Study of sediment transport mechanisms in agricultural watersheds

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Abstract

This study was conducted to improve understanding and prediction of sediment delivery through agricultural watersheds, with emphasis on the pathways from edge-of-field to receiving waters. The study was focused on agricultural watersheds within the University of Wisconsin (UW) - Platteville Pioneer Farm and one of the UW Discovery Farms located in southwestern Wisconsin. Artificial neural network (ANN) models were developed to predict runoff and sediment yield from agricultural watersheds that employ best management practices (BMPs). Results showed that input parameters representing BMPs were important for accurately simulating runoff and sediment yield from these watersheds. The study also showed that ANN models were able to successfully simulate runoff and sediment yield during training, validation and testing phases. Sediment eroded from upland source areas is often carried to the watershed outlet via grassed waterways. Critical shear stress of the soil is often estimated to determine the potential for soil to be detached. Previous studies suggest that critical shear stress may vary with antecedent moisture content. The dynamic nature of critical shear stress in an upland agricultural field and grassed waterway of a nested watershed was investigated at Pioneer Farm by measuring critical shear stress over a range of antecedent soil moisture conditions. Results showed that critical shear stress in both the grassed waterway and the agricultural field increased as soil moisture increased until the soil moisture content reached the plastic limit. Above the plastic limit, critical shear stress of the soil decreased significantly and was relatively constant, ultimately rendering the soil more susceptible to erosion. Finally, the process-based Water Erosion Prediction Project (WEPP) model was used to develop regressions equations that use channel, watershed and storm characteristics to estimate sediment delivery ratios (SDRs) for grassed waterways draining upland agricultural fields. Upland agricultural management scenarios considered included: (i) corn-oat-alfalfa crop
rotation, chisel plow tillage, and terraces, and (ii) corn-oat-alfalfa crop rotation, chisel plow tillage, and no-terraces. Better $R^2$ values resulted from equations developed for non-terraced fields compared to terraced fields suggested that channel and storm parameters were better able to explain the variation in SDR for grassed waterways draining from non-terraced fields.
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Chapter 1

1. Introduction

1.1 Introduction

Sediment delivered from agricultural fields is one of the major contributors to surface water pollution. Sediment has been reported as the second major cause of impairment for rivers and streams in the U.S. (USEPA, 2012). The same report suggests agriculture to be the most probable source of these impairments. Sediment is not only a pollutant but also acts as a carrier for other pollutants such as nutrients and chemicals to water bodies. Best management practices (BMPs) such as retention basins, vegetated filter strips, grassed waterways and strip cropping are often used to control runoff, sediment and other pollutants from entering receiving waters.

Accurately estimating the amount of soil eroded and transported from agricultural fields to surface waters is important so that appropriate management practices can be implemented to reduce sediment delivery to receiving waters. Water quality models such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), Water Erosion Prediction Project (WEPP) (Nearing et al., 1989), and Agriculture Non-Point Source Pollution (AGNPS) model (Young et al., 1989) are used for estimating sediment yield from watersheds. Some of the constraints while using physically-based models are that they are time consuming to set up and they require a greater degree of expertise to obtain meaningful results. Artificial Neural Networks (ANNs) are an alternative to physically-based models. These are “black-box” models designed to mimic the functionality of human brain. Several studies that have successfully developed ANNs for predicting runoff and sediment yield from watersheds include Minns and Haal (1996); Chiang et al. (2004), Riad et al. (2004), Srinivasulu and Jain (2006), Agarwal et al. (2006), Raghuwanshi et
al. (2006), Rai and Mathur (2007), Nourani and Kalantari (2010), Hsu et al. (2010), Singh and Panda (2011), Heng and Suetsugi (2013), Asadi et al. (2013) and Isik et al. (2013). But none of these studies have used BMP characteristics such as terracing, strip cropping, and grassed waterways as input parameters in developing the models for predicting runoff and sediment yield from an agricultural field.

Sediment exiting agricultural fields can be carried downstream to receiving waters via rills and gullies. Ephemeral gullies tend to contribute disproportionately high sediment losses in erosion-prone areas (Casali et al. 1998; Thomas et al. 1986; Laflen 1985). Constructed grassed waterways are an effective management practice that can prevent gully formation and safely convey runoff from fields to receiving waters. While a properly constructed grassed waterway prevents soil erosion by reducing runoff velocity and stabilizing the soil, it can also act as a source of sediment through re-suspension of previously deposited material or erosion in areas without sufficient vegetation.

Agricultural fields are important sources of sediment from soil erosion while grassed waterways represent an important connection between edge-of-field (source) and receiving waters (point of impact). Thus, in addition to estimating the sediment yield from agricultural fields it is also important that the amount of sediment eroded and transported through the grassed waterway is estimated accurately. A widely accepted method for estimating soil detachment is by determining the critical shear stress of the soil and comparing it with the shear stress exerted by the flow. Soil detachment in rills and gullies occurs when the shear stress exerted by flowing water exceeds the critical shear stress of the soil (Foster et al., 1995). Critical shear stress can vary due to variations in soil moisture, bulk density and composition (Charonko and Wynn, 2010). Soil moisture content affects both runoff generation and soil erosion (Ward and Bolton, 1991; Poesen
et al., 1999; Wei et al. 2007), therefore, understanding the relationship between soil moisture, which can vary significantly both during and between storm events, and critical shear is important for accurately estimating soil erosion. Furthermore, this relationship may differ among key features within an agricultural watershed (e.g. field and grassed waterway).

The amount of sediment delivered through grassed waterways can also depend on various channel properties such as length, slope, and manning’s roughness coefficient. Several studies have used physically-based models (e.g. WEPP) to investigate the sediment delivery processes in grassed waterways and assess their effectiveness in reducing runoff velocity and sediment yield (Hjelmfelt and Wang, 1997; Lee, 2008; Abaci et al. 2010; Dermisis et al., 2010). These studies found that the sediment delivery efficiency of grassed waterways depend upon various factors including surface topography, soil, vegetation and storm characteristics. Given the constraints (time and data requirements) in the application and testing of physically-based models, alternative models such as ANNs or regression models are needed in order to estimate sediment delivery through channels using more readily available inputs. As stated earlier, one of the alternatives could be ANN models; however, the setup of such an ANN model would require monitored data for a standalone grassed waterway system (e.g. with only a single inlet and outlet for runoff and sediment). Unfortunately, because of monetary constraints reliable monitored sediment delivery data are not available for an isolated grassed waterway system that could be used to develop and validate predictive equations. Until appropriate monitoring data become available, planners are forced to rely on existing sediment delivery processes described in previously validated process-based models such as WEPP. It is from these more sophisticated models that simplified sediment delivery equations can be developed. These regression equations can then be used to represent the relative distribution of sediment delivery potential across the landscape from a source (e.g. field)
to a point of interest (e.g. receiving water) while considering site specific physical characteristics of the conveyance system.

The overall goal of this study is to improve our understanding and prediction of sediment delivery through agricultural watersheds, with emphasis on the pathways from edge-of-field to receiving waters.

1.2 Objectives

The specific research objectives are:

Objective #1: Develop ANN models using input parameters that represent agricultural best management practice characteristics along with storm and landscape characteristics to predict runoff and sediment yield at the outlet of small agricultural watersheds.

Objective #2: Quantify relationships between critical shear stress and antecedent soil moisture for common agricultural landscape features to improve soil erosion prediction within small agricultural watersheds.

Objective #3: Develop regression equations for estimating sediment delivery ratios (SDRs) for grassed waterways to support targeted management.

1.3 Study Site

The study area consists of two farm sites located in Lafayette County in southwestern Wisconsin (Fig. 1). These sites consist of several agricultural watersheds and are separated by a distance of 10 km. The first site, Pioneer Farm is a 174 ha research farm managed by the University
of Wisconsin (UW) – Platteville. The second site is part of Discovery Farms Program and covers an area of 304 ha. Continuous monitoring data at the outlets of several watersheds within these farms have been collected by U.S. Geological Survey (USGS) since 2003. Both sites consist of productive agricultural silt loam soils from Ashdale and Tama soil series. These soil series are found within large portions of the Midwestern United States including southeast Minnesota, southern Wisconsin, eastern Iowa, northwest Illinois and western Indiana. These deep, well drained and dark colored silt loam soils are found in the driftless areas of the upper Mississippi River Basin (https://soilseries.sc.egov.usda.gov/OSD_Docs/T/TAMA.html). Details about the crop rotations and other management practices employed in the agricultural fields for both farms are presented in the following chapters.

1.4 Models Used

In our study we used three different kind of models: ANN, physically-based, and regression models. Each of these models have both benefits and drawbacks. The models were used based on their specific applications. In this section a brief history of the models is presented along with their advantages and drawbacks. Figure 2 provides a chart with the reasons for using a specific model along with the study area where each model was applied.

