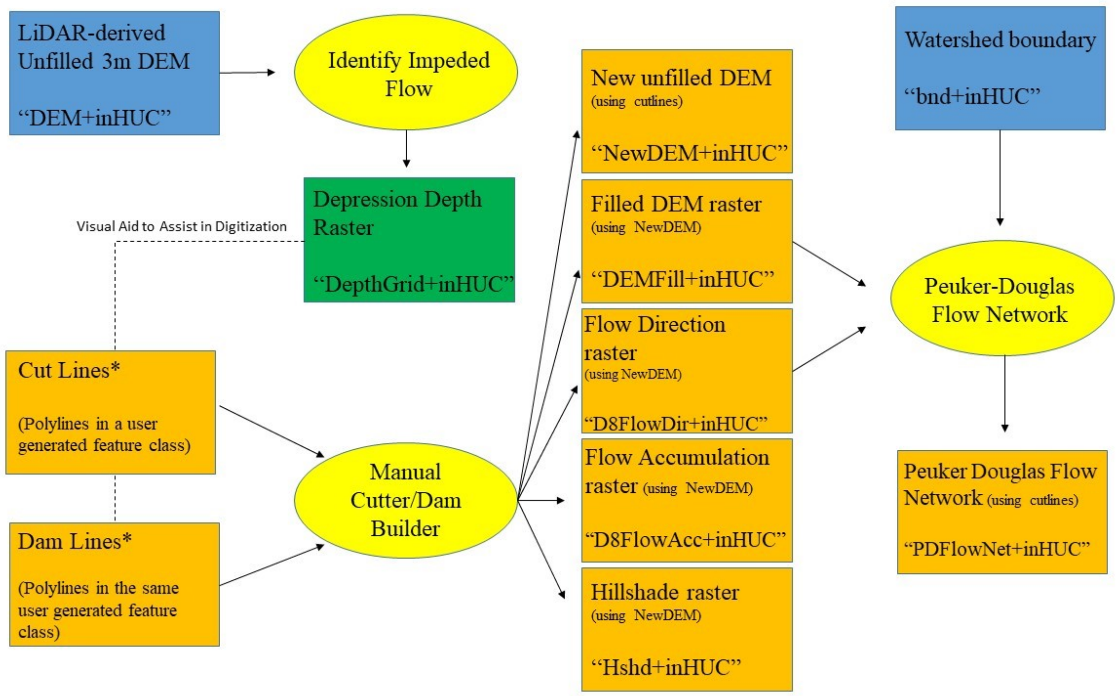

Figure 3: Hydrologically conditioning the DEM. Square-data layer; Oval-tool; Blue-original data from table 3; Green-data produced from one process; Orange-data produced from a user-generated layer. *User digitized lines.

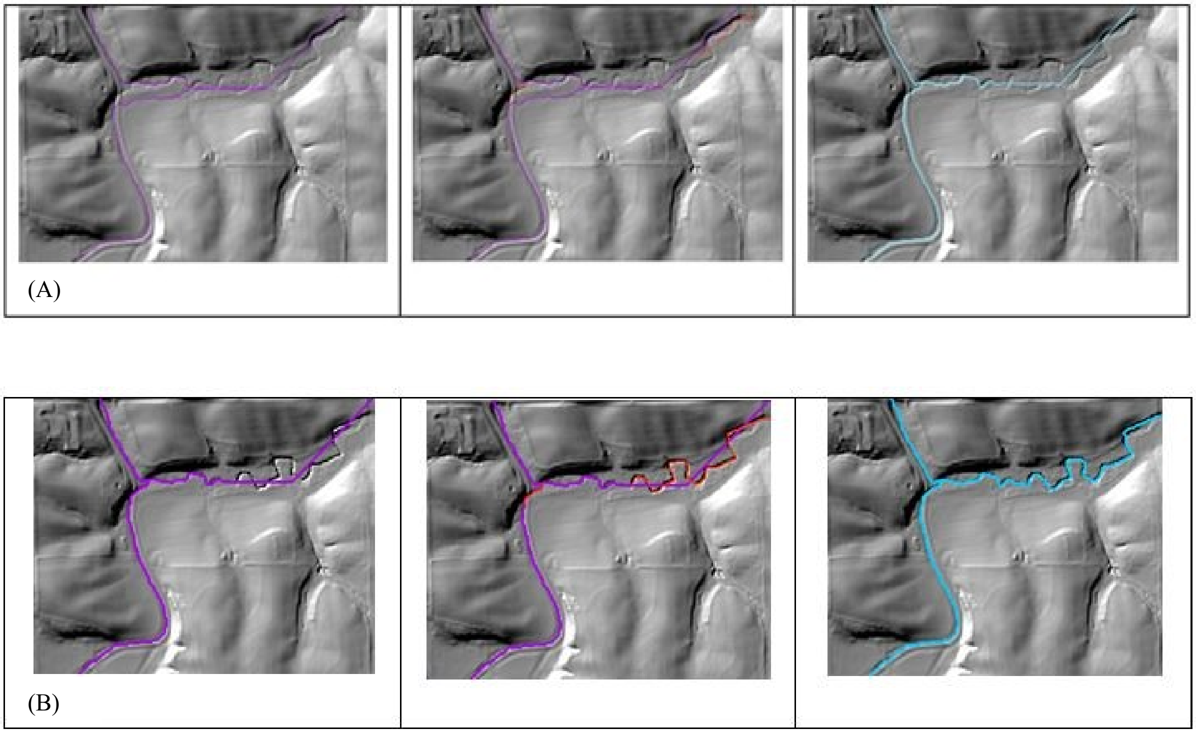

Figure 4: Creating a hydrologically conditioned DEM using the Manual Cutter/Dam Builder tool.
(A) Original flow network (left), network with cutlines (center), second created flow network (right)
(B) Second flow network (left), an additional series of cutlines (center), completed flow network (right)

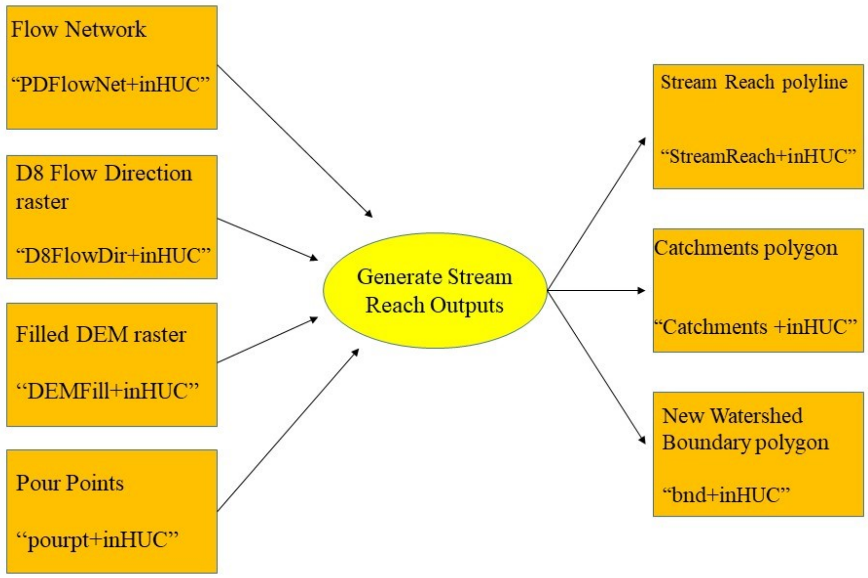

Figure 5: Generation of stream reach outputs. Square-data layer; Oval-tool; Orange-data produced from a user-generated layer.

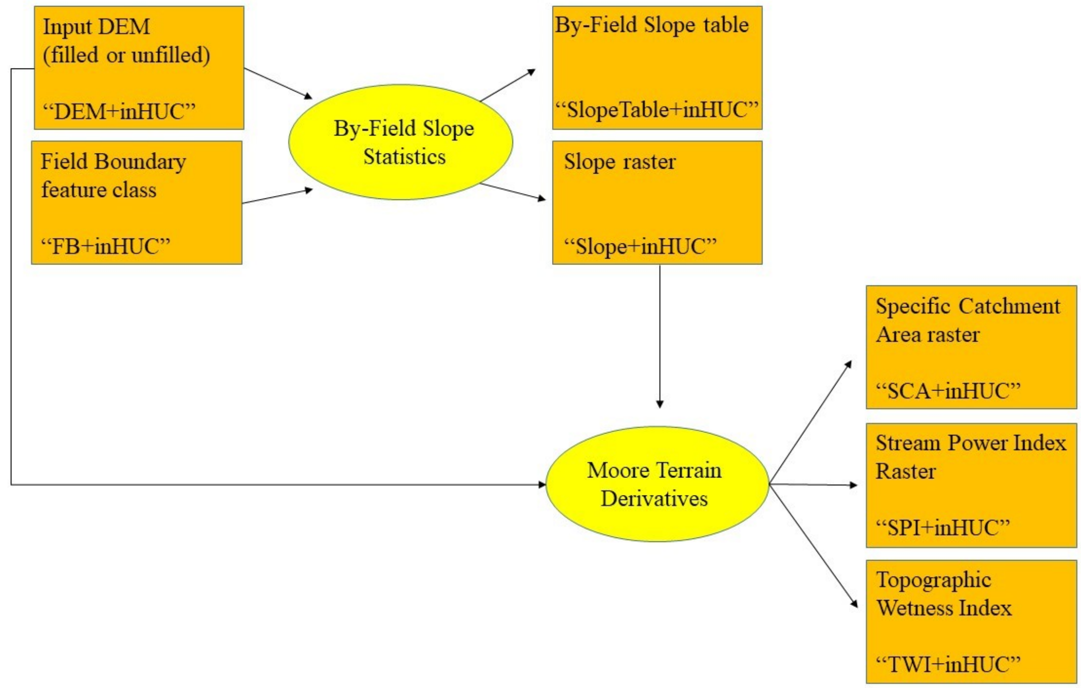

Figure 6: ACPF By-Field Slope Statistics and Moore Terrain Derivative tools. Square-data layer; Oval-tool; Orange-data produced from a user-generated layer.

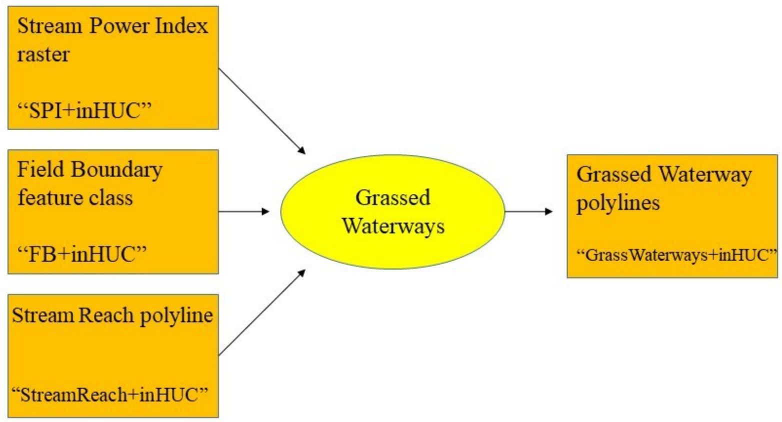

Figure 7: ACPF Grassed Waterways tool; Square-data layer; Oval-tool; Orange-data produced from a user-generated layer.

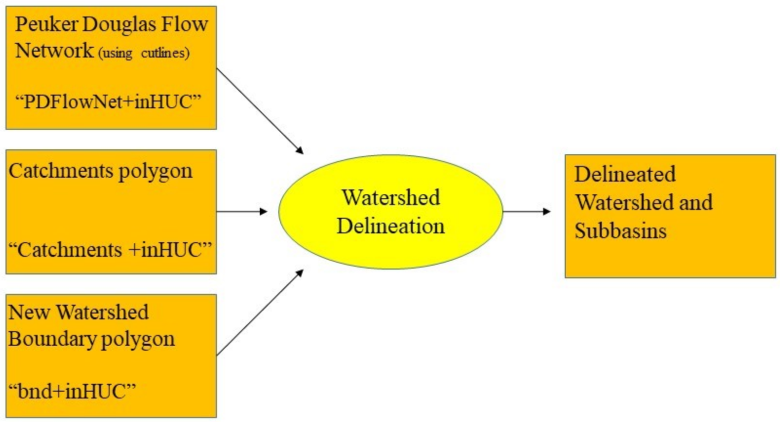

Figure 8: SWAT Watershed Delineation process, using the same inputs as ACPF; Square-data layer; Oval-tool; O

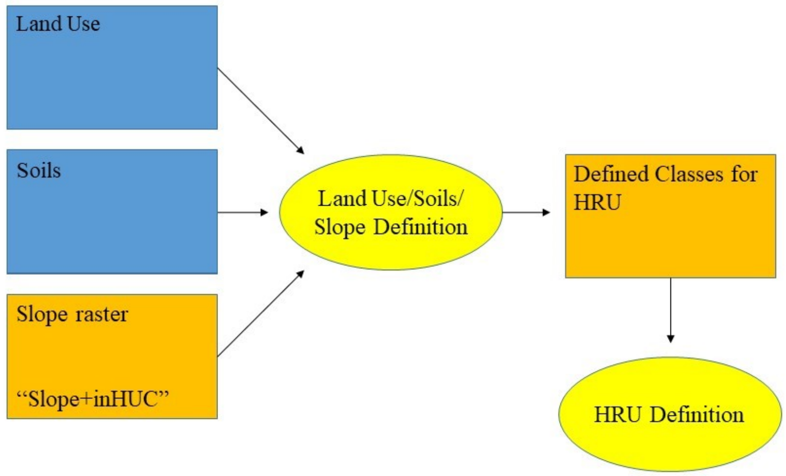

Figure 9: SWAT Land Use, Soils, and Slope Definition; Square-data layer; Oval-tool; Blue-original data from table 3; Orange-data produced from a user-generated layer.

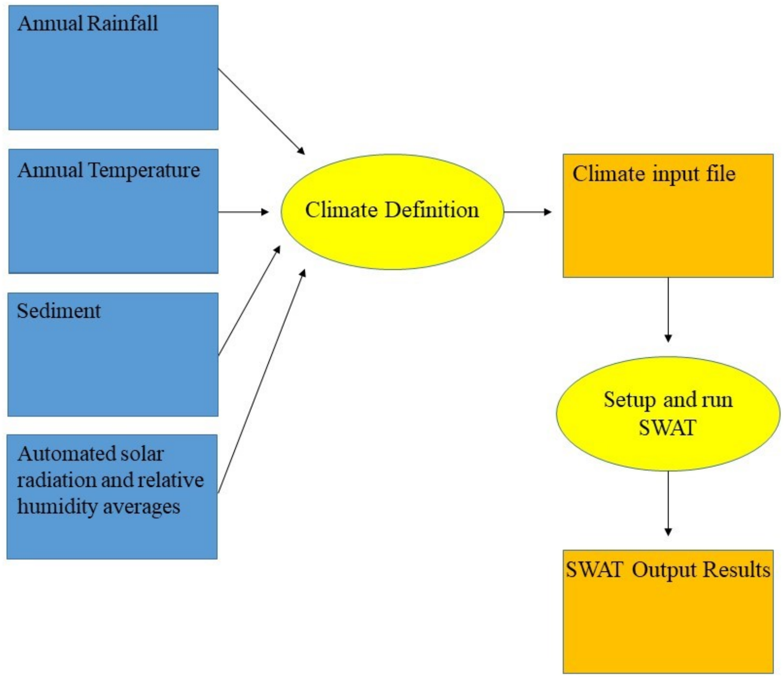

Figure 10: SWAT Climate Definition and modeling; Square-data layer; Oval-tool; Blue-original data from table 3; Orange-data produced from a user-generated layer.

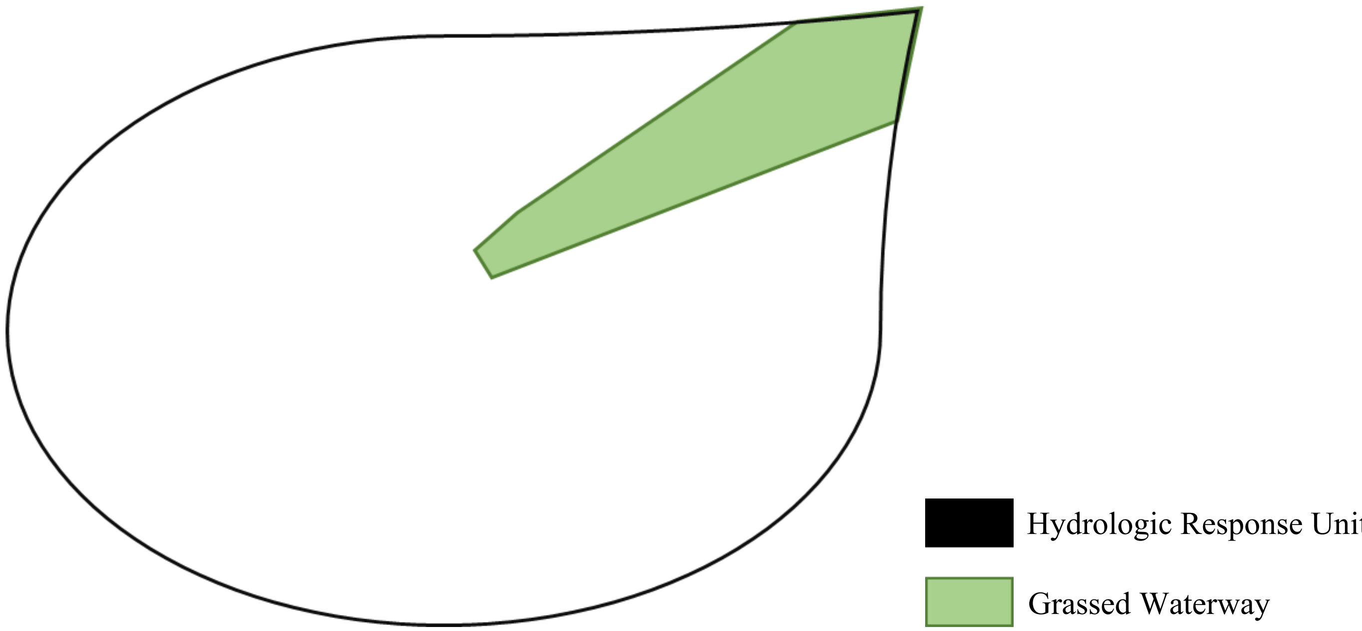

Figure 11: Visual representation of erosion reduction potential calculation example; if a potential grassed waterway location takes up 10% of an HRU area (not to scale) with a sediment yield of 15.0 t/h/year, the calculated grassed waterway reduction potential is up to 1.5 t/h/year

RESULTS

Objective 1: Create an Inventory of Existing Grassed Waterway Locations

Following the guidelines presented in the Methods section, the existing locations of grassed waterways in the Bridge Creek watershed were delineated. A map of the 149 grassed waterway locations identified is provided in figure 12. Once the existing locations were identified, further analysis was completed using the land use, soil, and slope datasets (Appendix B-11, B-12, and B-1). Table 4 shows the percentage of existing grassed waterways in each land use category. The existing grassed waterways are predominantly located within locations designated as corn (36%), grass/pasture (28%), or soybean (24%) land use areas. Table 5 shows the percentage of each Muckey soil classification mapped in an existing grassed waterway location. The most common soil and slope types are Chaseburg and Judson silt loams, with a 2 to 6 percent slope (24%); Seaton silt loam, with a 6 to 12 percent slope (15%); and the Tama-Downs complex, driftless, with 6 to 12 percent slope (10%); shown in table 5. These soils are all well-drained to moderately well-drained, highly productive for agriculture and highly erodible (National Resource Conservation Service 2012b).

Objective 2: Identify Potential Locations for Grassed Waterways

Using the procedure depicted in figures 2 through 7, ideal grassed waterway locations were modeled. A map of the 246 ACPF recommended potential locations within Bridge Creek is provided in figure 13. Further analysis was completed using land use, soil, and slope datasets. Table 6 shows the percentage of ACPF recommended grassed waterways in each land use category. The recommended grassed waterways are predominantly modeled within locations

designated as corn (41%), soybean (25%), or grass/pasture (21%) land use areas. Table 7 shows the percentage of each Muckey soil classification mapped in an ACPF recommended grassed waterway location. The most common soil and slope types are the Tama-Downs complex, driftless, with 6 to 12 percent slope (18%); Seaton silt loam, with a 6 to 12 percent slope (16%); and Tama-Downs complex, driftless, with 2 to 6 percent slope; shown in table 7. These soils are all well-drained and commonly used for agriculture in the watershed.

Objective 3: Locate Critical Source Areas for Sediment Erosion

Using the procedure outlined in figures 9 and 10, critical source areas of sediment erosion within the Bridge Creek watershed were identified using SWAT. Due to the delineation processes used in each toolset, the output watershed boundaries in ACPF and SWAT models are not identical (Appendix B-15); however, because existing and modeled grassed waterway locations are not near the watershed boundaries, this discrepancy did not alter the results. The land use, soil, and slope datasets were combined to create 2,174 hydrologic response areas (HRU) with unique combinations of land use, soil, and slope subwatershed characteristics. Each HRU was subsequently analyzed for average yearly sediment yield, in tonnes per hectare, using the annual rainfall, annual temperature, sediment, and automated solar radiation/relative humidity averages within the climate definition. The results can be seen in figure 14. Each HRU was delineated as a low, average, or critical source area for sediment erosion. The majority of the watershed is considered to have low or average rates of erosion, whereas a disproportionate amount of erosion is occurring in 17 critical source areas (out of 2,174 HRUs). The model results suggest that, while critical source areas only account for 0.8% of the watershed area, they create 84% of the yearly erosion in the watershed. The average yearly sediment yield for the entire

watershed is 3.7 t/ha, yet the average in critical source areas is 401.8 t/ha. These averages show significantly higher rates of erosion are occurring in the critical source areas.

Further analysis was completed using land use, soil, and slope datasets. Table 8 shows the percentage of critical source areas in each land use category. The critical source areas are predominantly within land uses designated as corn (41%) and grass/pasture (35%). Table 9 shows the percentage of each Muckey soil classification present within the critical source areas. The most common soil and slope types are the Tama-Downs complex, driftless, with 2 to 6 percent slope (29%), and Fayette silt loam, with 7 to 11 percent slope (18%). These soils are both well-drained and commonly used for agriculture in the watershed.

Analysis

Results from each objective were combined to create a prioritization for future implementation of grassed waterways. Figure 15 shows the distribution of ACPF recommended locations for grassed waterways overlaying the average rates of soil erosion modeled in each hydrologic response unit. The recommended grassed waterways that overlap a critical source area are highlighted as prioritized locations.

The eleven prioritized locations were then randomly assigned numbers to be used in spreadsheet analysis (figure 16). The ACPF toolset creates attributes for the modeled grassed waterway locations, including the length of the waterway in meters. The SWAT model creates attributes for each hydrologic response unit, including the sediment yield in tons per hectare, and the HRU area in meters squared. The grassed waterway dimensions were converted from length to area, by assuming a 5-meter average width. Next, the area of the grassed waterway was calculated as a percentage of the HRU. Finally, the percentage of grassed waterway area was

multiplied by the sediment yield amount modeled in the HRU to find the erosion potential of each modeled grassed waterway and ranked based on their modeled potential sediment yield reduction (tables 10 and 11). The calculated sediment yield reduction per grassed waterway ranges from 3.59t/ha/year to 36.32t/ha/year. The table demonstrates the most cost-effective locations to implement future grassed waterways to maximize conservation practice effectiveness.

Table 4: Percentage of each category within existing grassed waterways.

	Existing Grassed Waterways Land Use	
Count	Percentage	Land Use
260	36%	Corn
206	28%	Grass/Pasture
173	24%	Soybeans
46	6%	Alfalfa
35	5%	Deciduous Forest
4	1%	Developed/ Open Space
2	0%	Developed/ Low Intensity

Table 5: Percentage of each soil classification for existing grassed waterways.

	Soil Type Distribution in Existing Grassed Waterway Locations[1]			
Count	Percentage	Muckey	Description	Soil Loss Tolerance
484	24%	2216705	Chaseburg and Judson silt loams, 2 to 6 percent slopes	5
313	15%	398218	Seaton silt loam, 6 to 12 percent slopes, eroded	5
211	10%	2216797	Tama-Downs complex, driftless, 6 to 12 percent slopes, moderately eroded	5
189	9%	398301	Blackhammer-Southridge silt loams, 12 to 20 percent slopes, eroded	5
178	9%	2216738	Fayette silt loam, 7 to 11 percent slopes, moderately eroded	5
115	6%	398219	Seaton silt loam, 12 to 20 percent slopes, eroded	5
111	5%	2216795	Tama-Downs complex, driftless, 12 to 18 percent slopes, moderately eroded	5
88	4%	2216793	Tama-Downs complex, driftless, 2 to 6 percent slopes	5
74	4%	398217	Seaton silt loam, ridge phase, 2 to 6 percent slopes	5
43	2%	2216732	Dubuque and Whalan silt loams, 12 to 17 percent slopes, moderately eroded	2
42	2%	398300	Blackhammer-Southridge silt loams, 6 to 12 percent slopes, eroded	5
42	2%	2216736	Fayette silt loam, 12 to 17 percent slopes, moderately eroded	5
29	1%	2216735	Fayette silt loam, 2 to 6 percent slopes	5
19	1%	2216702	Alluvial land, medium textured, poorly drained	5
15	1%	2216741	Fayette silt loam, 18 to 45 percent slopes	5

Table 5: Percentage of each soil classification for existing grassed waterways. (continued)

Count	Percentage	Muckey	Description	Soil Loss Tolerance
12	1%	2216760	Mixed alluvial land, 0 to 6 percent slopes	-
11	1%	398305	Nodine-Rollingstone silt loams, 4 to 12 percent slopes, eroded	5
10	0%	398306	Nodine-Rollingstone silt loams, 12 to 20 percent slopes, eroded	5
8	0%	398271	Seaton silt loam, valleys, 12 to 20 percent slopes, eroded	5
8	0%	2216727	Dubuque and Whalan silt loams, 18 to 45 percent slopes	2
6	0%	398279	Festina silt loam, 6 to 12 percent slopes, eroded	5
3	0%	398268	Timula silt loam, 12 to 20 percent slopes, eroded	5
2	0%	398307	Lamoille-Elbaville silt loams, 20 to 30 percent slopes	5
1	0%	398216	Seaton silt loam, 1 to 3 percent slopes	5
1	0%	398239	Chaseburg silt loam, channeled, 2 to 6 percent slopes	5

[1]USDA Soil Data

Table 6:Percentage of each category within ACPF grassed waterways.

	ACPF Grassed Waterway Land Use	
Count	Percentage	Land Use
995	41%	Corn
594	25%	Soybeans
504	21%	Grass/Pasture
143	6%	Alfalfa
100	4%	Deciduous Forest
70	3%	Developed/ Open Space
6	0%	Developed/ Low Intensity
2	0%	Peas

Table 7: Percentage of each Muckey soil classification for ACPF grassed waterway locations.

	Soil Type Distribution in ACPF Grassed Waterway Locations[1]			
Count	Percentage	Mukey	Description	Soil Loss Tolerance
1163	18%	2216797	Tama-Downs complex, driftless, 6 to 12 percent slopes, moderately eroded	5
1032	16%	398218	Seaton silt loam, 6 to 12 percent slopes, eroded	5
718	11%	2216793	Tama-Downs complex, driftless, 2 to 6 percent slopes	5
675	10%	398219	Seaton silt loam, 12 to 20 percent slopes, eroded	5
557	8%	2216705	Chaseburg and Judson silt loams, 2 to 6 percent slopes	5
500	8%	2216738	Fayette silt loam, 7 to 11 percent slopes, moderately eroded	5
377	6%	398301	Blackhammer-Southridge silt loams, 12 to 20 percent slopes, eroded	5
283	4%	398239	Chaseburg silt loam, channeled, 2 to 6 percent slopes	5
161	2%	398307	Lamoille-Elbaville silt loams, 20 to 30 percent slopes	5
142	2%	2216795	Tama-Downs complex, driftless, 12 to 18 percent slopes, moderately eroded	5
97	1%	398236	Eitzen silt loam, channeled, 1 to 6 percent slopes	5
83	1%	2216736	Fayette silt loam, 12 to 17 percent slopes, moderately eroded	5
76	1%	398278	Festina silt loam, 2 to 6 percent slopes	5
73	1%	2216735	Fayette silt loam, 2 to 6 percent slopes	5

Table 7: Percentage of each Muckey soil classification for ACPF grassed waterway locations. (continued)

Count	Percentage	Mukey	Description	Soil Loss Tolerance
62	1%	398254	Muscatine silt loam	-
57	1%	2216732	Dubuque and Whalan silt loams, 12 to 17 percent slopes, moderately eroded	2
51	1%	398279	Festina silt loam, 6 to 12 percent slopes, eroded	5
47	1%	398300	Blackhammer-Southridge silt loams, 6 to 12 percent slopes, eroded	5
37	1%	398260	Port Byron silt loam, 1 to 3 percent slopes	-
33	0%	398217	Seaton silt loam, ridge phase, 2 to 6 percent slopes	5
33	0%	398268	Timula silt loam, 12 to 20 percent slopes, eroded	5
33	0%	398272	Seaton loam, valleys, 20 to 30 percent slopes	5
31	0%	398271	Seaton silt loam, valleys, 12 to 20 percent slopes, eroded	5
29	0%	398275	Mt. Carroll silt loam, 6 to 12 percent slopes, moderately eroded	5
24	0%	398306	Nodine-Rollingstone silt loams, 12 to 20 percent slopes, eroded	5
22	0%	398309	Beavercreek-Arenzville complex, 1 to 12 percent slopes	5
20	0%	398264	Lindstrom silt loam, 1 to 6 percent slopes	5
18	0%	398324	Sparta loamy sand, 0 to 6 percent slopes	5
17	0%	2216741	Fayette silt loam, 18 to 45 percent slopes	5

Table 7: Percentage of each Muckey soil classification for ACPF grassed waterway locations. (continued)

Count	Percentage	Mukey	Description	Soil Loss Tolerance
16	0%	398256	Plainfield sand, 0 to 6 percent slopes	5
16	0%	398277	Festina silt loam, 0 to 2 percent slopes	5
13	0%	398253	Kennebec silt loam, occasionally flooded	5
13	0%	398255	Dickinson sandy loam, 1 to 6 percent slopes	3
13	0%	2216801	Mantorville and Wykoff loams, 7 to 17 percent slopes, moderately eroded	4
12	0%	398274	Mt. Carroll silt loam, 2 to 6 percent slopes, moderately eroded	5
11	0%	398302	Lamoille-Dorerton silt loams, 30 to 45 percent slopes	4
11	0%	2216760	Mixed alluvial land, 0 to 6 percent slopes	-
9	0%	398289	Brodale cobbly fine sandy loam, rocky, 45 to 70 percent slopes	2
8	0%	398226	Arenzville silt loam	5
8	0%	398287	Littleton silt loam	5
8	0%	398325	Water	-
7	0%	398261	Port Byron silt loam, 3 to 6 percent slopes	-
6	0%	2216727	Dubuque and Whalan silt loams, 18 to 45 percent slopes	2
5	0%	398232	Colo silt loam, overwash	5
4	0%	398229	Terril loam, sandy substratum	-
4	0%	398269	Timula silt loam, 20 to 40 percent slopes	5

Table 7: Percentage of each Muckey soil classification for ACPF grassed waterway locations. (continued)

Count	Percentage	Mukey	Description	Soil Loss Tolerance
3	0%	398223	Madelia silt loam	-
3	0%	398270	Seaton silt loam, valleys, 6 to 12 percent slopes, eroded	5
3	0%	398315	La Farge silt loam, 12 to 20 percent slopes, eroded	3
2	0%	398259	Plainfield sand, 25 to 50 percent slopes	5
2	0%	398305	Nodine-Rollingstone silt loams, 4 to 12 percent slopes, eroded	5
2	0%	398308	Elbaville silt loam, 30 to 45 percent slopes	5
2	0%	2216702	Alluvial land, medium textured, poorly drained	5
1	0%	398294	Kalmarville silty clay loam, occasionally flooded	3
1	0%	2216792	Tama-Downs complex, driftless, 18 to 35 percent slopes, moderately eroded	5

[1]USDA Soil Data

Table 8: Percentage of each land use category for SWAT modeled critical source areas.