*Artificial Neural Networks for predicting runoff and sediment yield at the watershed outlets*

Artificial neural networks were first developed using electric circuits in 1943 by Warren McCulloch and Walter Pitts to explain the working of neurons in the brain. Since then these models have been used in several fields including forecasting, data validation, risk management, and water
quality modeling (Kaastra and Boyd, 1996; Maier and Dandy, 1996; Wu et al., 2005, Singh et al., 2009). More details about ANN models are presented in Chapter 2.

In this study, ANN models were developed for predicting runoff and sediment yield using data from multiple watersheds. The goal was to have a single model that represented a range of watershed and precipitation characteristics. While physically-based models can be used to simulate runoff and sediment yield, ANN models have several advantages over process-based models including: (1) they are less data intensive (2) they require less time to setup, and (3) the models can be trained using data from multiple watersheds simultaneously, whereas separate calibration for individual watersheds is required for process-based models such as WEPP in order to achieve satisfactory results. Another alternative for simulating runoff and sediment yield is regression models. Compared to regression models, ANN models are more capable of representing non-linear relationships due to additional hidden layers of neurons.

*Physically-based models for representing contributing source area and conveyance channel*

Development of physically-based (or process-based) models for representing hydrological cycle started in 1960’s (e.g. Dawdy and O’Donnell, 1965; Sugawara, 1967). A detailed history of the development of physically-based models is presented in Todini (2007). Physically-based hydrologic models are used to represent the physical processes associated with the hydrologic cycle. Several physically-based models are available that can be used to simulate runoff and sediment yield including the Soil and Water Assessment Tool (SWAT; Arnold et al., 1998), Annualized Agricultural Non-Point Source model (ANN-AGNPS; Bingner and Theurer, 2001) and Water Erosion Prediction Project (WEPP; Flanagan and Nearing, 1995).
WEPP was used in this study to represent the components of a nested watershed (described further in Chapter 4) to develop relationships for sediment delivery ratios from a source area through a conveyance channel. WEPP was selected because of its unique ability to simulate runoff and sediment yield for individual watershed components (hillslopes and channels) separately (McCullough et al., 2008). Details about the WEPP model and its setup are presented in Chapter 4. ANN models could not be used for this study because the required data for estimating runoff and sediment yield separately for individual watershed components were not available (i.e. inputs to and outputs from the grassed waterway were not measured). Another advantage of using WEPP was that once the model was setup it was easy to vary the channel parameters (e.g. length, roughness, slope) to estimate the effect of those parameters on sediment delivery ratios.

Regression models for predicting sediment delivery ratios

The history of regression models dates back to 1805 when Legendre published the method of least squares. Since then these models have been used in various fields including hydrology (Lewis, 1957; McIntyre et al., 2007; Imon et al., 2012) to derive relationships among the multiple variables. In Chapter 4 multiple regressions were used to develop simplified equations that estimate sediment delivery ratios using channel and storm event characteristics as input parameters. Of the three types of models discussed here, regression models are the easiest to use.

Physically-based models can be used to determine sediment delivery ratios, however they are data and time intensive and a simpler model that could use easily available data was desirable for estimating sediment delivery ratios. ANN models could not be used to predict sediment delivery ratios that represent a wide range of channel conditions because only one nested watershed
and hence one channel connecting an upstream source area to a watershed outlet was monitored. Several different channel configurations (length, slope, roughness) were required to train, validate and test the ANN models.

1.5 Overview

Chapter 2: This chapter focuses on the development of ANN models for estimating runoff and sediment yield from agricultural watersheds that employs best management practices. Both models were trained, validated and tested for various watersheds at the UW Platteville Pioneer Farm and a UW Discover Farm in southwestern Wisconsin. Sensitivity analysis was performed on the BMP parameters that were used for developing the ANN models.

Chapter 3: This chapter focuses on understanding the dynamic relationship between soil critical shear stress and antecedent moisture content in an agricultural watershed. Critical stress data was collected for varying soil moisture conditions in a nested agricultural watershed at Pioneer Farm. Exponential relationships were developed between critical shear stress and soil moisture content for a grassed waterway and agricultural field within the agricultural watershed.

Chapter 4: In this chapter the development of equations for estimating SDRs through a grassed waterway using channel, watershed and storm characteristics is discussed. The WEPP model was setup and calibrated for a nested watershed at Pioneer Farm (outlets connected through a grassed waterway) and subsequently used to acquire a dataset to develop predictive multiple regression equations for SDRs.

Chapter 5: This chapter presents a summary of the findings of the study along with suggestions for future work. Also presented is an example showing the use of critical shear stress and soil
moisture relationships (from Chapter 3) in WEPP. Comparison of WEPP and ANN models in predicting runoff and sediment yield for nested watersheds S5 and S4 is also presented.

1.6 References


Fig. 1 Pioneer Farm and Discovery Farm along with the outlets located in Southwestern Wisconsin. Orthophotos are also presented in the background of the watershed boundaries.
Fig. 2 A chart representing the reasons for selection of the particular models along with the study watersheds that were used for each model.
Chapter 2

2. Estimating runoff and sediment yield for agricultural watersheds with multiple management practices using ANN

2.1 Abstract

Best management practices (BMPs) are often used for controlling the amount of runoff and sediment yield being discharged from agricultural fields into receiving water bodies. Artificial neural network (ANN) models were developed to predict the runoff and sediment yield from agricultural watersheds that employ best management practices. The models used watershed, storm and management characteristics as input parameters. Model selection was performed among several different ANN models, comprising various number of input parameters and hidden nodes. Penalty related criteria along with the statistical parameters were used for identifying the optimum number of input parameters and hidden nodes and the best models in terms of goodness-of-fit and complexity. Selected models for runoff and sediment yield were trained, validated and tested using data from agricultural watersheds at two farms located at southwestern Wisconsin. Data from 7 watersheds ranging in size from 1.4 – 30.2 ha were used for training and validating the models and data from two additional watersheds within the same farms were used for testing the performance of the models. Results showed that input parameters representing best management practices were important for accurately simulating runoff and sediment yield. The study also showed that ANN models were able to successfully simulate runoff and sediment yield during training, validation and testing phase for the agricultural watersheds which contained best management practices. Sensitivity analysis for the BMP parameters showed that the runoff model was heavily influenced
by the length of grassed waterway and channel density while sediment yield model was mainly affected by upland erosion processes such as cropping and tillage.

2.2 Introduction

Soil loss and its effect on the productivity of agricultural land has been recognized since the 1930’s ‘dust bowl’ era. Since then many researchers have studied soil erosion (e.g. Bennett, 1931; Frye, et al., 1982; Pimentel et al., 1995; Stocking, 2003; Baker et al., 2004, Montgomery, 2007). Soil erosion not only affects agricultural productivity but also significantly affects surface water quality (Sharpley et al., 1994; Lal, 1998; Carroll et al., 2000). Sediment eroded from agricultural fields transports adsorbed chemical fertilizers, pesticides and heavy metals to receiving waters (Wauchope, 1978; Novotny, 1999), resulting in water pollution causing algal blooms, eutrophication, hypoxia, anoxia and other serious problems.

Best management practices (BMPs) such as retention basins, vegetated filter strips, grassed waterways (GWW) and strip cropping are often used to control runoff, sediment and other pollutants and prevent them from entering water bodies. It is important for various regulatory agencies to determine the effect of management practices on water quality (Bishop et al., 2005) in order to implement BMPs efficiently and effectively. For this purpose agencies such as the U.S. Environmental Protection Agency (USEPA), U.S. Department of Agriculture (USDA) and Wisconsin Department of Natural Resources (WDNR) use water quality models such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), Water Erosion Prediction Project (WEPP) (Nearing et al., 1989), and Annualized Agriculture Non-Point Source Pollution (ANN-AGNPS) model (Bingner and Theurer, 2001), among others. For example, the USEPA assessed the impact of BMPs on water quality of two watersheds in Indiana using SWAT (EPA, 2004) and
the USDA investigated the effect of BMPs on water quality in a Mississippi Delta watershed using AGNPS (USDA, 2002). Several other researchers have used physical models to estimate water quality impacts for watersheds in which BMPs are implemented (Ripa and Leone, 2006, Arabi et al., 2007, Parker et al., 2007, Rao et al., 2009, Flanagan et al., 2010, Hui et al., 2014). While various process-based models have been used for estimating runoff and sediment yield, setting up the models is time consuming and requires detailed knowledge of the physical processes and a certain degree of expertise to obtain meaningful results. An alternative to physical models is an Artificial Neural Network (ANN), which does not require in-depth knowledge about the system and processes (Vemuri, 1992; Agarwal et al., 2006, Kalin, 2010) but can still be used effectively to predict runoff and sediment yield. Another advantage of employing ANN models is that they can be used to predict runoff and water quality for ungauged watersheds (Dastorani et al., 2010, Kalin et al., 2010) with good accuracy, which is a challenging task to achieve with physical models.

ANNs are “black-box” models inspired by the functioning of the human brain. These models are designed to imitate the complex networking of biological neurons in the brain, using layers of nodes interconnected by different weights. Similar to the functioning of biological neurons, artificial nodes receive inputs, combine them and feed them through a transformation function to obtain the desired results. They have been used in various fields ranging from forecasting, data validation, and risk management, to water quality modeling (Kastra and Boyd, 1996; Maier and Dandy, 1996; Zhang and Stanley, 1997; Wen and Lee, 1998; Maier and Dandy, 2000; Yu et al., 2005; Wu et al., 2005, Singh et al., 2009). To develop an ANN model an input dataset is required, part of which is used to train the network and the remainder is used to test its performance during prediction. ANN has an advantage over other forecasting models in terms of flexibility of non-linear modeling for conditions where underlying processes are unknown but
sufficient observed data is available (Qi and Zhang, 2001). Additionally, ANN models do not require any prior knowledge of or assumptions about the data distribution (Singh and Chauhan, 2005).

Kalin (2010) used ANN to predict water quality parameters in ungauged watersheds in Georgia. Twelve watersheds were used to train the ANN while other independent watersheds were used to test the predictive performance of the ANN. The ANN performed well in predicting runoff and water quality for the test watersheds. Several other studies that have successfully developed ANNs for predicting runoff and sediment yield include Minns and Haal (1996); Chiang et al. (2004), Riad et al. (2004), Srinivasulu and Jain (2006), Agarwal et al. (2006), Raghuvanshi et al. (2006), Rai and Mathur (2007), Nourani and Kalantari (2010), Hsu et al. (2010), Singh and Panda (2011), Heng and Suetsugi (2013), Asadi et al. (2013) and Isik et al. (2013). However, management and conservation practices were not used as inputs for developing these models, rather most of these studies relied on climate, land use and soil characteristics to develop the model. In contrast, Licznar and Nearing (2003) included some management and cropping factors (canopy cover, interrill cover, canopy height, leaf area index, residue on ground cover etc.) in addition to climate and soil factors in their comparison of ANN versus WEPP in predicting runoff and soil loss for standard USLE plots. Although the ANN performed better than WEPP, one drawback of the study was the unavailability of requisite observed input data for all input factors. The input layer for six of these input factors was generated using outputs such as canopy cover, interrill cover etc. from WEPP. To our knowledge, studies have not used characteristics of BMPs such as terracing, strip cropping, and grassed waterways to develop an ANN model for predicting runoff and sediment yield.
Important factors that influence erosion include climate, topography, land cover and soil characteristics (Gobin et al., 2004) and these factors have been the focus of previous ANN development. Management practices also play a crucial role in soil erosion (Basic et al., 2004) and thus far their characteristics have not been included as input factors in the development of ANN models for predicting agricultural runoff and erosion. Thus, the overall goal of this study was to develop ANN models using input parameters that represent agricultural best management practice characteristics along with storm and landscape characteristics to predict runoff and sediment yield.

The objectives of the study were to: (1) identify the most sensitive management, storm and landscape parameters that affect runoff and sediment yield in small agricultural watersheds, and (2) use the selected parameters to train, validate and test ANN models to predict runoff and sediment yield.

2.3 Methodology

In this study we developed ANN models to predict runoff and sediment yield from agricultural watersheds in which BMPs are utilized. The optimized number of input parameters and hidden nodes were identified for developing the ANN models during the model selection procedure. The models were optimized, trained, validated and tested using data from small agricultural watersheds at two southwestern Wisconsin farm sites: the University of Wisconsin (UW) – Platteville Pioneer Farm and a privately owned farm that is part of the UW Discovery Farms Program (Fig. 1). The UW Platteville Pioneer Farm is a research farm operated by the UW-Platteville. The Discovery Farms Program conducts environmental research on privately owned farms throughout the state of Wisconsin.
2.3.1 Study sites

The UW-Platteville Pioneer Farm, is located in southwestern Wisconsin (Fig. 1). The USGS has collected water quantity and quality data for watersheds within the farm since 2001. The watersheds range in size from 1.4 – 30.2 ha with average slopes ranging from 5 – 6.9%. The dominant soil types in this area are Ashdale and Tama soil series, and both are characterized as silty loam with underlying limestone. Management and conservation practices within these watersheds include grass waterways, terraces and seven year crop rotation of three years corn, one year oat-alfalfa and three years alfalfa. Chisel plow is used for fall tillage which is typically done during the first week of October and a soil finisher is used typically in the first week of May to prepare the seed bed.

University of Wisconsin Discovery Farms are located throughout Wisconsin. The Discovery farm selected for the study is located approximately 10 km from UW Platteville Pioneer Farm. Data have been collected by the USGS since 2003 for three different small watersheds within this farm. A three year crop rotation is practiced at this farm with corn for grain, corn for silage and soybean while conservation practices include gassed waterways and terraces. The dominant soil type for the three watersheds is classified as Tama soil series with average slope of 5%. Direct-plant management was employed in the Discovery Farm watersheds.

2.3.2 Artificial Neural Networks (ANNs)

ANN models are comprised of multiple layers and each layer is composed of several nodes. These layers are classified into three different types: input layer, hidden layer and output layer (Fig. 3). While the input and output layers are single layers, the hidden layer can consist of several intermediate layers. The values from the input layer are multiplied by corresponding random
weights and the weighted values from different inputs are added together to obtain node values of the hidden layers. This type of network is known as a feed forward network (Haykin, 1994) and weighted values from one layer are used sequentially to create the next layer until the output layer is reached. During the training phase, the ANN network is allowed to adjust weights until the simulated values are close to the observed output values.

In this study we developed three layer feed forward ANN models for predicting storm event runoff volume and total suspended sediment load using Tiberius v7.0.7 software (Tiberius Data Mining Inc., Melbourne, Australia). This program uses a back-propagation algorithm (Werbos, 1974 and Rumelhart et al., 1986) for training the ANN model.

The input layer for the models consisted of values for different input variables \((X_1, X_2, X_3 \ldots \ldots X_n)\) (Fig. 3) describing watershed, storm and management characteristics. The list of input variables considered are presented in Table 1 along with a short description of each. Soil parameters were not considered because soil properties are similar at both farms; soils that belong to Ashdale or Tama soil series are similar in terms of hydrologic group, texture and structure. The major difference between the soil series is that Tama soil is deeper than Ashdale soil (Watson, 1966), but this difference was not sufficient to include in the model.

2.3.3 Input and Output Parameters

Watersheds varied in sizes and shapes as presented in Table 2. Also presented are the characteristics of GWW and terrace channels which varied significantly in terms of length and density among different watersheds (Table 2). Table 3 presents average storm event precipitation, runoff and total suspended sediment yield data measured for the watersheds. Runoff was measured
at the outlet of each basin using an H-flume (Tracom, Inc., Alpharetta, GA). The stage-discharge was measured every minute during the runoff events. Precipitation was recorded at each farm’s weather station every minute during rainfall events using a tipping bucket rain gauge (H340SDI, Design Analysis Associates, Logan, UT). Soil moisture was measured using CS616 soil moisture probes (Campbell Scientific Inc., Logan, UT) every fifteen minutes at the weather station. Runoff samples were collected by automated ISCO samplers (Isco Inc., Nebraska) and analyzed for sediment, nutrients and other constituents. Further details about the data collection can be found in Stuntebeck et al. (2008). Individual storm event data were used to train, test and validate the ANN models.

2.3.4 Model Optimization

Node (input and hidden nodes) optimization is important in order to select the best ANN model alternatives (Angus, 1991, Wanas et al., 1998). While an excessive number of nodes tends to overfit the data, an insufficient number of nodes can prevent obtaining meaningful results. Some of the widely used criteria for this purpose include Akaike’s information criterion (AIC) (Murata et al., 1994; Qi and Zhang, 2001; Isik et al., 2013; Ren and Zhao, 2002) and Bayesian information criterion (BIC) (De Groot and Wurtz, 1992; Swanson and White, 1995). The purpose of these criteria is to penalize the models which tend to overfit by over parameterization and thus help in selecting the best combination of input parameters and hidden layers. The Akaike’s information criterion with correction (AICC) (Brockwell and Davis, 1991; Burnham and Anderson, 1998) is an improved version of AIC which penalizes more severely than AIC for using excessive input and hidden parameters. In this study, we used these three penalty related criteria along with the
statistical parameters $R^2$ and RMSE to select the best model among various possible ANNs (Qi and Zhang, 2001). Equations for each criterion are presented below:

\[
\begin{align*}
AIC &= \log(\hat{\sigma}_{MLE}^2) + \frac{2n}{T} \\
BIC &= \log(\hat{\sigma}_{MLE}^2) + \frac{n \log(T)}{T} \\
AICC &= \log(\hat{\sigma}_{MLE}^2) + \frac{2n}{T-n-1} \\
RMSE &= \hat{\sigma}_{MLE} = \sqrt{\frac{\Sigma_T (y_i - \hat{y}_i)^2}{T}} \\
R^2 &= 1 - \frac{\Sigma_T (y_i - \hat{y}_i)^2}{\Sigma_T (y_i - \bar{y})^2}
\end{align*}
\]

Where, $\hat{\sigma}_{MLE}^2$ is the maximum likelihood estimate of the variance of the residual term, $n$ is the number of parameters in the model, $T$ is the number of observations, $y_i$ and $\hat{y}_i$ are the observed and simulated values, respectively, and $\bar{y}$ is the mean of the observed data.