	Critical Source Area Land Use[1]	
Count	Percentage	Land Use
7	41%	Corn
6	35%	Grass/Pasture
2	12%	Soybeans
2	12%	Urban

[1]USDA Land Use Data

Table 9: Percentage of soil classification for SWAT modeled critical source areas.

	Soil Type Distribution in Critical Source Areas[1]			
Count	Percentage	Muckey	Description	Soil Loss Tolerance
5	29%	2216793	Tama-Downs complex, driftless, 2 to 6 percent slopes	5
3	18%	2216738	Fayette silt loam, 7 to 11 percent slopes, moderately eroded	5
2	12%	2216797	Tama-Downs complex, driftless, 6 to 12 percent slopes, moderately eroded	5
2	12%	2216705	Chaseburg and Judson silt loams, 2 to 6 percent slopes	5
2	12%	2216735	Fayette silt loam, 2 to 6 percent slopes	5
1	6%	398301	Blackhammer-Southridge silt loams, 12 to 20 percent slopes, eroded	5
1	6%	398217	Seaton silt loam, ridge phase, 2 to 6 percent slopes	5
1	6%	2216801	Mantorville and Wykoff loams, 7 to 17 percent slopes, moderately eroded	4

[1] USDA Soil Data

Table 10: Sediment yield reduction potential spreadsheet analysis.

GW Number	Grassed Waterway Sediment Yield Reduction Potential						
	GW Length (m)	HRU Number	HRU Sed. Yield (t/ha)	HRU Area (m2)	GW Area (m2)	Area Ratio*	Sed. Yield (t/ha)
1	115.12	183	515.96	13000	575.61	4%	22.85
2	76.86	181	516.71	25000	384.32	2%	7.94
3	78.00	172	530.22	14000	389.99	3%	14.77
4	191.82	172	530.22	14000	959.08	7%	36.32
5	65.72	183	515.96	13000	328.59	3%	13.04
6	45.40	172	530.22	14000	226.99	2%	8.60
7	95.38	156	496.72	66000	476.92	1%	3.59
8	81.50	183	515.96	13000	407.50	3%	16.17
9	52.32	171	529.99	7600	261.60	3%	18.24
10	87.33	171	529.99	7600	436.63	6%	30.45
11	285.22	117	529.95	47000	1426.11	3%	16.08

Note: Grassed waterways are assumed to be equally effective at any width or length and critical source areas are assumed to have uniform erosion rates across the area. Grassed waterways are also estimated to have a width of 5 m.
*Grassed waterway area / hydrologic response unit area

Table 11: Modeled grassed waterway locations ranked according to potential sediment yield reduction.

	Grassed Waterway Prioritization	
Rank	Grassed Waterway Number	Modeled Sediment Yield Reduction (t/ha)
1	4	36.32
2	10	30.45
3	1	22.85
4	9	18.24
5	8	16.17
6	11	16.08
7	3	14.77
8	5	13.04
9	6	8.60
10	2	7.94
11	7	3.59

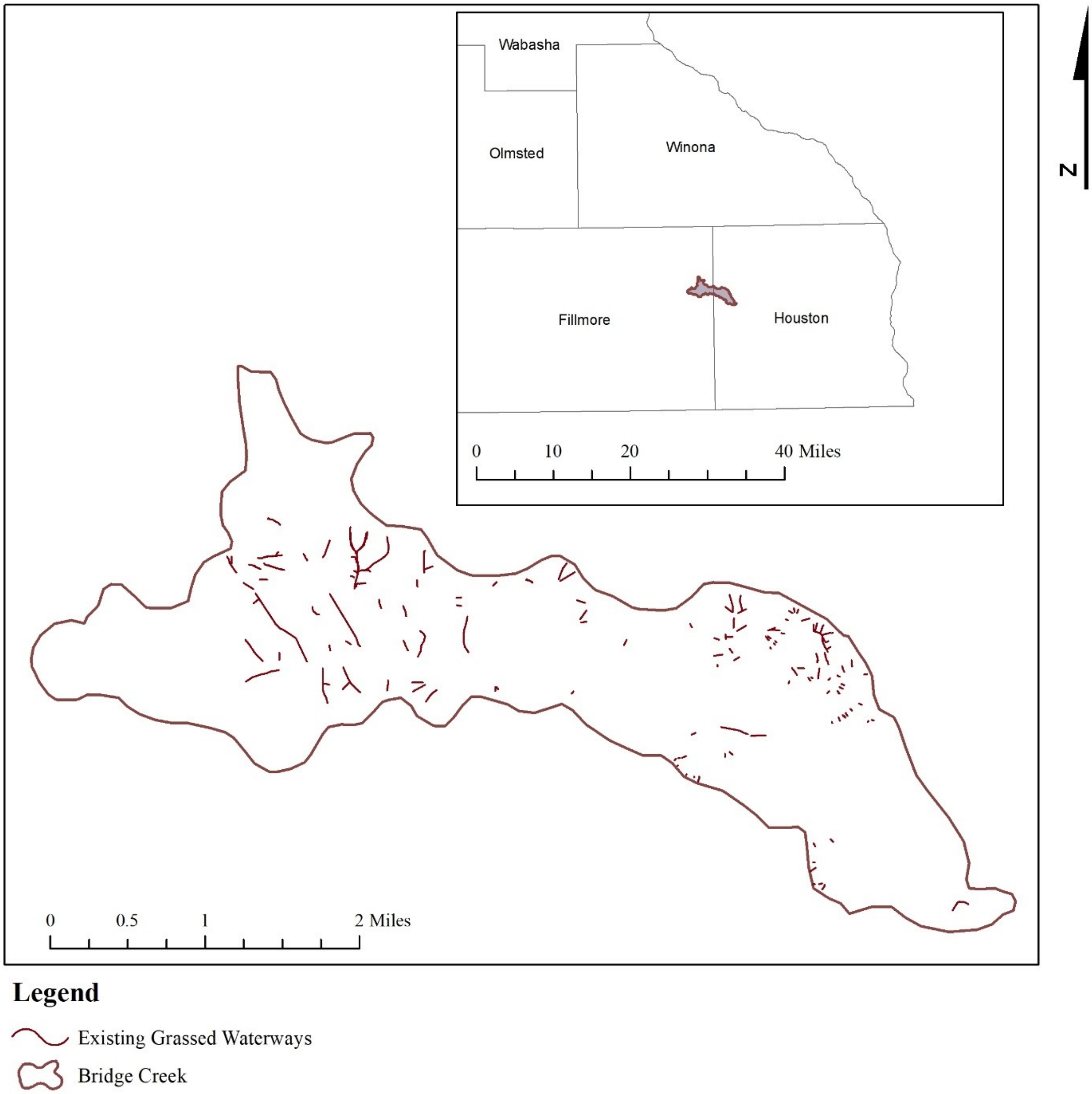

Figure 12: Existing grassed waterway locations.

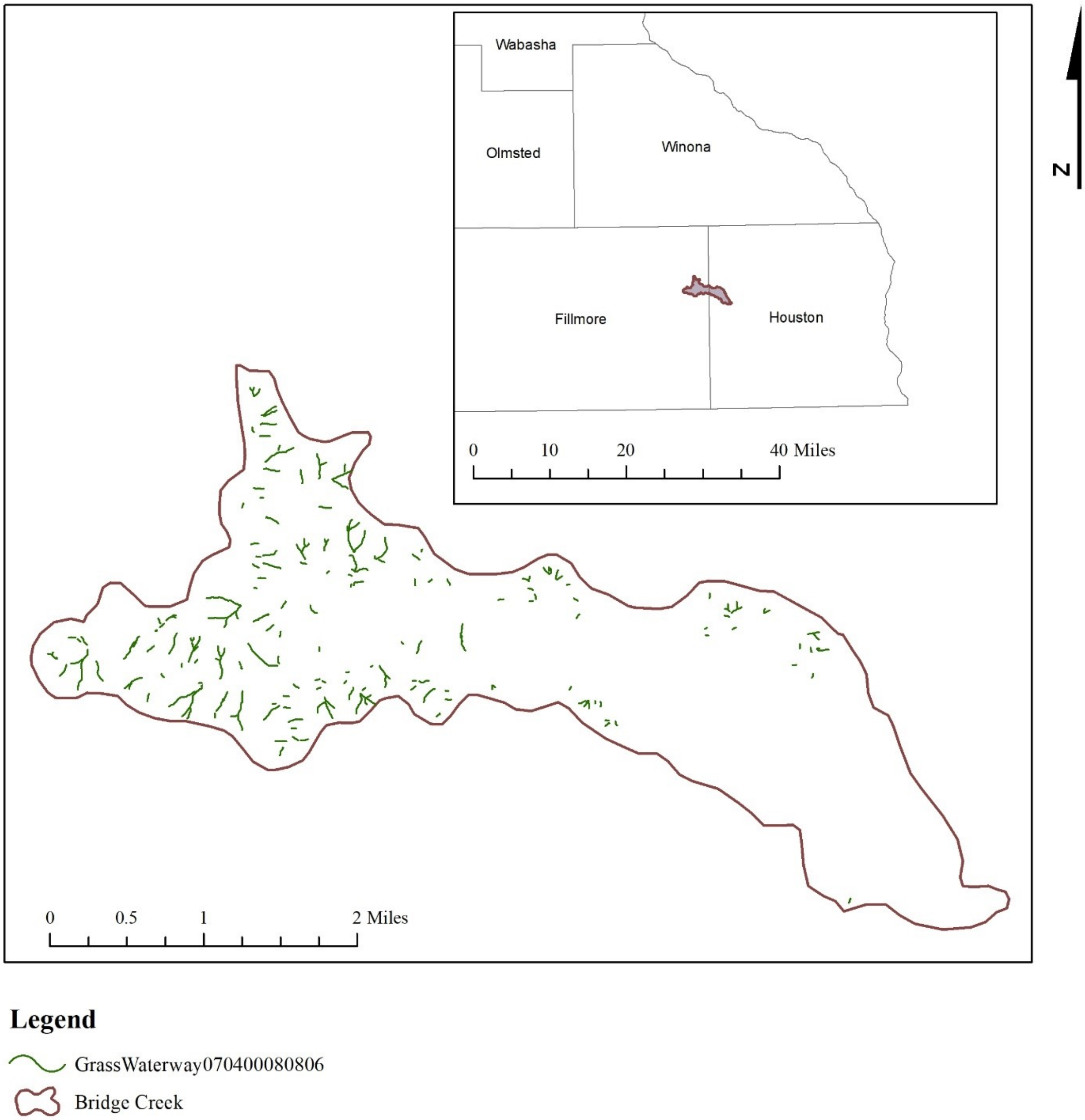

Figure 13: ACPF modeled ideal locations for grassed waterways, 246 locations within Bridge Creek watershed.

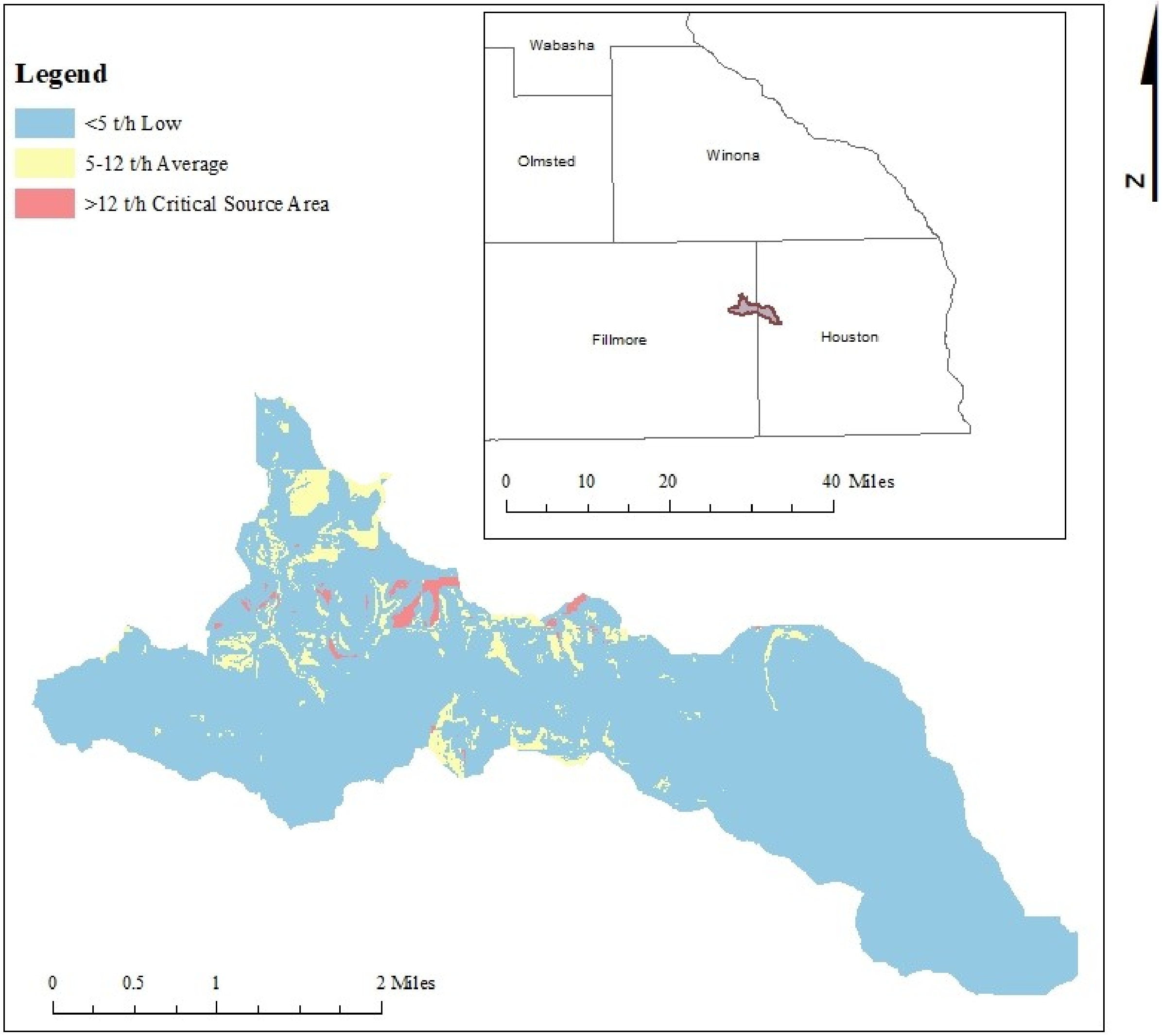

Figure 14: SWAT hydrologic response units symbolized by annual erosion in tons per hectare (t/h). Ranked in categories of low erosion, average erosion, and critical source area for erosion.