The objective of the model optimization process was to find best model that had the overall lowest values for the penalty related criteria and highest $R^2$ and RMSE values. Equations 1, 2 and 3 consist of two components: the first component (variance of residual term) is an estimate of the goodness-of-fit, and the second component gives an indication about the complexity of the equation. A more complex model (with higher number of input and hidden nodes) can provide lower values for the first component, however it will increase the value of second term. Therefore, the model with the lowest value for all penalty related criteria is selected; in other words the simplest model with the best possible fit.
To determine the optimum number of parameters we started with 15 parameters (Table 1) and trained separate models for runoff and sediment yield using the entire Pioneer and Discovery Farm datasets. Using the penalty and statistical parameters (equations 1-5), the best model for predicting runoff was selected. We then used the observed runoff in place of rainfall and flow rate in place of rainfall intensity plus the remaining 13 parameters (Table 1) to develop the ANN model for predicting sediment yield. This concept follows the rationale of the Modified Universal Soil Loss Equation (MUSLE) by Williams (1975) where a runoff energy factor is used in place of the USLE rainfall energy factor to predict sediment yield. William (1981) identified that the runoff factor is better suited for predicting sediment yield for individual storms as it accounts for the energy required for both sediment detachment and transport.

Normalizing the input and output dataset is useful in case there is a large difference in the amplitude (Flood et al., 1994, Skidmore, 1997). Input and output values were normalized using the following equation:

\[
x = \left\{ \left( \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \right) - 0.5 \right\} \times 2
\]

Where, \(x\) is the input or output value, \(x_{\text{min}}\) is the minimum value and \(x_{\text{max}}\) is the maximum value.

### 2.3.5 Model Performance evaluation for training, validation and testing phase

Data from five watersheds at Pioneer Farm (S4, S5, S8, S10, S11; Fig. 1) and two Discover Farms (R1, R2; Fig. 1) were used to train and validate the ANN models. Data from two additional watersheds, one at Pioneer Farm (S2, Fig. 1) and one at Discovery Farm (R3; Fig. 1), were used to test the models. Watersheds were selected to incorporate the full range of management and cropping system characteristics during the training phase. During the training and validation phase,
data from the seven watersheds were combined and 60% was randomly selected and used to train the models, while the remaining 40% was used to validate the model. The trained and validated models were then tested with data from the two remaining watersheds.

Model performance was evaluated for the training, validation and testing phases using scatter plots and statistically using the coefficient of determination \( R^2 \) (equation 5), Nash-Sutcliffe coefficient \( E_{ns} \) and Normalized root mean square error (NRMSE). \( E_{ns} \) which is a measure of how closely the modeled values match their observed counterparts was calculated as:

\[
E_{ns} = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)}{\sum_{t=1}^{T}(Q_o^t - Q_{av})} \tag{7}
\]

where, \( Q_o \) is the observed value, \( Q_m \) is the modelled value and \( Q_{av} \) is the average of observed values. NRMSE was calculated using equation 8 below to estimate the normalized absolute difference between the magnitudes of observed and modeled values:

\[
NRMSE = \frac{RMSE}{Q_{max} - Q_{min}} \tag{8}
\]

where, \( Q_{max} \) and \( Q_{min} \) are the maximum and minimum observed values and RMSE is calculated using equation 4.

### 2.3.6 Sensitivity Analysis

Sensitivity analysis was performed on the BMP parameters that were used in developing the ANN models. The analysis was carried out in order to achieve the information that can help in cost-optimization of BMP selection. To determine the sensitivity of the BMP parameters,
sensitivity index \( (S_i) \) was calculated using equation 9. A higher sensitivity index for a particular parameter reflects higher sensitivity of the model output towards the change in that parameter.

\[
S_i = \frac{Q_{\text{max}} - Q_{\text{min}}}{Q_{\text{max}}}
\]

Where, \( Q_{\text{max}} \) and \( Q_{\text{min}} \) are the modelled values when the parameter is set to its maximum and minimum values, respectively.

2.4. Results and Discussion

2.4.1 Model selection

Thirty-two different models were developed for predicting runoff and sediment yield using different combinations of number of input parameters \( (n; \text{ranged from 8 - 15}) \) and number of hidden nodes \( (p; \text{ranged from 8 - 11}) \). The values of all performance measures are presented in Tables 4a and 4b for the runoff and sediment model, respectively.

Using individual criterion, the best models for simulating runoff and sediment yield are presented in Table 5. Model 7 which is comprised of 9 input parameters and 8 hidden nodes was selected for runoff modeling and model 8 comprised of 8 input and 8 hidden node was selected for sediment modeling. These models were chosen because they were selected by all the penalty related criteria AIC, AICC and BIC (minimum values) and had high \( R^2 \) values (runoff: 0.81 and sediment yield: 0.76) indicating the models perform well. Overall, models 7 and 8 for runoff and sediment yield respectively, were the best considering trade-offs between goodness of fit and complexity of the model. Selection of the input parameter was based on the sensitivity of input parameters towards the runoff and sediment yield outputs (Table 6). Table 6 presents the relative importance of
parameters in explaining each model. Results show that properties representing best management practices were important for accurately simulating runoff and sediment yield.

Slope was not an important factor for either of the models (Table 6). This could be an artificial effect in ANN modelling as we had very small slope range (5% to 6.2%) and in such cases this input parameter is left out by the model. It was interesting to note that while type of terraces was important for the runoff model, it was not that important for sediment yield. Terraces can reduce the runoff from the field considerably (Zhang et al., 2008) making it an important parameter for estimating the amount of runoff exiting a watershed. The terraces will have a similar effect on sediment yield, but since we are using the observed runoff as an input parameter to the sediment yield model, the effect of terraces on the magnitude of sediment yield may already be captured in the runoff parameter rendering it less important in comparison to other parameters. It is also important to note that drainage area was one of the important parameters in sediment yield model. This was expected though as previous studies had established a relationship between drainage area and sediment delivery ratios (Renfro, 1975; William, 1977 etc.).

2.4.2 Training

Fig 4a and 4b present the performance results of the ANN models in predicting runoff and sediment yield during the training phase. As shown in this visual comparison between observed and model simulated runoff and sediment yield, the models predicted runoff and sediment yield well during the training phase. The scatter points for runoff are close to the 1:1 line for both higher and lower flows suggesting a good model fit. As shown in Fig 4a, during smaller flow events, the model underestimates runoff in certain cases. It is interesting to see that the sediment yield model did a better job than the runoff model; this can be attributed to the use of observed runoff as an input parameter for predicting the sediment yield. It is important to note here that, while modeled
runoff can be used as an input for the sediment yield model, we used observed runoff data to avoid introducing additional error into the model prediction. In cases where observed runoff data are not available modeled runoff can be used. In order to substantiate the visual findings, the statistical performance measures, $R^2$, $E_{ns}$ and NRMSE were also calculated (Table 7). The high values for $R^2$ and $E_{ns}$ along with low NRMSE indicate that the models performed well in simulating runoff and sediment yield during the training phase.

### 2.4.3 Validation

The ANN networks developed during the training phase were used in the validation phase for predicting runoff and sediment yield. The weights obtained for the neural networks during training were kept constant and the remaining 40% of the input dataset was substituted into the networks. Fig 5a and 5b illustrate the performance of the ANN models in predicting runoff and sediment yield during validation. Model performance was further evaluated using statistical parameters presented in Table 7. As shown in the scatter plot, while the models were able to accurately simulate higher runoff and sediment yield, the variation among observed and modeled runoff and sediment yield during smaller events was higher. Both models performed well during the validation phase as indicated by high values for $R^2$ and $E_{ns}$ (Table 7). Although higher values of $E_{ns}$ could be a result of the sensitivity of this parameter to extreme events, the lower value of NRMSE, which integrates advantages of error index and normalization, verifies that the model performed well during the validation phase.
2.4.4 Network Testing

The trained and validated ANN networks were tested by simulating runoff and sediment yield for the two remaining watersheds S2 (Pioneer Farm) and R3 (Discovery Farm). Observed and simulated runoff and sediment yield from these watersheds matched well (Fig 6a and 6b). The $R^2$ values calculated for the model performance during the testing phase were even better than for the validation phase (Table 7). The $E_{ns}$ values dropped for the testing phase as the model was not able to predict some of the higher events accurately, also $E_{ns}$ is biased towards extreme events. Although the models had different variations among the actual and modeled values for runoff and sediment yield for certain events, this was expected as the models were not trained for these watersheds. Statistical parameters also verified that models were performing well during the testing phase. Overall the model performance during testing phase indicated that the model can be used successfully for predicting runoff and sediment yield for watersheds with characteristics similar to those used for training.

2.4.5 Sensitivity Analysis

Results for the sensitivity analysis conducted on the BMP parameters selected for developing the runoff and sediment yield models are presented in Table 8. Sensitivity analysis of the calibrated ANN model indicates that grassed waterway length and channel density were the top two parameters affecting surface runoff volume while crop type, crop growth stage, and tillage were the key parameters affecting sediment yield in the study area watersheds. This indicates that surface runoff volume in these agricultural watersheds was heavily influenced by the drainage network density and its conveyance capacity while sediment yield was mainly affected by upland erosion processes. Runoff depth will decrease with increased grassed waterway length as it provide
mores opportunity for infiltration. For the sediment yield model, “strip-cropping” provides minimum sediment yield. These results aide in making decisions about the cost-effective selection of BMP’s for improving water quality.

### 2.5 Summary and Conclusions

ANN models were developed to predict runoff and sediment yield from small agricultural watersheds. Input parameters included landscape characteristics (e.g. size, shape, management practices) and storm characteristics (e.g. rainfall intensity, duration). Observed runoff and sediment yield data for various watersheds at two farms in southwestern Wisconsin were used for developing and evaluating the ANN models. Thirty-two different ANN models comprising differing numbers of input parameters and hidden nodes were developed. Penalty related and statistical criteria were used for identifying the most sensitive parameters and selecting the best model in terms of goodness-of-fit and complexity of the model. Results from the model selection showed that input parameters representing the management practices were important in developing ANN models for predicting runoff and sediment yield. Selected runoff and sediment yield models were trained and validated using data for 7 watersheds from the two farms. Observed and simulated runoff and sediment yield data were compared during training and validation phases. Results showed that simulated runoff and sediment yield corresponded with the measured data.

The ANN network was finally tested on two watersheds (one watershed each at farm). Comparison between the observed and simulated data showed that performance of the ANN models in predicting runoff and sediment yield was acceptable. An analysis was done in order to determine the sensitivity of the BMP parameters used in developing the models. The analysis
indicated that while the runoff model is most sensitive to grassed waterway length and channel density, upland processes such as cropping and tillage are the most sensitive parameters for the sediment yield model. ANN networks developed during this study can be used to predict runoff and sediment yield for other ungauged agricultural watersheds with similar characteristics and management practices such as terraces, strip cropping and grassed waterways. The model can also be used to predict changes in runoff and sediment yield with changes in management practices. Results from the study can also be used in making decisions for cost-effective selection of BMPs to improve water quality.

2.6. References


Table 1. List of input variables along with their abbreviation, units and description that were considered for developing ANNs for runoff volume and sediment yield.

<table>
<thead>
<tr>
<th>Watershed characteristics</th>
<th>Abbreviation</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Area</td>
<td>A</td>
<td>m(^2)</td>
<td>Total area contributing to the runoff at the outlet</td>
</tr>
<tr>
<td>Form Factor</td>
<td>FF</td>
<td>m(^2)/m(^2)</td>
<td>Form factor is the ratio of basin area to the square of basin length (Horton, 1932) and describes the shape of the watershed</td>
</tr>
<tr>
<td>Average Slope</td>
<td>S</td>
<td>%</td>
<td>Average slope of the entire watershed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Storm Characteristics</th>
<th>Abbreviation</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total rainfall</td>
<td>TR</td>
<td>mm</td>
<td>Depth of rainfall during a storm</td>
</tr>
<tr>
<td>Duration of rainfall</td>
<td>Dur</td>
<td>min</td>
<td>Duration of the storm</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>MC</td>
<td>%</td>
<td>Moisture content on the day of the storm</td>
</tr>
<tr>
<td>Previous day moisture content</td>
<td>PMC</td>
<td>%</td>
<td>Moisture content on the day preceding the storm</td>
</tr>
<tr>
<td>Rainfall Intensity</td>
<td>RI</td>
<td>mm/hr</td>
<td>Amount of rain over the duration of storm</td>
</tr>
<tr>
<td>Observed Runoff</td>
<td>OR</td>
<td>mm</td>
<td>Depth of runoff during a storm</td>
</tr>
<tr>
<td>Flow rate</td>
<td>FR</td>
<td>mm/hr</td>
<td>Amount of runoff over the duration of runoff</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Management properties</th>
<th>Abbreviation</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total channel length</td>
<td>ChL</td>
<td>m</td>
<td>Combined length of grassed waterway and terrace channels</td>
</tr>
<tr>
<td>Maximum grassed waterway length</td>
<td>MGWW</td>
<td>m</td>
<td>Length of the longest grassed waterway</td>
</tr>
<tr>
<td>Channel density</td>
<td>ChD</td>
<td>m/acre</td>
<td>Channel length divided by the area</td>
</tr>
<tr>
<td>Crop growth stage</td>
<td>CS</td>
<td>-*</td>
<td>Stages of crop growth (Allen et al., 1998): Initial “1” - Planting date to 10% of ground cover Crop development “2” - 10 % ground cover to full cover Mid-season “3” - Full cover to start of maturity Late season “4” - Full maturity to harvest</td>
</tr>
<tr>
<td>Crop Type</td>
<td>CT</td>
<td>-</td>
<td>Type of crop: Annual “1” – corns, oats, soybean Perennial “2” – alfalfa Strip cropping “3” – combined</td>
</tr>
<tr>
<td>Type of terraces</td>
<td>TT</td>
<td>-</td>
<td>Narrow based “1”, Broad based “2” or no terrace “0”</td>
</tr>
<tr>
<td>Tillage</td>
<td>TI</td>
<td>-</td>
<td>Chisel plow or Direct-plant</td>
</tr>
</tbody>
</table>

* Unitless parameters
Table 2. Summary of the watershed, GWW and channel input parameters for agricultural watersheds at Pioneer and Discovery Farms.

<table>
<thead>
<tr>
<th>Pioneer Farm</th>
<th>Drainage Area (acres)</th>
<th>Form Factor (m²/m²)</th>
<th>Slope (%)</th>
<th>Total channel Length (m)</th>
<th>MGWW (m)</th>
<th>Channel Density (m/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>20.9</td>
<td>1.49</td>
<td>5.0</td>
<td>337.6</td>
<td>223.3</td>
<td>10.6</td>
</tr>
<tr>
<td>S4</td>
<td>74.7</td>
<td>0.48</td>
<td>6.0</td>
<td>4003.3</td>
<td>714.0</td>
<td>53.6</td>
</tr>
<tr>
<td>S5</td>
<td>14.3</td>
<td>0.94</td>
<td>6.4</td>
<td>933.9</td>
<td>182.1</td>
<td>65.3</td>
</tr>
<tr>
<td>S8</td>
<td>28.8</td>
<td>0.39</td>
<td>5.0</td>
<td>1692.4</td>
<td>441.9</td>
<td>15.3</td>
</tr>
<tr>
<td>S10</td>
<td>10.3</td>
<td>0.52</td>
<td>6.9</td>
<td>557.5</td>
<td>206.8</td>
<td>54.1</td>
</tr>
<tr>
<td>S11</td>
<td>3.36</td>
<td>0.89</td>
<td>5.0</td>
<td>183.8</td>
<td>72.3</td>
<td>54.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Discovery Farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
</tr>
<tr>
<td>R2</td>
</tr>
<tr>
<td>R3</td>
</tr>
</tbody>
</table>
Table 3. Average storm event precipitation depth, runoff depth, and sediment yield for the watersheds at Pioneer and Discovery Farms (with standard deviations in parentheses).

<table>
<thead>
<tr>
<th>Number of events</th>
<th>S2</th>
<th>S4</th>
<th>S5</th>
<th>S8</th>
<th>S10</th>
<th>S11</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall (mm)</td>
<td>30.5 (19.9)</td>
<td>31.2 (16.6)</td>
<td>32.4 (19.3)</td>
<td>30.3 (14.2)</td>
<td>37.2 (20.9)</td>
<td>32.2 (19.9)</td>
<td>36.3 (15.8)</td>
<td>32.1 (11.6)</td>
<td>35.3 (13.4)</td>
</tr>
<tr>
<td>Runoff (mm)</td>
<td>3.3 (4.9)</td>
<td>1.2 (1.5)</td>
<td>2.7 (3.6)</td>
<td>2.5 (4.7)</td>
<td>3.8 (4.4)</td>
<td>5.1 (7.2)</td>
<td>4.4 (5.9)</td>
<td>4.9 (6.4)</td>
<td>2.1 (2.5)</td>
</tr>
<tr>
<td>Sediment yield (Kg/ha)</td>
<td>196.1 (401.6)</td>
<td>27.9 (82.9)</td>
<td>46.0 (150.4)</td>
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Table 4a. Penalty related and statistical parameter values for different combinations of input parameters and hidden nodes for predicting runoff.

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\* m = (p x (n+2)) + 1
Table 4b. Penalty related and statistical parameter values for different combinations of input parameters and hidden nodes for predicting sediment yield.

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Table 5. Models selected for runoff and sediment yield by individual criterion.

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<td>0.153</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7. Statistics for model performance during training, validation and testing for runoff and sediment yield.