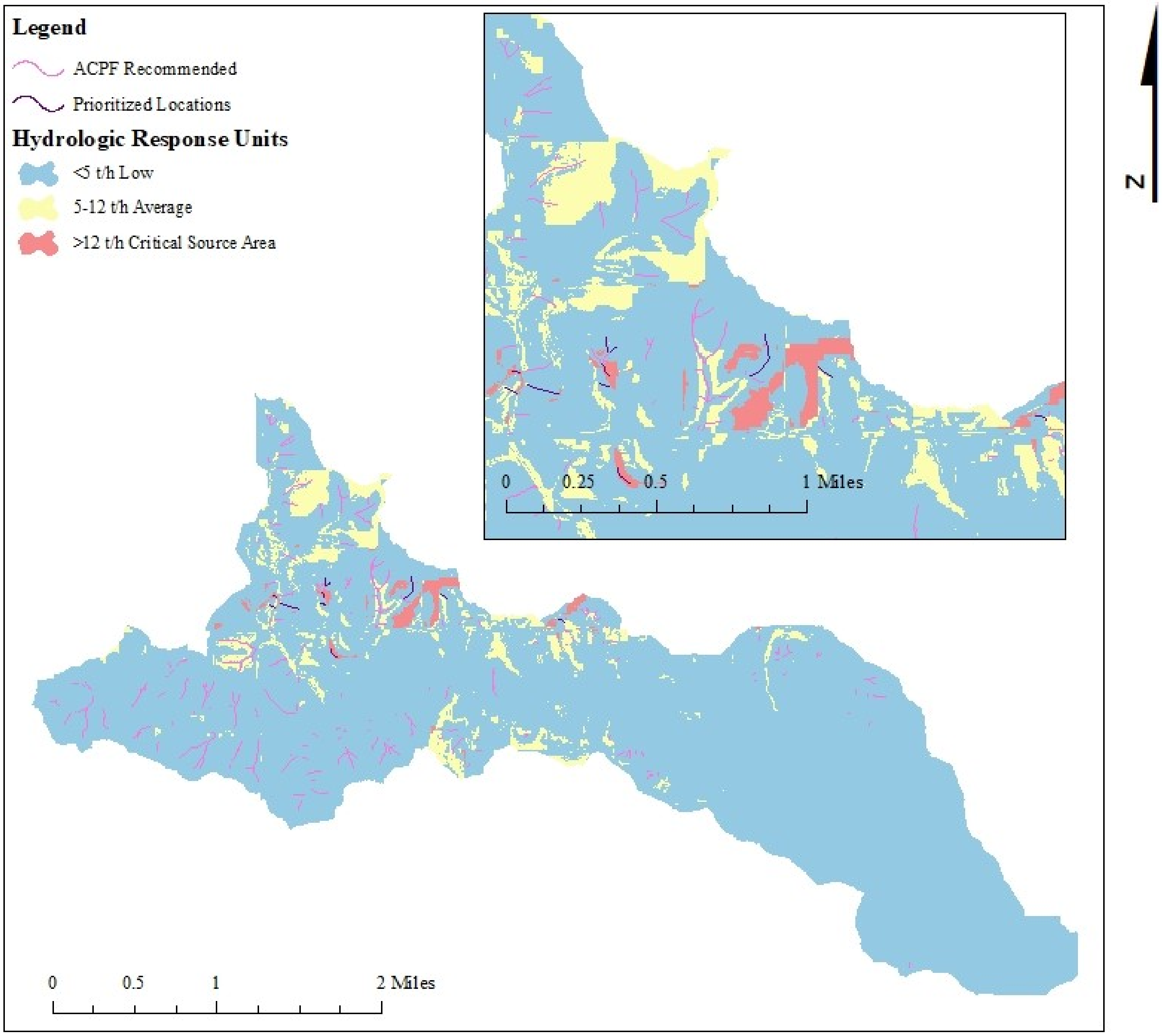

Figure 15: ACPF modeled ideal locations for grassed waterways, locations within critical source areas for sediment erosion highlighted as prioritized.

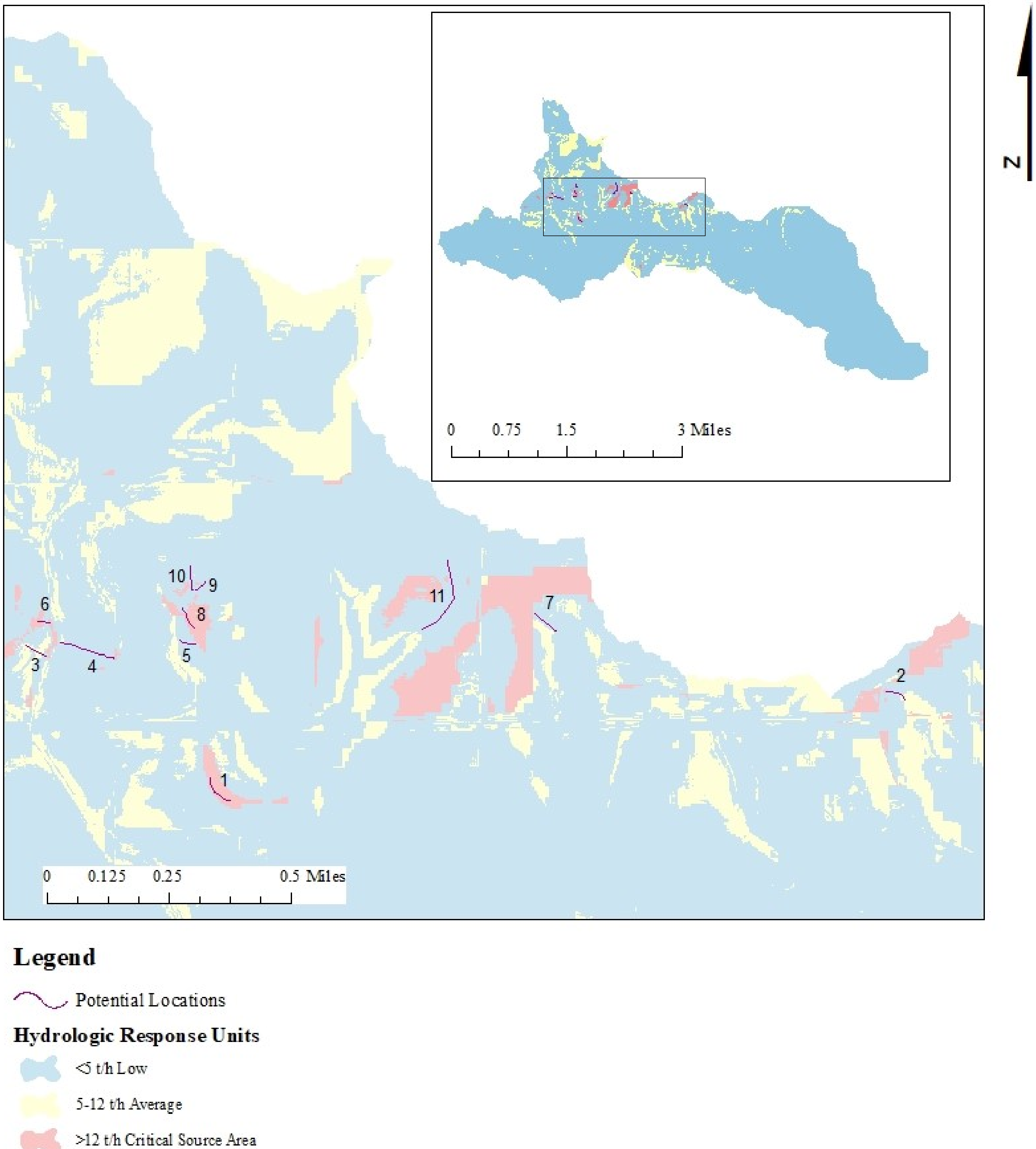

Figure 16: Modeled locations for grassed waterways with corresponding numbers used for analysis.

DISCUSSION

The research shows a relationship between existing grassed waterways and locations modeled using ACPF (figures 13 and 14). Comparatively, the geospatial distribution of existing and modeled locations are similar. Both figures show that the majority of grassed waterways are located in the western portion of the watershed due to the topography, soils, slope, and predominant agricultural land use in that area.

Tables 4, 5, 6, and 7 show the existing and ACPF modeled grassed waterway characteristics. Grassed waterways in both the existing and modeled locations are most often in areas designated as corn land use, with grass/pasture and soybeans alternating as the second and third most frequent. However, the most common Muckey soil and slope combinations slightly differ from existing to modeled locations (tables 5 and 7). While the soil and slope classifications are not identical, the predominant soils are all agricultural soils with a soil loss tolerance of 5 and a slope between 2-12%, including Chasburg and Judston, Seaton Silt Loam, and Tama-Downs Complex.

In addition to understanding the characteristics of grassed waterways in the watershed, the results also provide guidance for future construction specifications. The average length of the existing grassed waterways in Bridge Creek is 106.5 m; however, the average length of an ACPF recommended grassed waterway is 84.5 m, a considerable difference. In addition to identifying ideal locations for BMPs, the ACPF model is useful for planning and design. The difference of 20 m in length, with an average width of 5 m, translates to an 100 m^2 (0.025 acre) area of grassed waterway that landowners could allocate for crops. The average cost of a grassed waterway is $3,744.90 per acre, translating to a potential average construction savings of $93.62

per grassed waterway (USDA NRCS 2013). In addition, the average profit per acre of corn in southern Minnesota is $4.25/acre/year, whereas the expected lifespan of a grassed waterway is a minimum of 10 years (USDA NRCS 2002; University of Minnesota Extension 2020). Therefore, in allocating an additional 0.025 acres to grassed waterways, a landowner loses 0.025 acre x $4.25/acre = $0.11 x 10 years = $1.10 of potential future yield. Construction costs, plus the additional potential yield, equals a savings of $94.72 per grassed waterway. The addition of the ACPF toolset would be a beneficial cost-saving step for more efficient, economical designs for grassed waterways in Bridge Creek and other agricultural watersheds.

Forty-one of the existing grassed waterways are in ACPF-recommended locations, as seen in figure 17. These locations reiterate that the ACPF toolset can recommend viable grassed waterway locations, which enhances the ability of decision-makers and landowners to optimize grassed waterway placement. However, only 41 of 166 existing locations are what the model considers ideal, representing the potential for more effective conservation in the watershed. The difference is attributed to locations being unsuited for grassed waterways; therefore, further supports using a modeling approach to determine which best management practices would effectively yield the largest soil conservation benefit, as well as where landowner and government funds would be best invested in the future. This modeling approach would enable conservation entities to approach landowners with cost-share opportunities to develop the right best management practices where they would be most effective.

Of the 246 recommended locations, 72.7% do not currently have a BMP implemented (figure 17). With increased pressure to stretch tax dollars, government entities are increasingly moving to data-driven allocation of funds. The non-developed locations could be used as a financial quantifier for future projects. The sum of non-developed grassed waterway lengths,

5571.2 m, can be converted to a dollar amount using the average cost to construct grassed waterways in Bridge Creek, $3,744.90 per acre (USDA NRCS 2013). With a width of 5 meters, the total cost for 5571.2 m (6.88 acres) would be $25,764.92. This information is useful in estimating the maximum potential investment of funds necessary to address conservation efforts for future development. In addition, the potential net loss of profit for converting the 6.88 acres to grassed waterways can also be calculated. The average profit per acre of corn in southern Minnesota is $4.25/acre/year (University of Minnesota Extension 2020). Therefore, in allocating an additional 6.88 acres to grassed waterways, combined landowner losses equate to 6.88 acre x $4.25/acre = $29.24 loss per year in potential corn production profit. However, it is important to note that maintenance costs are not included in the previous calculations, but would affect potential landowner costs.

Results from the SWAT model show that erosion is occurring in disproportionately in specific areas of the watershed. Seventeen critical source areas, with erosion rates of 12.0 t/h or higher, were found, supporting the original hypothesis that critical source areas exist within the watershed. Not only do critical source areas exist, but the ACPF toolset also recommended grassed waterways within the critical source areas. Figures 16 and 17 show potential grassed waterway locations that were prioritized based on their location in critical source areas.

A simple spreadsheet analysis was completed to rank the prioritized locations based on potential effectiveness, depicted in figure 11. Future studies should investigate the capability of the spreadsheet method in calculating the erosion reduction potential of grassed waterways, as well as the SWAT model's precision in erosion rate estimation.

Eleven grassed waterways were analyzed; the modeled sediment yield reduction rates are presented in table 10. However, the modeled erosion rates of some of the critical source areas are

significantly larger than what the model and literature present as average, as seen in table 2. Therefore, the sediment yield reduction values were used to proportionately rank the grassed waterways, but may exaggerate the quantity of erosion occurring in select critical source areas.

The spreadsheet analysis is a powerful tool for watershed management. When making soil and water conservation decisions, the ability to prioritize BMP’s based on sediment yield reduction potential would allow for more efficient and practical projects. Instead of allocating funds to the landowners that approach agencies, decision-makers could approach the landowners of critical source areas to propose projects that have a higher erosion reduction potential in the watershed.

While this study focuses on erosion occurring in agricultural land use areas, erosion is a dynamic problem that occurs across a watershed. Tables 9 and 10 show that 88% of the critical source areas for sediment erosion in Bridge Creek are occurring in agricultural (corn, pasture, soybeans) land use areas within agricultural soils. Agricultural best management practices, such as grassed waterways, have the potential to mitigate the majority of erosion in Bridge Creek’s critical source areas. However, 12% of the critical source areas are within urban land use areas. Implementation of a diverse array of best management practices, in both agricultural and urban areas, would methodically reduce erosion in the watershed.

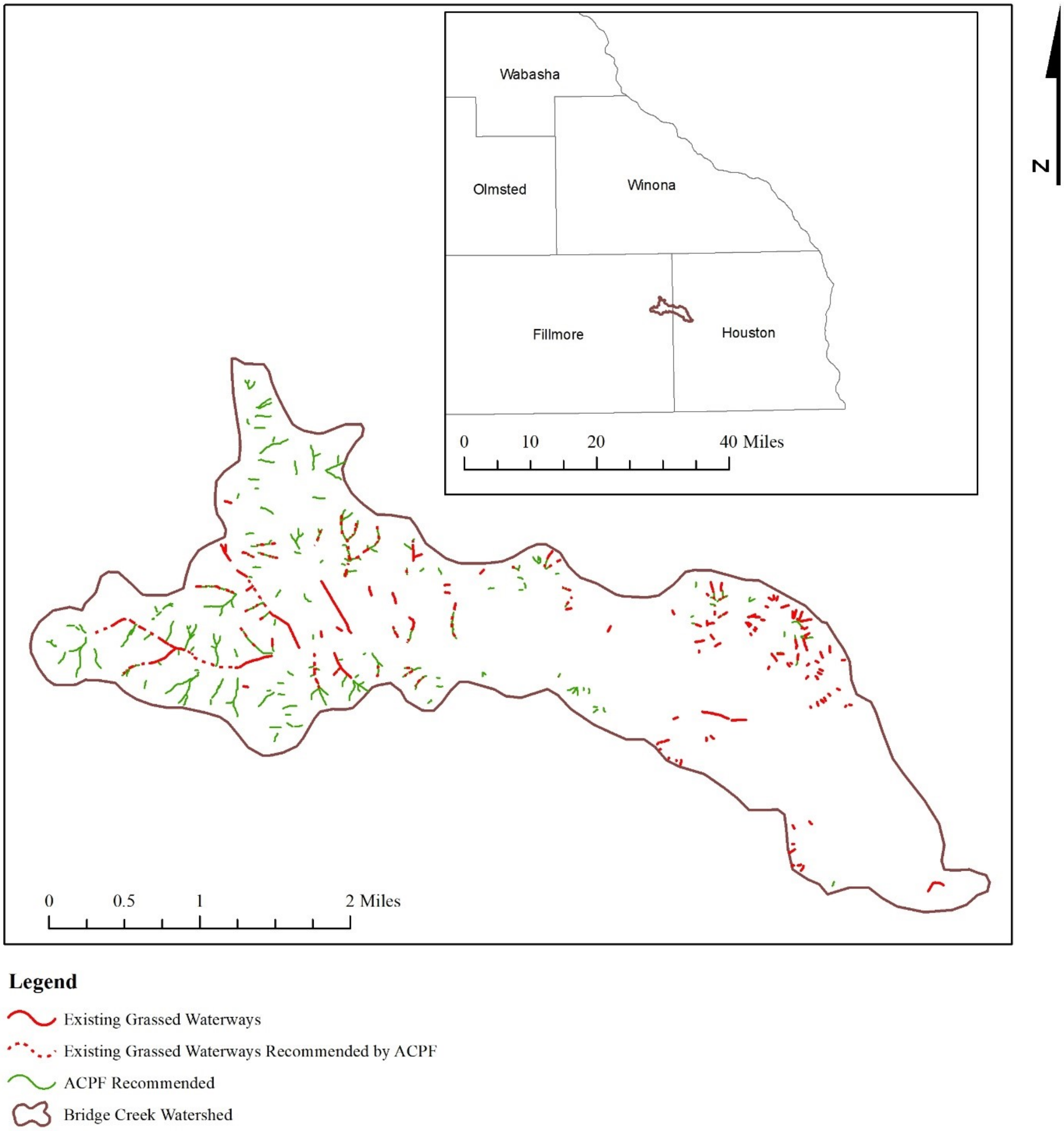

Figure 17: Existing and ACPF recommended grassed waterway locations, highlighting the 41 existing waterways within ACPF modeled ideal locations

CONCLUSION

Erosion is a dynamic problem for farmers and watershed managers alike. Removal of soil from the land degrades soil health and reduces productivity. Simply put, increased sedimentation decreases water quality. The data shows that <1% of the area in the Bridge Creek watershed contributes >80% of the sediment erosion in the watershed. Mitigating erosion is in the best interest of a diverse set of stakeholders, including the producers who own the critical source areas. Acknowledging that critical source areas exist, identifying them, and reducing their impact is crucial to address problems of agricultural sediment erosion.