<table>
<thead>
<tr>
<th></th>
<th>Training</th>
<th></th>
<th>Validation</th>
<th></th>
<th>Testing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Runoff</td>
<td>Sediment yield</td>
<td>Runoff</td>
<td>Sediment yield</td>
<td>Runoff</td>
<td>Sediment yield</td>
</tr>
<tr>
<td>R-square</td>
<td>0.89</td>
<td>0.93</td>
<td>0.79</td>
<td>0.92</td>
<td>0.86</td>
<td>0.76</td>
</tr>
<tr>
<td>Ens</td>
<td>0.88</td>
<td>0.93</td>
<td>0.78</td>
<td>0.90</td>
<td>0.50</td>
<td>0.68</td>
</tr>
<tr>
<td>NRMSE (%)</td>
<td>6.42</td>
<td>3.63</td>
<td>10.16</td>
<td>4.0</td>
<td>12.46</td>
<td>12.1</td>
</tr>
</tbody>
</table>
Table 8. Sensitivity index results for BMP parameters selected for runoff and sediment yield model.

<table>
<thead>
<tr>
<th>Runoff</th>
<th>Sensitivity Index</th>
<th>Sediment yield</th>
<th>Parameter</th>
<th>Sensitivity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum grassed waterway length</td>
<td>-17.25</td>
<td></td>
<td>crop type</td>
<td>-4.35</td>
</tr>
<tr>
<td>channel density</td>
<td>2.60</td>
<td></td>
<td>crop growth stage</td>
<td>0.80</td>
</tr>
<tr>
<td>tillage</td>
<td>1.8</td>
<td></td>
<td>tillage</td>
<td>0.61</td>
</tr>
<tr>
<td>type of terraces</td>
<td>0.98</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>crop type</td>
<td>0.68</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 3 Schematic of a feed forward neural network
Fig. 4 Artificial Neural Network predictions for (a) runoff and (b) sediment yield during training phase.
Fig. 5 Artificial Neural Network predictions for (a) runoff and (b) sediment yield during validation phase.
Fig. 6 Artificial Neural Network predictions for (a) runoff and (b) Sediment yield during testing at Discovery Farm.
Chapter 3

3. Effect of antecedent soil moisture content on soil critical shear stress

3.1 Abstract

Agricultural fields act as major source of sediment pollution for surface waters. Grased waterways are often used as a best management practice to control the amount of sediment delivered from the edge of agricultural fields to receiving water bodies. Accurate estimation of the amount of soil being eroded and transported is therefore critical for applying management practices appropriately. One widely accepted method for estimating soil erosion is by determining the critical shear stress and comparing it with the shear stress exerted by the flow. Previous studies suggest that critical shear stress may vary with the antecedent moisture content. Furthermore, the relationship between soil moisture and critical shear stress may differ among key features within an agricultural watershed (e.g. field and grassed waterway). Critical shear stress data was collected for varying soil moisture conditions in an agricultural watershed located in Southwestern WI. Soil properties such as bulk density, organic matter content, plastic limit, liquid limit and plasticity index were also measured. Results from the study showed that critical shear stress in the grassed waterway and in the agricultural field increased as soil moisture increased until the soil moisture content reached the plastic limit. Above the plastic limit critical shear stress of the soil decreased significantly making the soil more susceptible to erosion. Exponential relationships were developed between critical shear and soil moisture for the grassed waterway and agricultural field. These relationships were used in conjunction with the continuous soil moisture measurements to explain the changes in soil erosion during varying soil moisture conditions.

**Keywords:** Agricultural field, Grassed waterway, Critical shear stress, Soil Moisture, Plastic limit.
3.2 Introduction

Sediment is responsible for polluting nearly 11.9% of surface waters in the United States, with agriculture as the most probable contributing source (US EPA, 2013). Accurately estimating the amount of soil eroded and transported from agricultural fields to surface waters is important so that appropriate management practices can be implemented to reduce sediment delivery to receiving waters. Soil erosion can occur in the form of sheet, rill or gully erosion and its magnitude depends on various factors including storm characteristics, soil properties, management and conservation practices (Wischmeier and Smith, 1978; Renard et al., 1991; Pimentel et al., 1995). Soil detachment in rills and gullies occurs when the shear stress exerted by flowing water exceeds the critical shear stress of the soil. The detachment capacity, $D_c$ (kg·s$^{-1}$·m$^{-2}$), by flow can be estimated as (Foster et al., 1995),

$$D_c = K (\tau_f - \tau_c)$$  

(1)

where, $K$ (s·m$^{-1}$) is the erodibility parameter, $\tau_f$ (Pa) is the flow shear stress, and $\tau_c$ (Pa) is the critical shear stress of the soil. There is a significant increase in the erosion process once the shear stress exerted by flow on soil surpasses the critical shear stress of soil (Teisson et al., 1993).

Ephemeral gully erosion may contribute to high amounts of sediment loss in erosion-prone areas (Laflen, 1985; Thomas et al., 1986; Casali et al., 1999). Grassed waterways are commonly used to convey runoff from agricultural fields and to prevent gully formation. While a properly constructed grassed waterway prevents soil erosion by reducing the runoff velocity and allowing eroded sediment to settle before entering receiving waters, it can also act as a source of sediment through re-suspension of previously deposited material or erosion in areas without sufficient
vegetation. For vegetative channels (e.g. grassed waterways), the total shear stress of water is partitioned between vegetal elements (vegetal shear) and soil particles (particle shear) (Einstein, 1950; Graf, 1971; Wilson, 1993; Samani and Kouwen, 2002) and the particle shear stress is used to compute soil detachment (equation 1).

One of the key factors affecting erosion is antecedent soil moisture (Luk, 1985). Defersha et al. (2011) found that the rate of interrill erosion varied significantly with antecedent moisture content; sediment yield from wet soils was 50% less than from air-dried soils. Bissonnais and Singer (1992) examined the effects of soil water content and successive rainfall simulations on soil crusting, runoff and erosion from silty clay loam and silt loam soil. They found that runoff and erosion were lower for prewetted soils as compared to initially air dry soils. Lewis and Schmidt (1977) observed that erosion decreased with increasing moisture content below the plastic limit. This relationship was attributed to changes in the percentage of air voids. As the water content rises in the voids, the cohesive force (hydrogen bonding between water particles) increases resulting in a decrease of soil erosion. Above the plastic limit erosion increased as moisture content increased. The increase in erosion was a result of a reduction in cohesion forces. Several other studies have shown that antecedent soil moisture condition is an important factor governing runoff generation, erosion and sediment delivery (Truman and Bradford, 1990; Ward and Bolton, 1991; Karnieli and Been-Asher, 1993; Poesen, et al., 1999; Mamedov, et al., 2006; Wei et al. 2007; Radatz et al. 2013).

Antecedent soil moisture affects soil shear strength (Luk and Hamilton, 1986). In Luk and Hamilton’s rainfall erosion study, soil loss differed by as much as 800 times over a full range of antecedent soil moisture content (wilting point (10%) – saturation (45%)). This difference was attributed to significant changes in soil shear strength with soil moisture content. The authors also
showed that the relationship between shear strength and soil moisture changes with wetting and drying cycles. Similarly, Govers and Loch (1993) found that shear strength was higher for soils with initially higher water content compared to initially air dried soils. Manuwa and Olaiya (2012) evaluated the effects of soil moisture and applied pressure on strength indices of soils including shear strength. They observed that shear strength increased with moisture content for soil moistures below the plastic limit; above the plastic limit shear strength decreased with further increase of moisture content.

While several studies have focused on the relationship between soil moisture and shear strength (Spoor and Godwin, 1979; Luk and Hamilton, 1986; Fan and Su, 2008 and Manuwa and Olaiya, 2012), others have focused on the relationship between soil shear strength and critical shear stress (Krishnamurthy, 1983; Franti et al. 1985; 1999, Torri et al., 1987; Rauws and Govers, 1988; Crouch and Novruz, 1989; Elliot et al., 1989; Merz and Bryan, 1993; Ghebreiyessus et al., 1994; Poesen et al., 1998; Gime´nez and Govers, 2002). Data from these studies were analyzed by Leonard and Richard (2004) and they concluded that a significant linear relationship ($\tau_c = 0.00026\sigma_s$) exists between saturated soil shear strength ($\sigma_s$; kPa) and critical grain shear stress ($\tau_c$; Pa).

Critical shear stress is usually estimated using soil physical and chemical properties that are assumed to be constant for a given soil, however, critical shear stress can change due to variations in soil moisture, bulk density and composition (Charonko and Wynn, 2010). Critical shear stress has been estimated with relationships developed using physical and chemical properties of soils such as particle size; percent sand, silt, clay, and organic matter; and soil water content at 1.5 MPa, and others (Smerdon and Beasely, 1961; Neill, 1973; Simanton et al. 1987; Elliot et al., 1989; Gilley et al., 1993). Given the importance of soil moisture content in runoff
generation and soil erosion, understanding the relationship between, soil moisture which can vary significantly both during and between storm events, and critical shear stress is important for accurately estimating soil erosion. To the best of our knowledge we are not aware of any study that focused on the direct relationship between soil moisture and critical shear stress. Furthermore, this relationship may differ among key features within an agricultural watershed (e.g. field and grassed waterway). Agricultural fields can be an important source of soil erosion while grassed waterways represent an important connection between edge-of-field (source) and receiving waters (point of impact).

Therefore, the overall goal of this study is to further understand the dynamic nature of soil critical shear stress with moisture content in an agricultural watershed. The specific objectives were to: (i) measure critical shear stress over a range of antecedent soil moisture contents and (ii) evaluate differences in the relationship between critical shear stress and soil moisture between a relatively “undisturbed” grassed waterway and a “disturbed” agricultural field. We hypothesized that for soil moisture content below the plastic limit, critical shear stress would increase with increasing soil moisture and when soil moisture exceeds the plastic limit critical shear stress would decrease.

3.3 Methodology

3.3.1 Study area

This study was conducted at the University of Wisconsin-Platteville Pioneer Farm, located in Lafayette County in southwestern Wisconsin (Fig. 7). The farm is spread over 174 ha and is used to demonstrate and evaluate various management practices that can help farmers increase their
efficiency of production. The region is dominated by silty loam soils of Ashdale and Tama series and underlying limestone bedrock. Land use within Pioneer Farm is approximately 40% cropland, 30% pasture and the remainder is primarily woodland. Fields within the farm are cropped with a corn-oat-alfalfa rotation. The U.S. Geological Survey (USGS) installed monitoring stations at the outlets of several watersheds within the farm, ranging in size from 0.2–30.2 ha. These stations have been used to monitor flow and sediment yield at the outlet of the basins since 2001. The fields are connected through networks of grassed waterways that are used to control gully erosion.

Watersheds with outlets at monitoring stations S4 and S5 (Fig. 7) were used in our study. These two watersheds were selected because they form a nested watershed and their outlets are connected by a grassed waterway. Watershed S5 has an area of 5.8 ha and S4 is the largest watershed in Pioneer Farm with an area of 30.2 ha. S4 includes two sub-watersheds S10 and S11 in addition to S5 (Fig. 7). Management practices in S5 include terraces and grassed waterways. Management practices in S4 include terraces, strip cropping and grassed waterways. Fall tillage is done by chisel plow and a soil finisher is used in the spring to prepare the seedbed. The average slope for S4, S5 and the grassed waterway is 6.1%, 6.4%, and 2.4%, respectively. Measurements for this study were made between June 2013–June 2014. During the study period, the agricultural field was planted with corn in both years (2013 and 2014) and tillage was done on 7 October 2013 on 2 May 2014.

3.3.2 Data collection

Measurements were made in both the agricultural field and grassed waterway including soil critical shear stress, suspension index, soil moisture, precipitation, soil texture, bulk density,
and organic matter content. Additionally, the soil was tested for its liquid limit, plastic limit and plasticity index.

*Critical shear stress and soil moisture:* Critical shear stress was measured using a Cohesive Strength Meter (CSM). The CSM is a commercially available portable unit that can measure critical shear stress for cohesive soils (Tolhurst et al. 1999) and has been used in several studies for *in situ* measurements of critical shear stress (e.g. de Deckere et al.; 2001; Defew et al., 2002; Chen et al., 2012; Prellwitz and Thompson, 2014). The CSM includes a test chamber that is inserted vertically into the soil surface and filled with water. The transparency of water inside the chamber is constantly measured using an infrared optical sensor. A jet of water is pulsed perpendicular to the soil surface inside the chamber and is sequentially increased to the point of soil detachment. The pressure at which the soil surface starts to detach is determined by the reduction in light transmission across the test chamber as sediment fills the chamber.

The decrease in light transmission corresponds to an increase in soil erosion (Mehta et al., 1982). The increasing pressure and corresponding transmission data were logged automatically by the onboard computer in the CSM unit. An erosion profile was developed from a time series plot of the transmission and corresponding pressure data. The pressure at which the transmission drops below 90% is considered the critical erosion threshold. The vertical pressures were converted to equivalent horizontal shear stress using the equation from Tolhurst et al. (1999) and transmission values were converted to suspended sediment concentration using the equation of Black (2007). The resultant two-series plot of sediment concentration versus time and horizontal shear stress versus time was used to estimate critical shear stress according to Black (2007). In addition to
critical shear stress, an estimate of erosion rate was also obtained. This erosion rate represents the erosion rate produced by the vertical jet of water and is referred to as the suspension-index ($S_i$) by Tolhurst et al. (1999).

Critical shear stress was measured within a 3 m X 3 m grid (Fig. 8) in both the grassed waterway and in one of the agricultural fields in the S5 basin. The grid cell in the center was not used so as to not disturb other grid cells while accessing the center cell. Each 1 m X 1 m grid cell was further divided into 25, 0.2 m X 0.2 m sub-cells. One of the 25 sub-cells within each 1 m x 1 m grid cell was randomly selected for critical shear stress measurement at each sampling event. Each sub-cell was sampled only once. The grid in the grassed waterway was located 150 m downstream of the S5 outlet. The grid in the agricultural field was located 100 m upslope of the S5 outlet. Measurements in the grassed waterway were made in bare soil patches while measurements in the agricultural field were made in troughs between crop rows. The S2 (maximum pressure of 137.9 kPa with increments of 3.45 kPa) and S1 (maximum pressure of 82.74 kPa with increments of 2.07 kPa) CSM default tests were used for the grassed waterway and agricultural field, respectively.

Antecedent soil moisture, integrated over the top 5 cm, was measured within the same 0.2 m X 0.2 m sub-cell as the CSM measurement using a Delta-T portable soil moisture probe (TH2O Soil Moisture Meter, Dynamax Inc.). The paired critical shear stress ($\tau_c$) and antecedent soil moisture measurements were made in the grassed waterway and in the agricultural field eleven times between 14 June 2013 and 13 June 2014 (Table 9), to cover a range of natural antecedent soil moisture conditions. Critical shear stress could not be measured in the agricultural field on 14 June 2013 because of equipment problems and on 7 October 2013 because the field was being tilled.
Continuous Soil Moisture and precipitation: Soil moisture was monitored continuously at 15 min intervals between 14 June – 21 November, 2013 and between 10 April–13 June, 2014 within the grassed waterway (Fig. 8). EC-5 soil moisture smart sensors (S-SMC-M005; Decagon Devices, Inc., Pullman, WI) were installed along with the compatible data logger (H21-002; HOBO, Bourne, MA). These probes measure volumetric water content with an accuracy of ± 3%. Two EC-5 probes were installed within the grassed waterway at a depth of 5 cm located 1 m downslope of the 3 m X 3 m grid (Fig. 8) used for critical shear stress measurements. One probe was inserted along the center of the grid and the other probe was inserted between the center and the edge of the grid. The soil moisture probe wires were encased in PVC tubing and buried at a depth of 5 cm to prevent damage. The data logger was mounted on a post at the edge of the grassed waterway (Fig. 8), in order to avoid interference with regular field activities. One metal U-post was placed near the location of each soil moisture probe to indicate its location and prevent tire traffic over the probe. A rain gauge smart sensor (S-RGA-M002; Decagon Devices, Inc., Pullman, WI) was mounted on the U-post to measure precipitation. The rain gauge was connected to the same data logger as the soil moisture probes.

Continuous soil moisture data was measured for a companion study in the same watershed aimed at improving sediment delivery through grassed waterways. In the present study the data are used: (1) to assess the variation in soil moisture during intra and inter storm drying and wetting cycles and (2) in conjunction with the critical shear stress data to describe variability in potential detachment capacity as moisture conditions vary.
Soil texture, bulk density and organic matter: Three soil cores were collected downslope from each grid in both the grassed waterway and agricultural field at depths of 0-3.8 cm and 3.8-7.6 cm on 10 July 2013, 21 November 2013 and 10 April 2014 (total of 18 samples each for the grassed waterway and field). Soil texture (percent sand, silt and clay) was determined for each core collected on 10 July 2013 using the hydrometer method (Bouyoucos, 1962). All soil cores (18 each for the grassed waterway and agricultural field) were analyzed for bulk density using the core method (Blake, 1965) and organic matter using the weight loss on ignition method (Combs and Nathan, 1998 and Schulte and Hopkins, 1996). Field capacity and saturated moisture content for the grassed waterway and field were determined from the average percentage of sand, clay and organic matter over the 0-7.6 cm depth (Saxton and Rawls, 2006).

Liquid limit, plastic limit and plasticity index: Soil cores collected in the grassed waterway and agricultural field on 10 July and 21 November, 2013 were analyzed for liquid limit (LL), plastic limit (PL) and plasticity index (PI). Soil cores collected on both days were composited separately for the grassed waterway and agricultural field in order to obtain sufficient soil for the analysis. The analysis was carried out by Construction Geotechnical Consultants (CGC) Inc., Madison, WI, using the Atterburg test (Seed et al. 1967) which is used to determine critical water contents for soil such as shrinkage limit, liquid limit and plastic limit.