This research presents a combination of models that identify new locations for productive grassed waterways and quantify the erosion occurring within the watershed. This combination allows for modeling individual grassed waterway effectiveness and the prioritization of sites for future implementation.

The geospatial data and software programs used in this study are free and readily available in the US. In the Bridge Creek watershed, the ACPF modeled locations for grassed waterways replicate the locations chosen through scientific fieldwork; however, the construction dimensions are dissimilar. This study supports the use of modeling as a reconnaissance tool to assist in the selection of future best management practice sites as well as the construction dimensions used for projects.

While this study focuses on erosion reduction potential, many factors affect the practicality of grassed waterways in a location. To truly understand the cost-benefit relationships between conservation practice implementation and financial, agricultural, political, and environmental variables, future studies will need to be completed.

The ACPF model is a beneficial tool in understanding and allocating future funds for agricultural conservation. The combination of the ACPF and SWAT models provides a straightforward way to assess problems in conservation, a quantifiable way to make financial decisions, and useful tools in diagnosing critical source areas and potential ways to address them. If watershed managers can identify critical source areas within their catchment systems, sediment erosion and other environmental problems associated with agriculture can be better mitigated. The comparisons for ideal and existing grassed waterways prove that there is room for improvement in Bridge Creek, which can be extrapolated to agricultural watersheds throughout the nation.

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APPENDICES

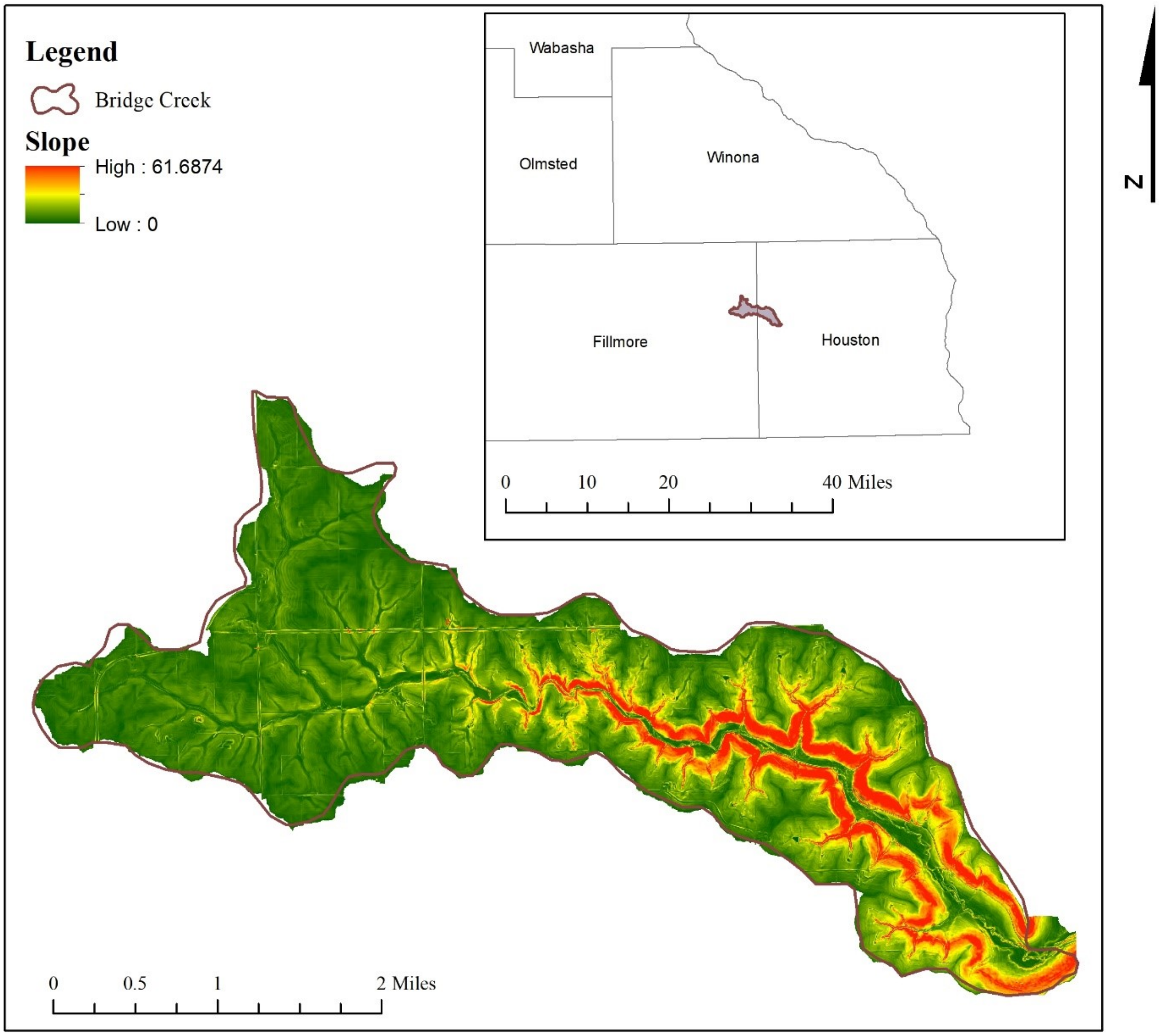
Appendix A: Alphabetical Glossary of Terms

Term	Map of Data Layer	Definition
By-Field Slope Statistics	Appendix B-1	Definition
D8 Terrain Processing	-	"Generates two outputs: 1) a slope raster and 2) a slope table, containing slope related statistics on a field-by-field basis" (Porter, 2016, p. 27).
Delineate Subbasins	-	"Acts on the input DEM to generate four terrain processing derivatives" which include flow direction, filled DEM, flow Accumulation, and Hillshade rasters. (Porter, 2016, p. 12)
Explode Multipart Feature	-	Separation of the watershed into smaller areas, (subbasins and hydrologic response units), for modeling simplification. (Neitsch, 2009)
Filled DEM	Appendix B-2	"Separates the component parts of a multipart feature into single-part features with attribute values that match the original multipart feature" (esri, "Explode a multipart feature", accessed August 2019).
Flow Accumulation	Appendix B-3	"Sinks (and peaks) are often errors due to the resolution of the data or rounding of elevations to the nearest integer value. Sinks should be filled to ensure proper delineation of basins and streams. If the sinks are not filled, a derived drainage network may be discontinuous. The Fill tool… iterates until all sinks within the specified z limit are filled." (*esri*, "How Fill works", accessed August 2019).

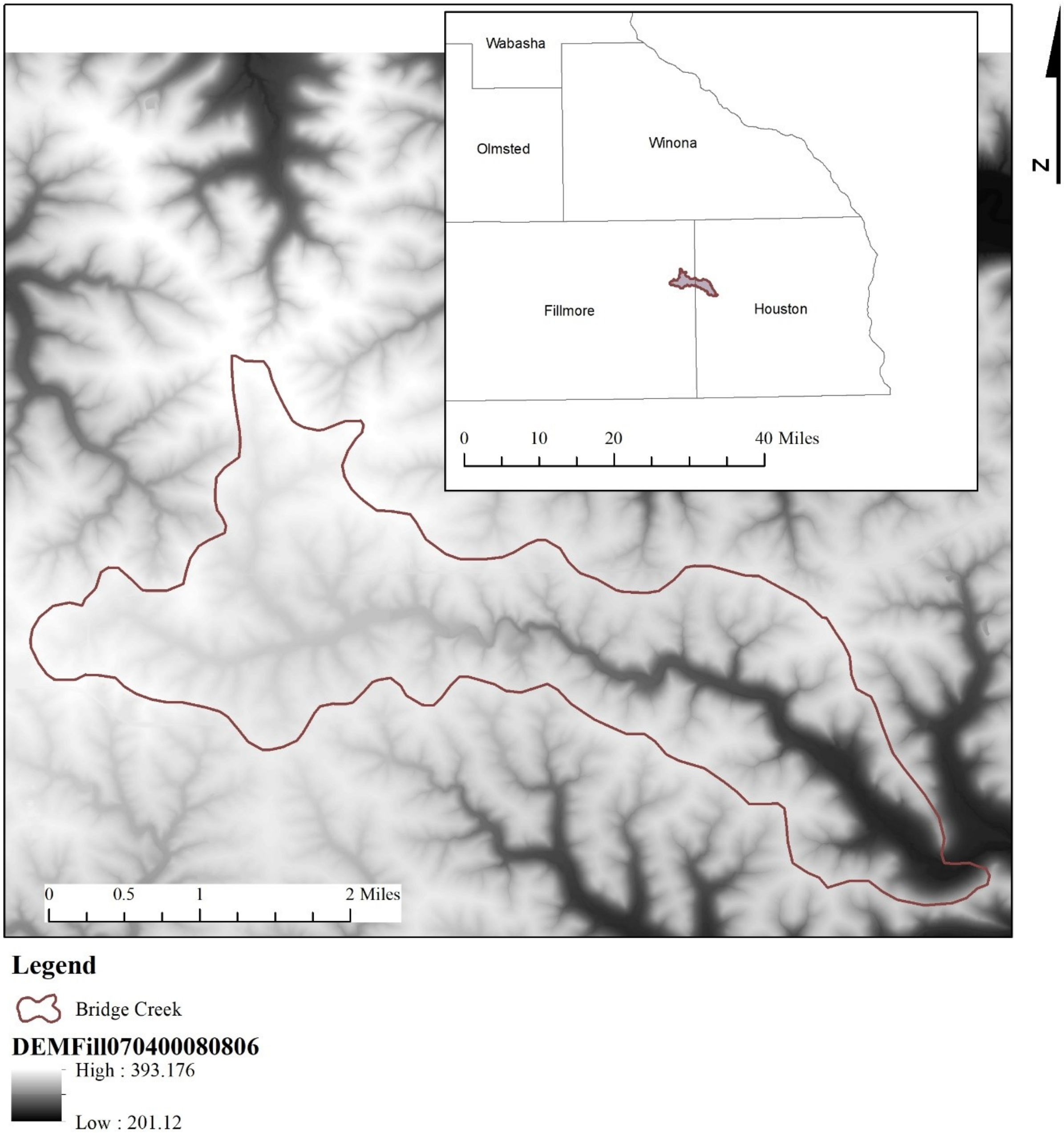
Flow Direction	Appendix B-4	"The Flow Accumulation tool calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster" (esri, "How Flow Accumulation works", accessed August 2019).
Flow Network Definition-Peuker-Douglas	Appendix B-5	"This tool takes a surface as input and outputs a raster showing the direction of flow out of each cell" (esri, "How Flow Direction works", accessed August 2019).
Hillshade	Appendix B-6	"Generates a flow network polyline for the watershed. This method is founded in classical geomorphology and historical studies that evaluated relationships between watershed size and channel slopes and lengths (found between confluences) in different regions" (Porter, 2016, p. 15). This tool ranks streams into Strahler Stream Orders, where each segment of a stream or river within the network is treated as a node in a tree, with the next segment downstream its parent. When two first-order streams merge, they form a second-order stream.
Moore Terrain Derivatives	-	"The hillshade tool obtains the hypothetical illumination of a surface by determining illumination values for each cell in a raster. It does this by setting a position for a hypothetical light source and calculating the illumination values of each cell in relation to neighboring cells" (esri, "How HillShade works", accessed August 2019).
Polygon to Raster	-	"The Moore Terrain Derivatives tool generates two… secondary topographic attributes from an input digital elevation model, and can be used to infer surface characteristics about the susceptibility of landscapes to erosi on (Stream Power Index – SPI) and the landscape

		distribution of soil water movement and accumulation (Topographic Wetness index – TWI)" (Porter, 2016, p. 42)
Pour Points	-	"Converts polygon features to a raster dataset" (esri, "Polygon to Raster", accessed August 2019).
Stream Catchments	Appendix B-7	-"The automated process selects the highest flow accumulation grid cells (>4 standard deviations from the mean flow accumulation value) that fall along the border of the USGS-derived watershed boundary. These locations are then converted to points and used as input to the tool… It is strongly suggested that the automatically generated pour point file… be manually reviewed and edited by the user to ensure the appropriate location of the pour point(s)." (Porter, 2016, p. 16)
Stream Power Index	Appendix B-8	Polygon feature class representing catchment areas (Porter, 2016, p. 25)
Stream Reach	-	"The stream power index is a measure of the erosive power of flowing water based on the assumption that discharge (q) is proportional to specific catchment area" (Porter, 2016, p. 43).

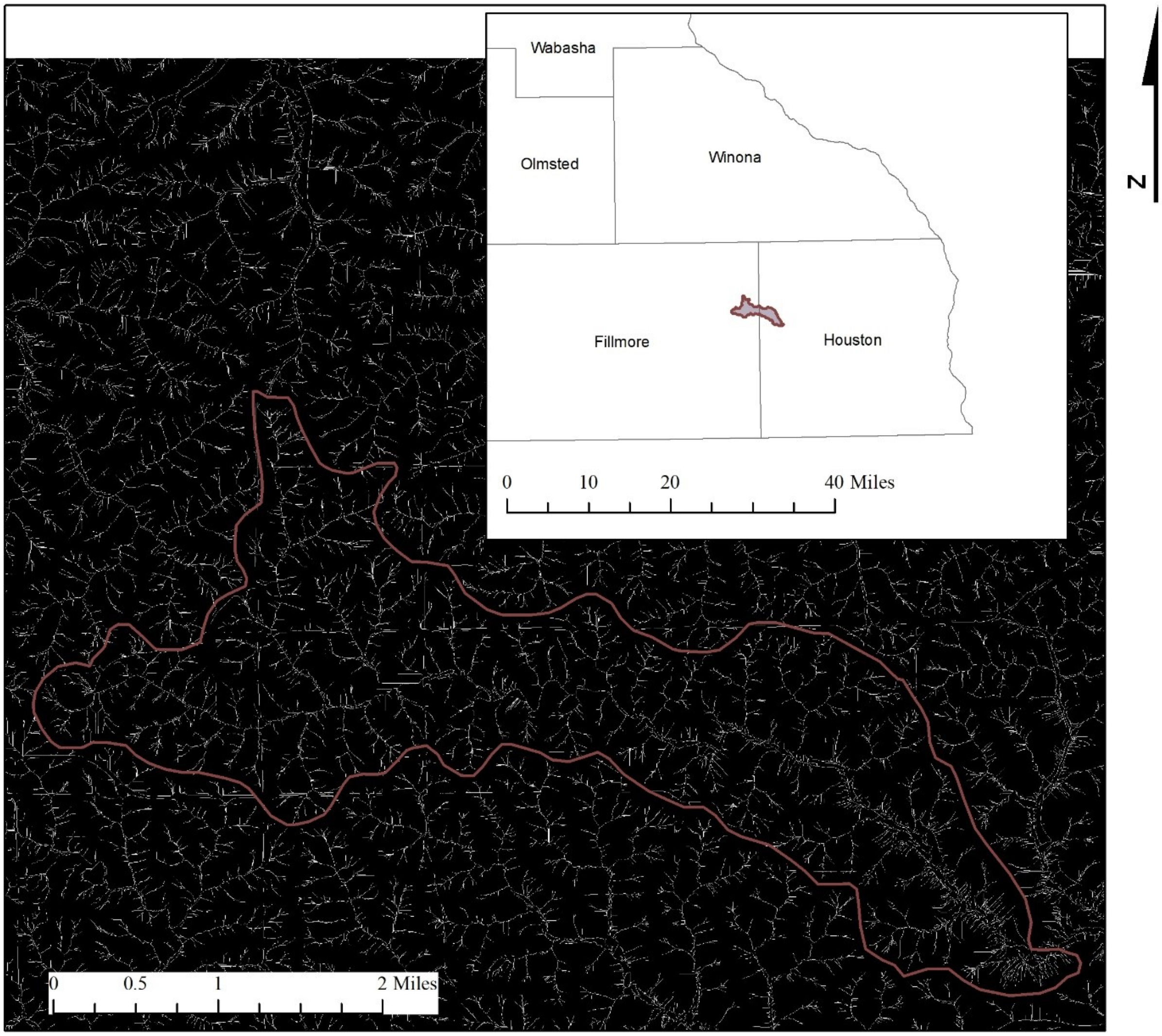
Appendix B: Maps of Geospatial Data Layers



Appendix B-1: ACPF Slope raster in percent rise



Appendix B-2: ACPF Filled DEM using HUC naming convention



Legend

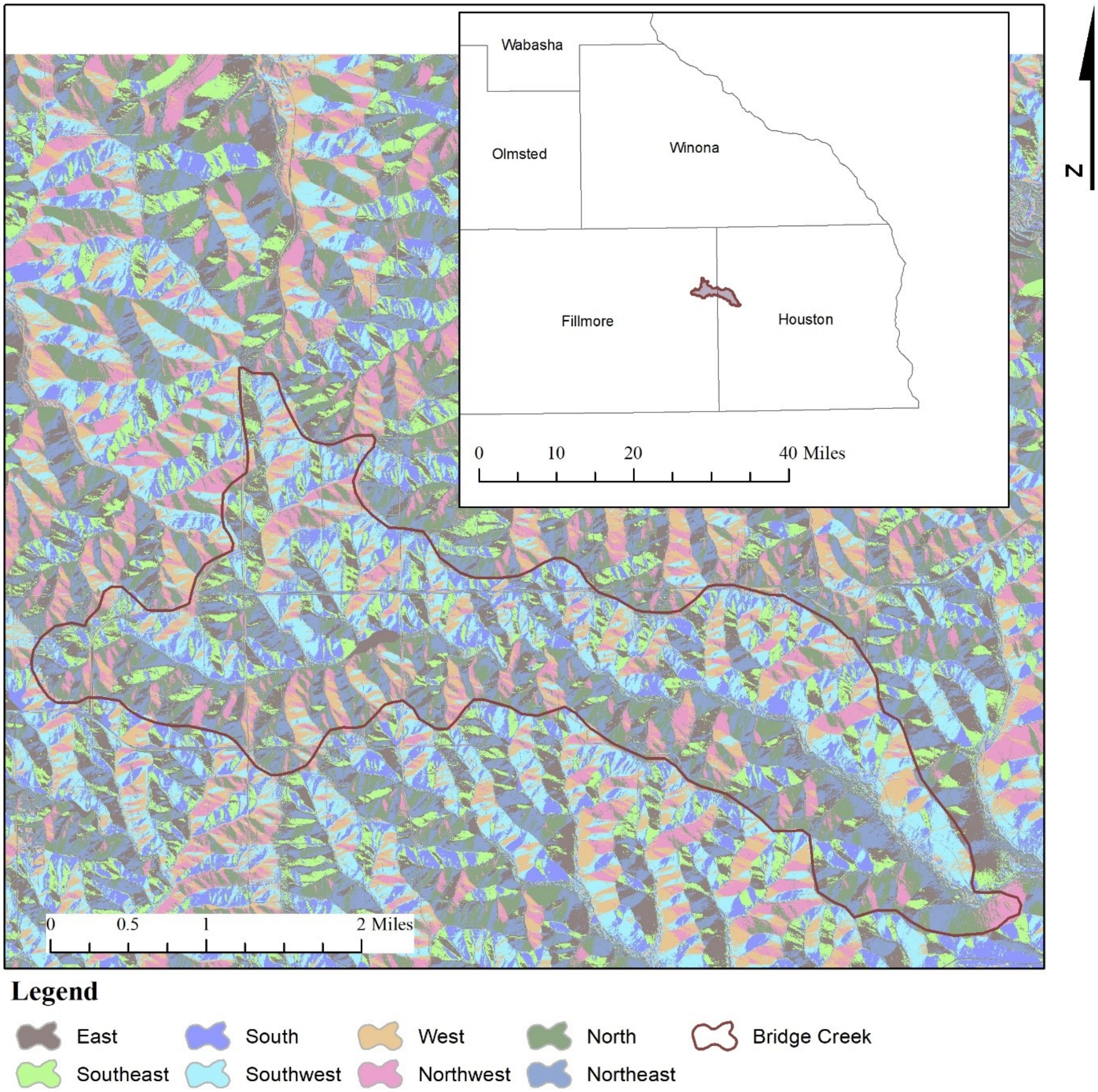
Bridge Creek

D8FlowAcc070400080806

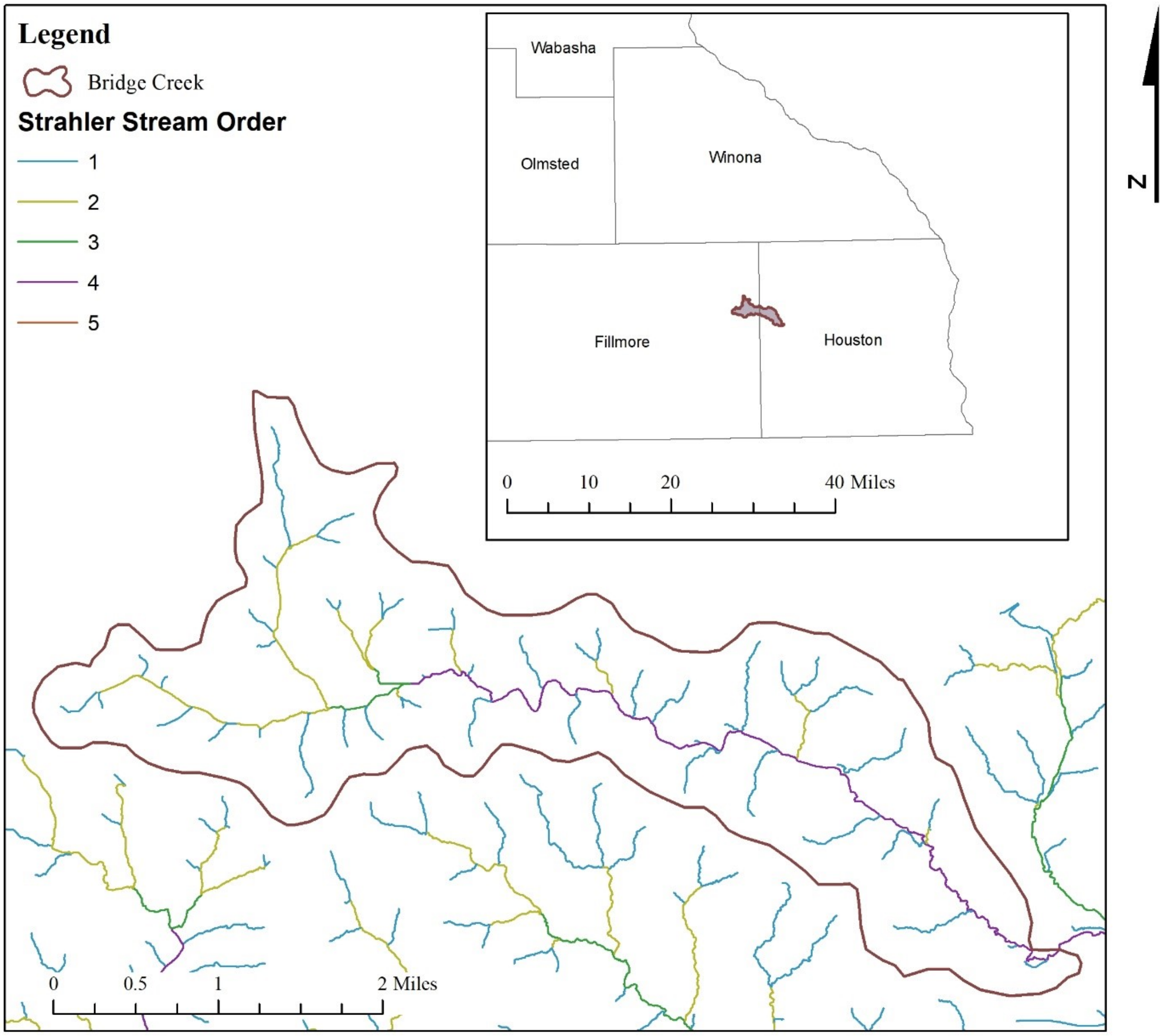
<100

>100

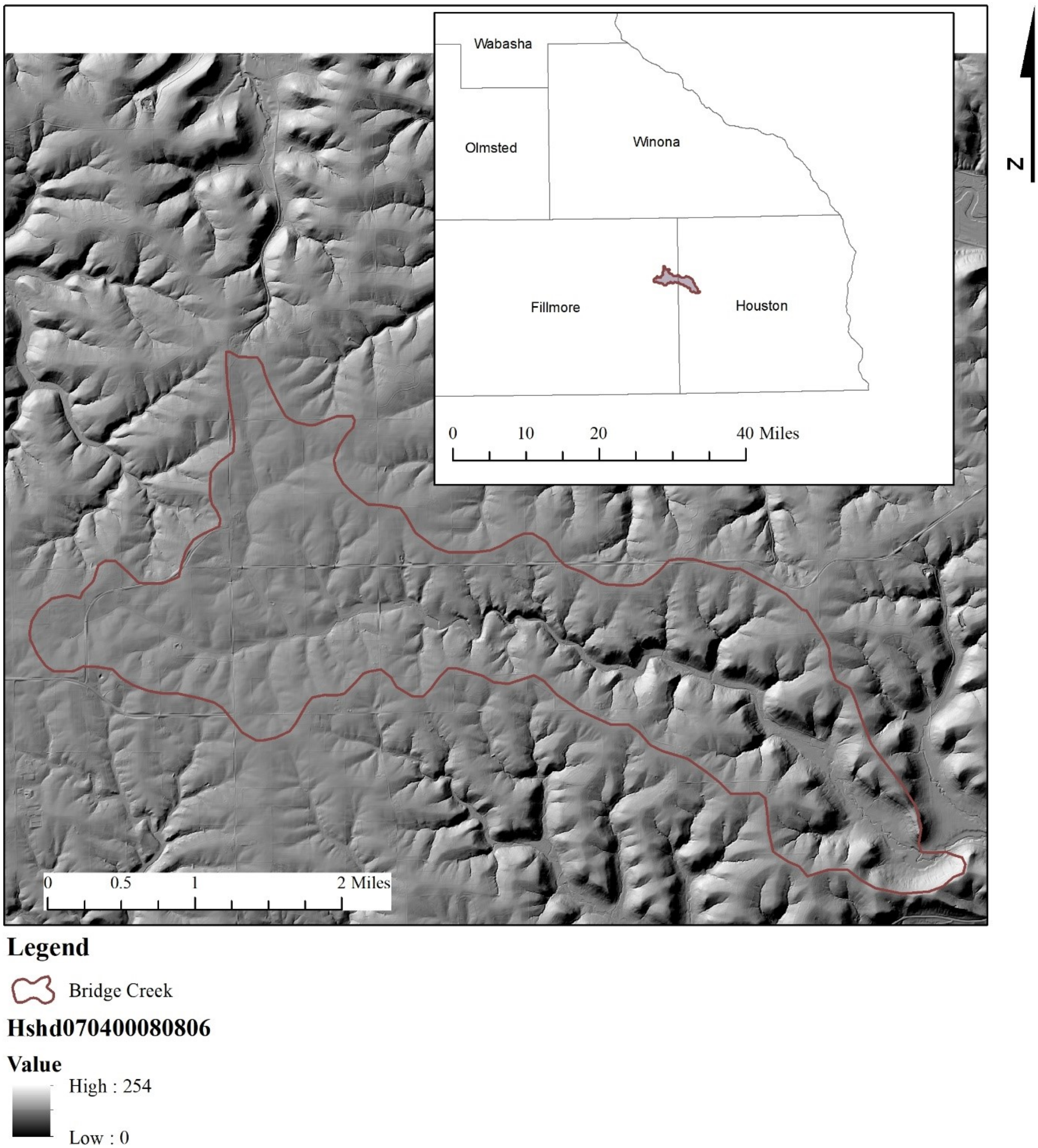
Appendix B-3: ACPF Flow Accumulation using HUC naming convention. Symbology used to exaggerate stream networks visibly



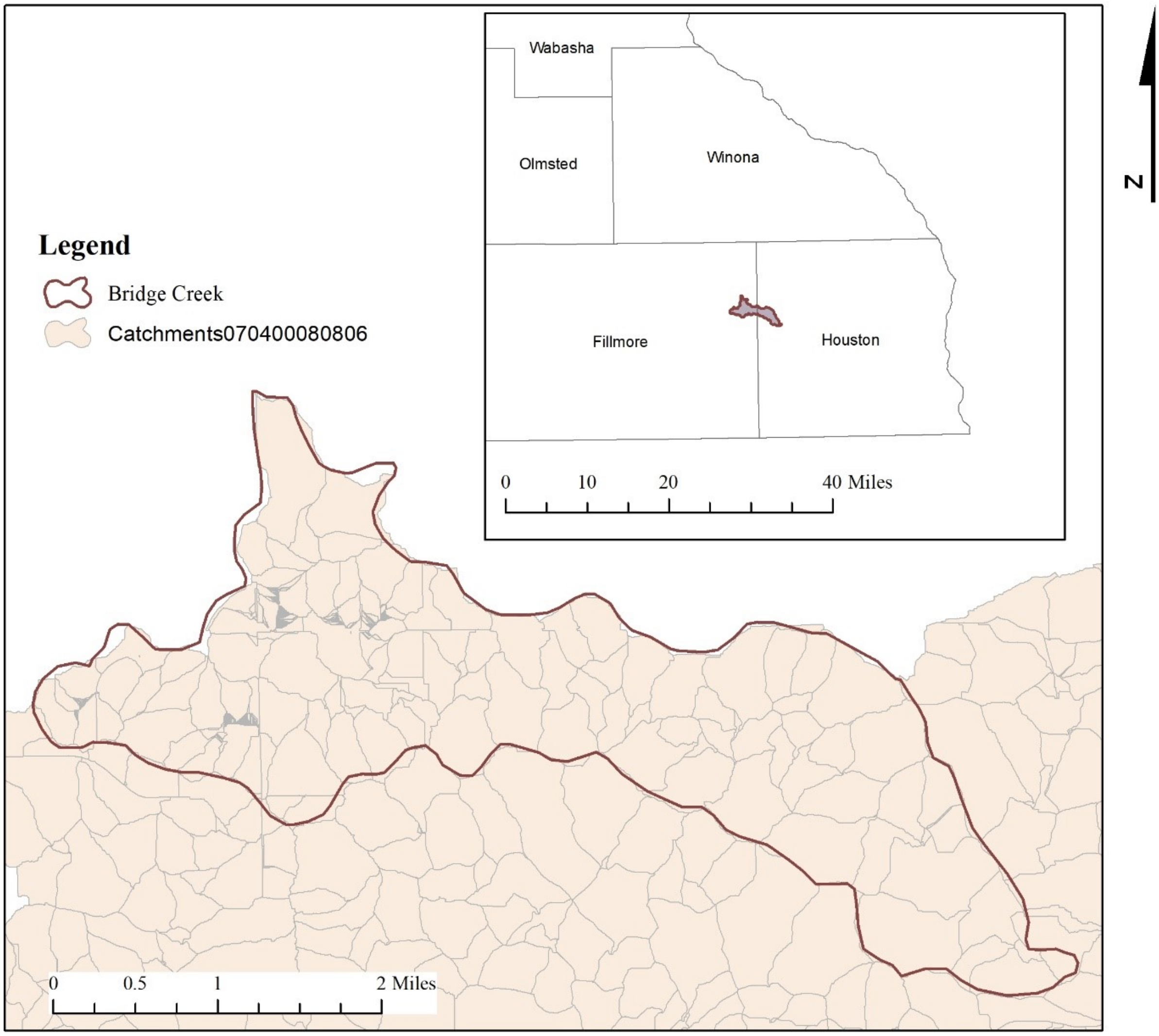
Appendix B-4: ACPF Flow Direction



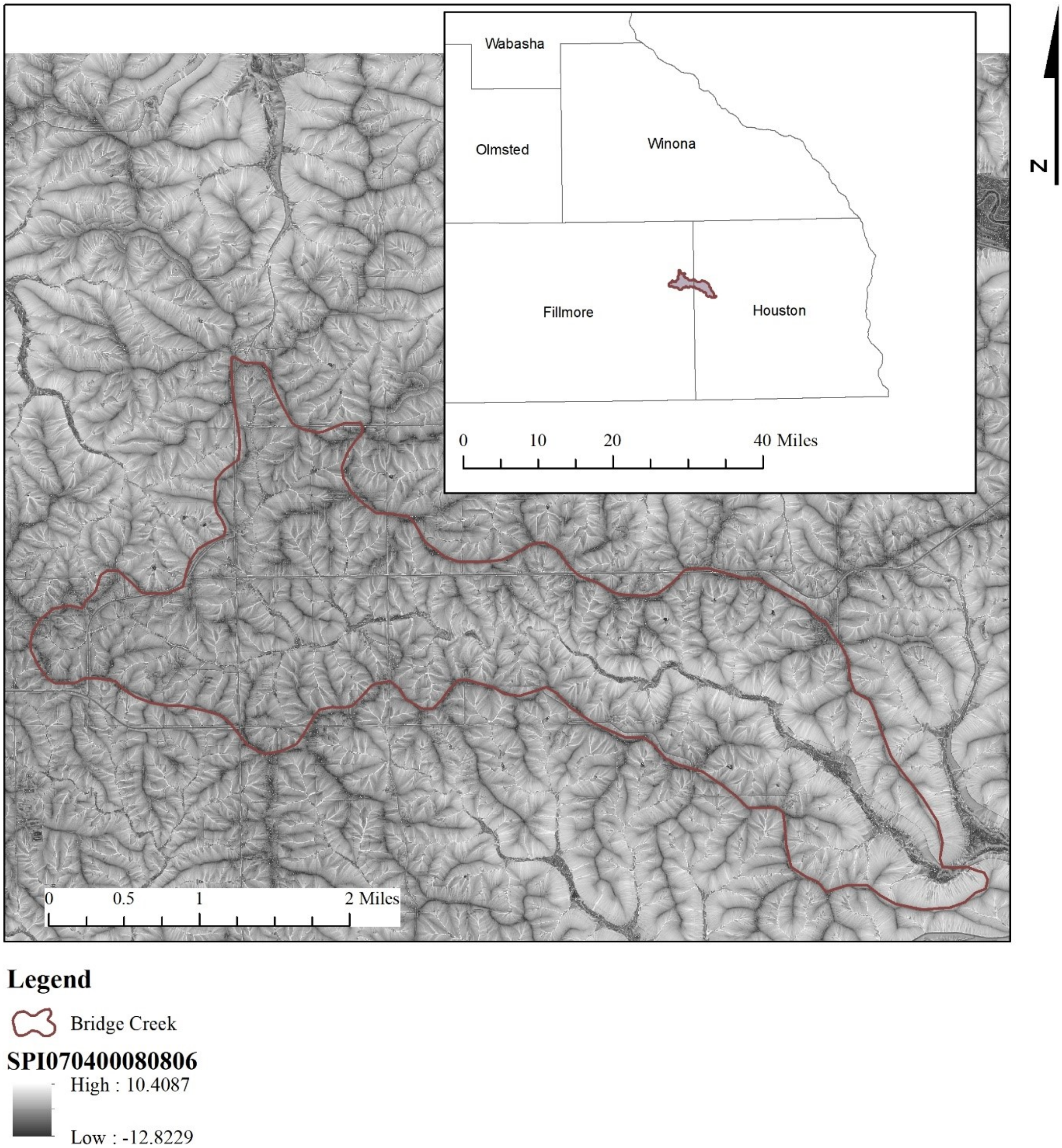
Appendix B-5: Peuker Douglas Flow Network used for both ACPF and SWAT models, symbolized using Strahler Stream Order



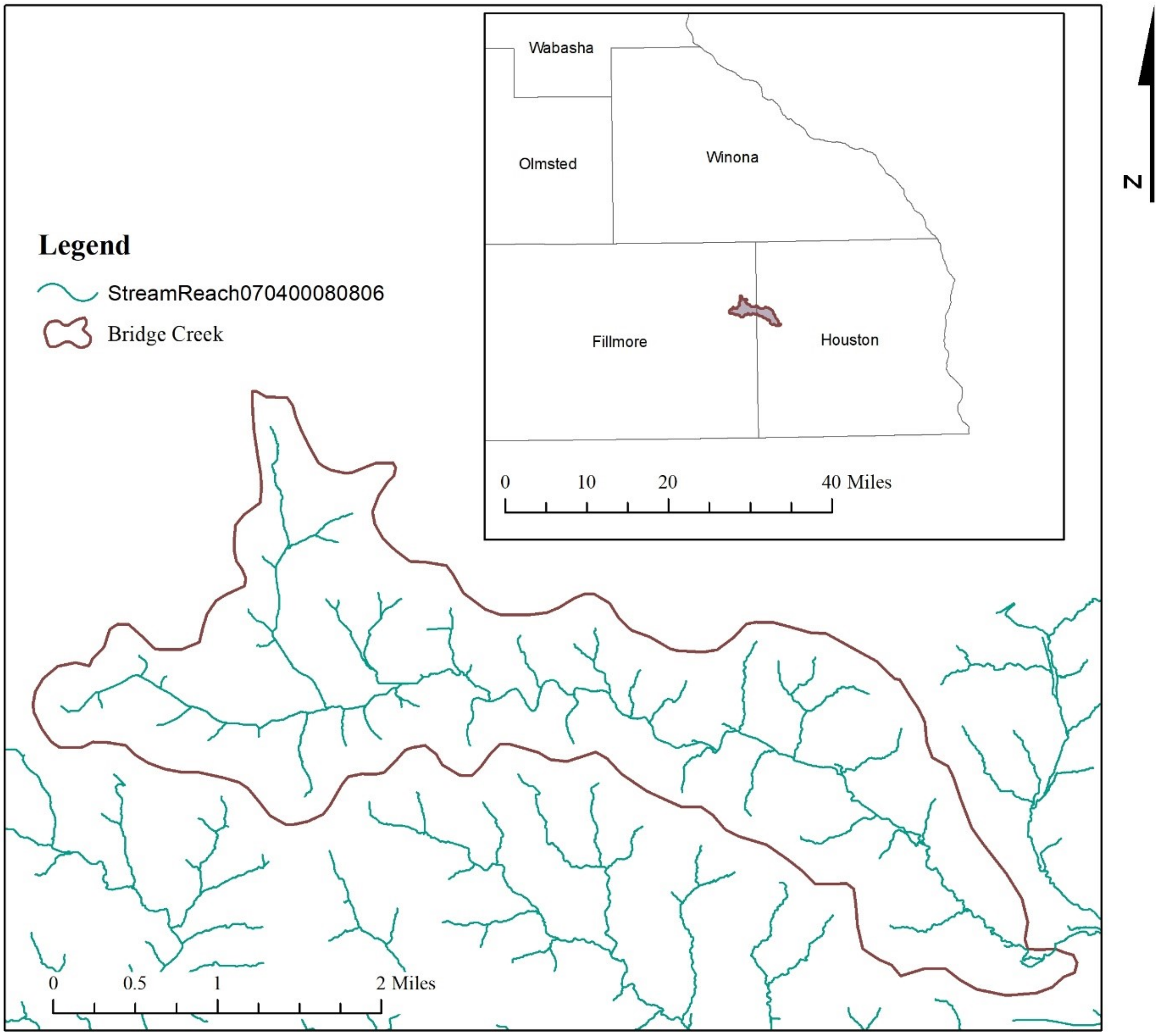
Appendix B-6: ACPF Hillshade raster using the HUC naming convention



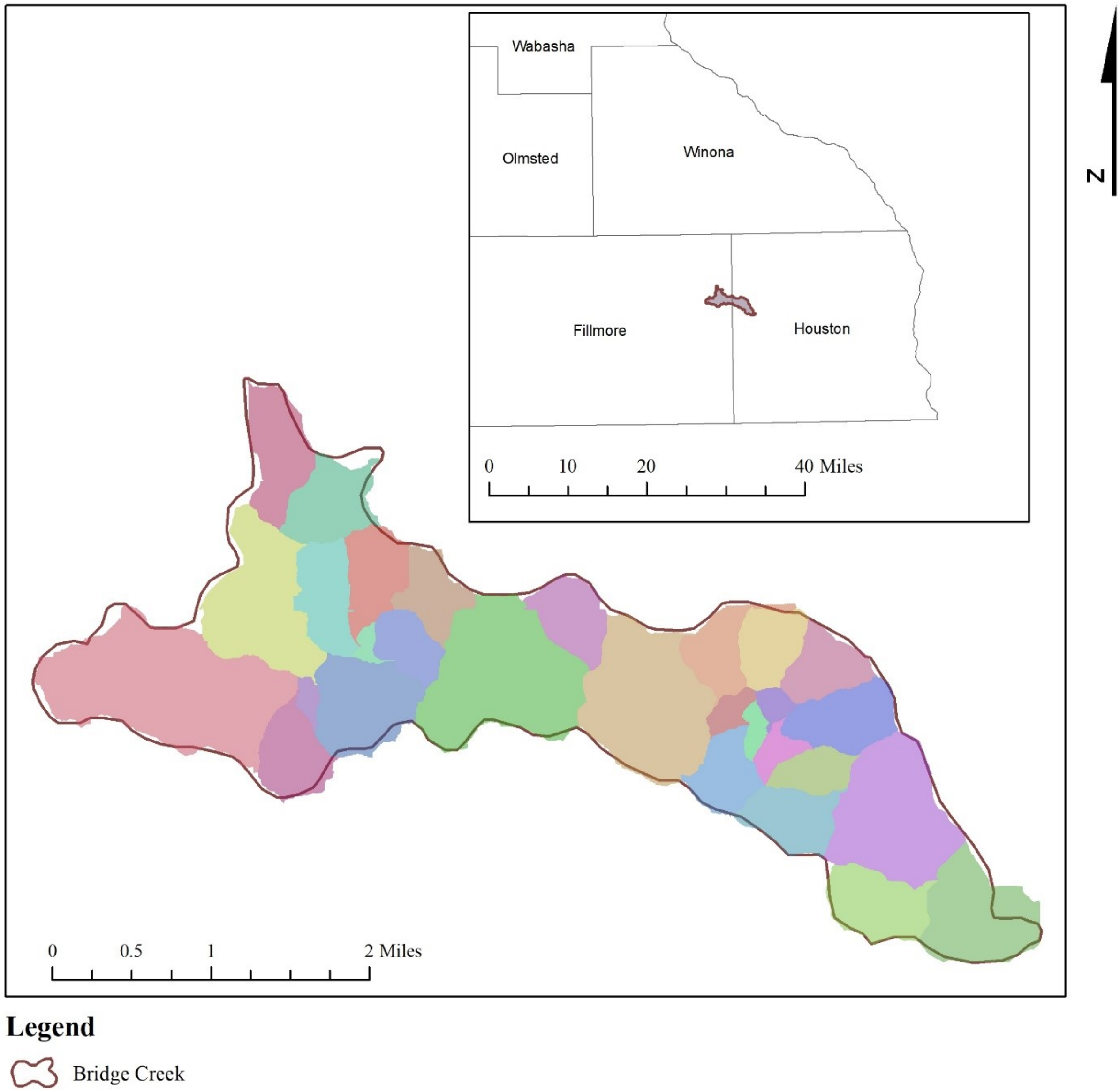
Appendix B-7: Stream Catchments used for both ACPF and SWAT models, using HUC naming convention



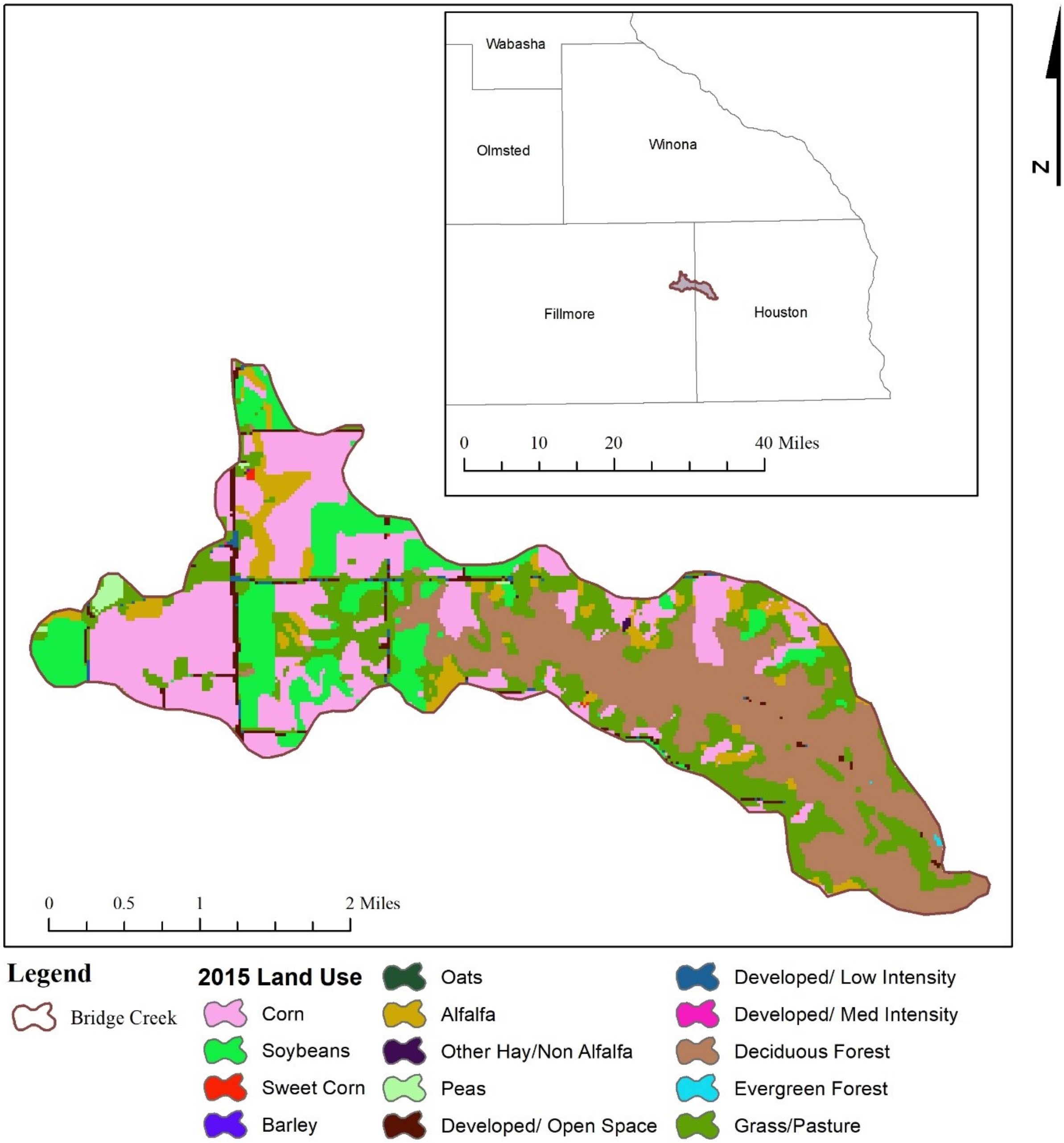
Appendix B-8: ACPF Stream Power Index, symbology to exaggerate upslope erosion strength



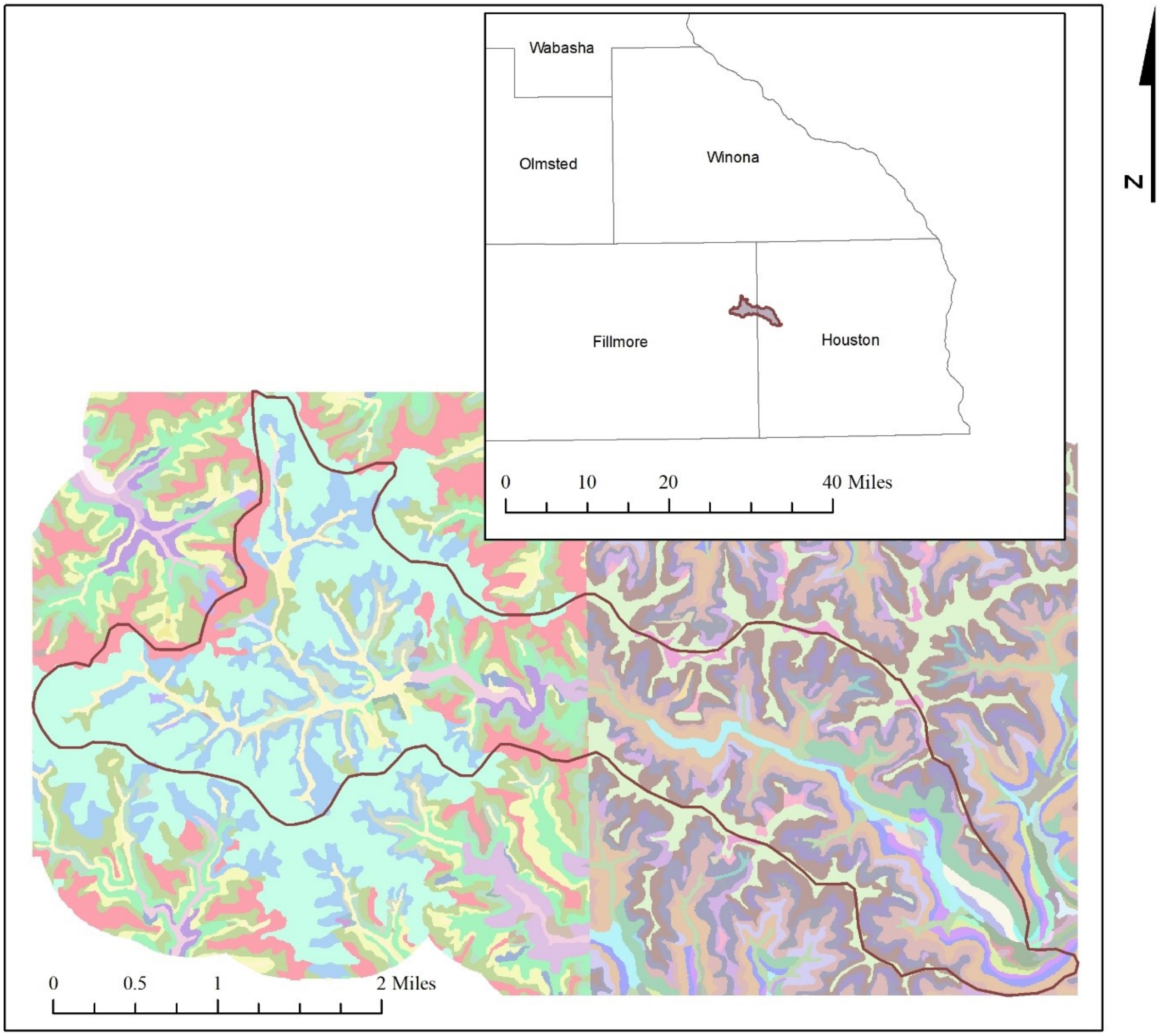
Appendix B-9: Stream Reach used for both ACPF and SWAT models, with HUC naming convention



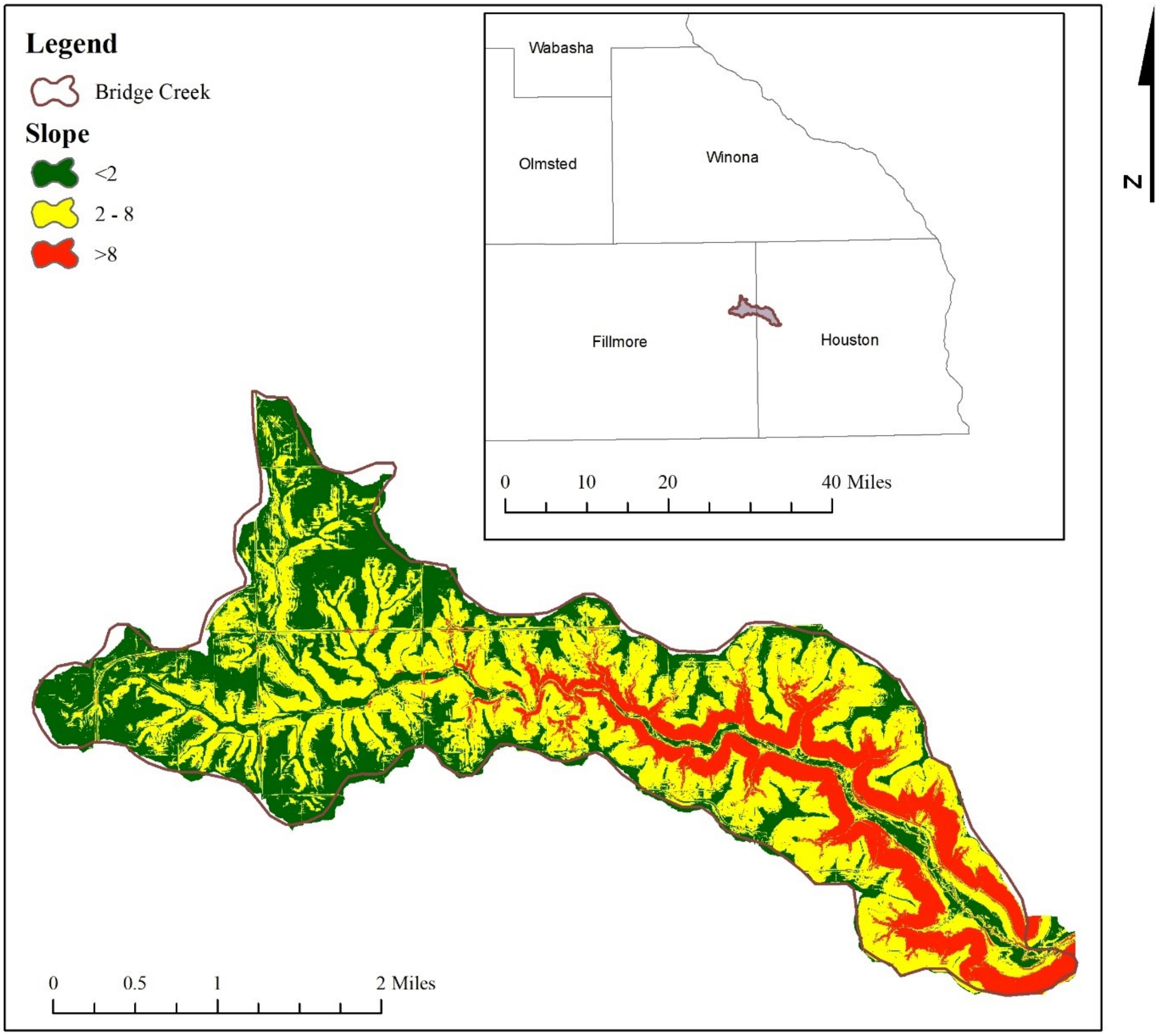
Appendix B-10: Subbasins used in the SWAT model



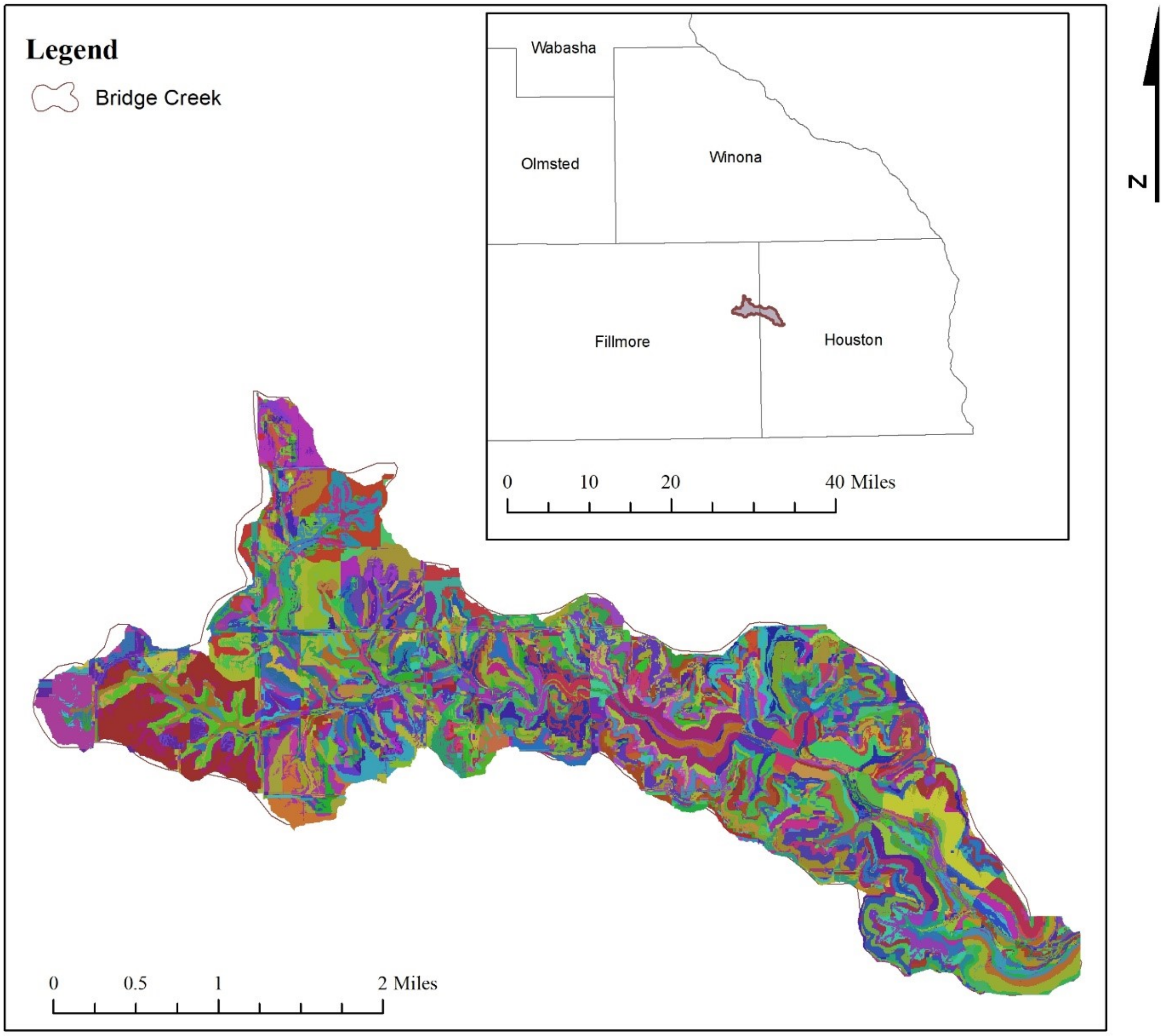
Appendix B-11: NRCS 2015 Land Use



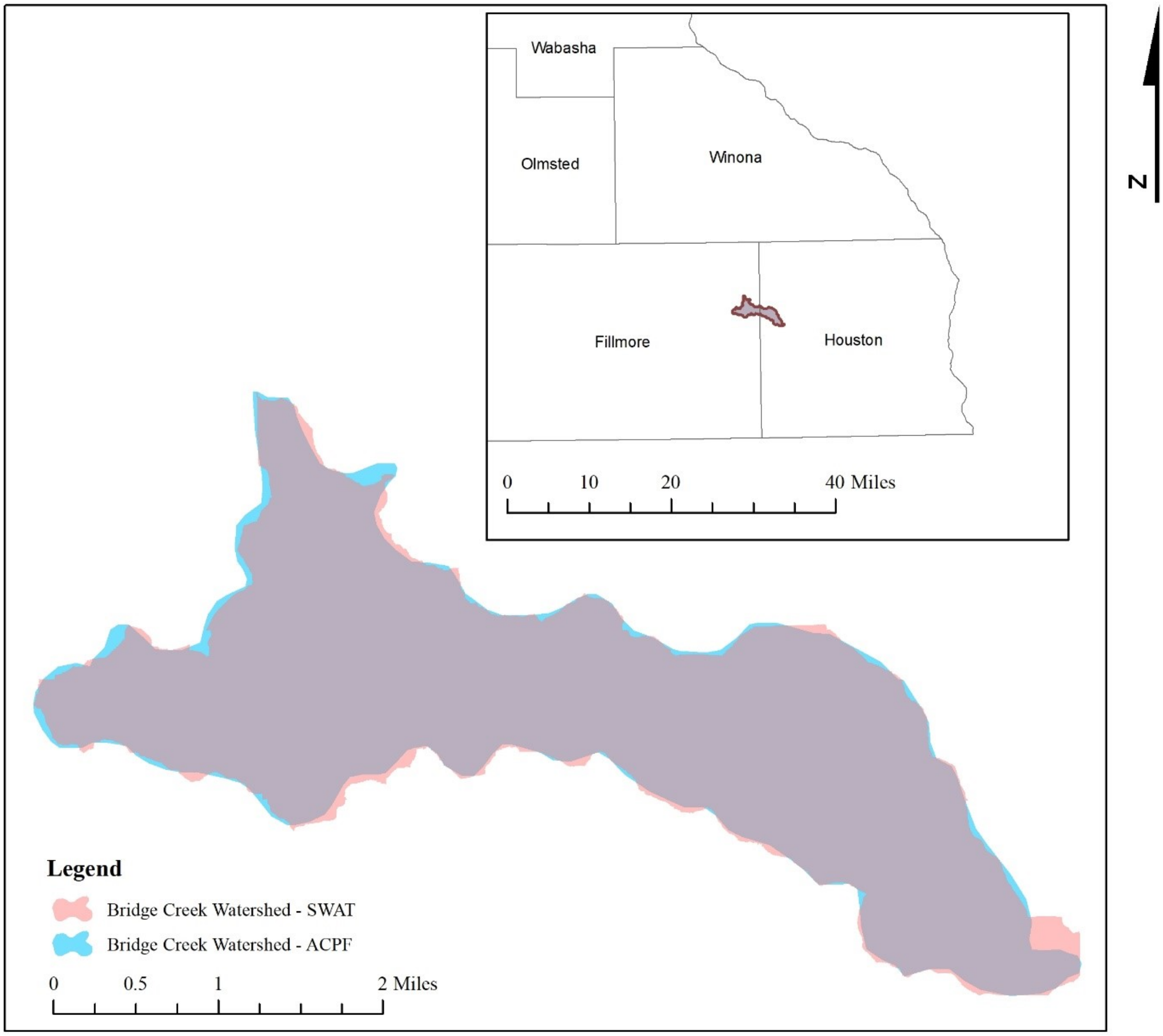
Appendix B-12: SSURGO soil data. Note definition between Fillmore and Houston counties.



Appendix B-13: Slope used for SWAT model grouped in categories of percent rise



Appendix B-14: SWAT Hydrologic Response Units (HRU), 2173 polygons were used for analysis



Appenxix B-15: Watershed boundary difference between SWAT and ACPF models.