Statistical Analysis: Statistical analysis included two-way t-tests (Snedecor and Cochran, 1980) to determine significant differences between two sets of data. The test compares means of two sample populations in order to determine if they are significantly different from each other. The tests were
performed using Statistical Analysis System (SAS 9.3; SAS Institute Inc, Cary, NC) software at the significance level of $P < 0.05$.

### 3.4 Result and Discussion

*Soil texture, bulk density and organic matter:* Soil texture for the surface (0-3.8 cm) and the subsurface (3.8-7.6 cm) is classified as silt loam for both the grassed waterway and agricultural field. Percentages of silt, sand and clay for the grassed waterway and agricultural field are presented in the Table 10. The percentages of sand, silt and clay were more similar for the subsurface compared to the surface for both the grassed waterway and agricultural field. The soil at the surface is subjected to erosion and deposition processes which may explain the larger differences in percent of sand, silt and clay between the surface of the grassed waterway and agricultural field.

Bulk density and organic matter content for soil cores collected from the grassed waterway and agricultural field are presented in Table 11. Average bulk density of soil in the top 3.8 cm was significantly different ($p < 0.05$) between the grassed waterway and agricultural field (1.1 and 0.9 g/cm$^3$, respectively). The average bulk density for soil at depth of 3.8–7.6 cm was not significantly different ($p = 0.152$) between the grassed waterway and agricultural field (bulk density = 1.1 g/cm$^3$ for both grassed waterway and agricultural field). The bulk density was consistent in grassed waterway at both depths ($p = 0.531$). This was expected, considering there was no tillage in the grassed waterway. The surface and subsurface bulk density of the soil in the agricultural field differed significantly ($p = 0.032$). This result is consistent with a study by Shaver et al. (2002) in which crop residue resulted in decreased bulk density in the top 2.5 cm of surface soil; crop residue is lighter than soil and it also promotes aggregation. Average soil organic matter content in the
grassed waterway was significantly higher compared to the agricultural field for both the top 3.8 cm (p < 0.001) as well as the 3.8-7.6 cm depth (p < 0.0005). This could be attributed to the cut grass left in the grassed waterway after mowing. Organic matter content between the two depths was not significantly different for either the grassed waterway (p = 0.221) or the agricultural field (p = 0.0578).

*Liquid limit, plastic limit and plasticity index:* Results from the Atterburg test conducted on soil cores from the grassed waterway and agricultural field are presented in Table 12. All Atterberg Limits (Plasticity Index, Plastic Limit, and Liquid Limit) were similar, although slightly greater, for the grassed waterway compared to the agricultural field. According to De Jong et al. (1990), liquid limit, plastic limit and plasticity index are all positively correlated with organic matter content. However, the relationship is only significant for liquid limit and plasticity index. This could explain the higher Atterberg limits for soil within the grassed waterway (average organic matter = 7.9; Table 11) compared to the agricultural field (average organic matter = 5.6; Table 11).

*Soil Moisture and precipitation:* Average daily soil moisture in the grassed waterway for the study period is presented in Fig. 9. Moisture content (15 min intervals) in the grassed waterway ranged from 13 to 37%. Discrete antecedent soil moisture measurements (Delta-T-probe) at the time of critical shear stress measurements ranged from 11.2 to 40.2% in the grassed waterway, and from 5.6 to 37.8% in the agricultural field (Fig. 9). Table 13 shows that average soil moisture was lower for the agriculture field compared to the grassed waterway (p < 0.0001), indicating that moisture is retained in the grassed waterway as a result of the concentrated flow path and reduced velocity
from the dense vegetation which enhances infiltration (Chow et al., 1999). The field capacity and saturation moisture contents determined using the equations presented by Saxton and Rawls (2006), were 32.3% and 40.9% for grassed waterway and 31.7% and 41.1% for the field respectively.

While continuous soil moisture was not measured in the agricultural field, the range in discrete soil moisture measurements was similar between the grassed waterway and the agricultural field. Therefore it is reasonable to assume that fluctuations (not magnitude) in the continuous soil moisture will follow similar trends in the agricultural field as well (except during the early and late stages of the growing season when the ground cover in the grassed waterway and agricultural field will be most different). The continuous soil moisture measured in the grassed waterway was used to assess the variation of soil moisture during drying and wetting cycles. The continuous soil moisture data also demonstrate the variability in soil moisture content during different inter and intra storm conditions. While continuous storm events (e.g. 22 June to 29 June 2013) resulted in elevated soil moisture at the end of the storms (32.3%), a gap of a few days between storms (e.g. 30 June to 6 July 2013) resulted in drier conditions (11.8%).

**Critical shear stress and suspension index:** Table 13 presents the average and standard deviation values for soil moisture, critical shear stress and suspension index for all measurements made within the grids in the grassed waterway and agricultural field. It also includes the separate averages for measurements made below plastic limit (<PL) and above plastic limit (>PL).

The overall average critical shear stress of all the measurements of the relatively undisturbed soil in the grassed waterway was significantly greater than that of the disturbed (tilled)
soil in the agriculture field (p < 0.0001). Critical shear stress was greater for the grassed waterway compared to the agricultural field when soil moisture was below plastic limit (p < 0.0001); above the plastic limit critical shear stress was not significantly different between the grassed waterway and agricultural field (p < 0.0001) (Table 13). Above the plastic limit, soil behaves like fluid and vegetation is not as effective at holding the soil particles together resulting in lower critical shear stress values for both the grassed waterway and agricultural field.

Greater critical shear stress corresponds to lower susceptibility to erosion. The average suspension index of all the measurements for the grassed waterway was significantly lower than that of the agricultural field (p < 0.0001). Similar to the critical shear stress results, above the plastic limit the average suspension index was not significantly different for the grassed waterway and agricultural field (p < 0.0001). The results indicate that once erosion is initiated it will proceed at a slower rate in the grassed waterway for soil moisture lower than plastic limit. This trend was expected as disturbed soils are more prone to erosion compared to undisturbed and vegetated soils. For example, using a submerged jet test on stream banks in Southwestern Virginia, Wynn and Mostaghimi (2006) found critical shear stress increased while erosion rates decreased with increasing vegetation. Franti et al. (1999) found that critical shear stress for tilled soil was half that of no-till soil (both planted with continuous corn), and soil erodibility was seven times greater for tilled soil than for no–till soil. Our results indicate the combined effect of dense vegetation and un-tilled soil: the average critical shear stress for the grassed waterway is about 1.6 times greater than that of the agricultural field, whereas the suspension index for the grassed waterway is 1.7 times less than that of the agricultural field.
Relationship between antecedent soil moisture and critical shear stress: Critical shear stress for the grassed waterway and agricultural field under different antecedent soil moisture conditions are presented in Fig. 10a and 10b. The difference between the maximum and minimum measured moisture content was similar for the grassed waterway (29.0%) and agricultural field (32.2%), however the average moisture content in the grassed waterway (27.3%) was higher compared to the agricultural field (20.8%). Critical shear stress in the grassed waterway increased as soil moisture increased until the soil moisture content reached the plastic limit (Fig. 10a). During dry conditions soil particles are loosely bound together by their own friction and they are stable as long as their internal angle is lower than or equal to the angle of repose (angle of particle in the loosest state) (Alt et al., 2009). As moisture content increases, so does the angle of repose (Mason et al. 1999; Nedderman, 1992) and soil particles are held together by the surface tension between water and the solid particles. As moisture content and particle stability increase so does the critical shear stress of the soil rendering it less susceptible to erosion. The angle of repose decreases as the soil moisture approaches the plastic limit and the soil starts to behave as a fluid. This is reflected in the lower critical shear stress values (average of 2.6 Pa) for soil moisture content greater than the plastic limit of soil in the grassed waterway.

A similar, although less prominent, relationship was observed for the agricultural field (Fig. 10b). In general, over the range of soil moisture contents measured, critical shear stress values for the agricultural field were lower compared to critical shear stress values for the grassed waterway. The field soil was subjected to spring and fall tillage, resulting in disturbed soil particles that are more prone to erosion. The results indicate that while critical shear stress increases with antecedent soil moisture, the magnitude of the increase is less because tillage and other management practices
such as planting and harvesting loosen the soil surface resulting in lower overall critical shear stress of the soil.

Regression equations were developed to describe the relationship between critical shear stress and antecedent soil moisture, for soil moisture less than the plastic limit (Table 14). The higher $R^2$ value (0.69) for the relationship in the grassed waterway indicates that soil moisture explained more of the variability in critical shear stress compared to the agricultural field ($R^2 = 0.27$). The low $R^2$ for agricultural field suggests that other factors may have greater impact on critical shear stress than soil moisture. The rise in critical shear stress with soil moisture was less in the agricultural field compared to the critical shear stress in the grassed waterway, however the positive exponent in the best-fit exponential regression confirms that critical shear stress increases with increasing soil moisture for both the grassed waterway and agricultural field.

**Relationship between soil moisture and suspension index:** The Suspension Index ($S_i$) values for the grassed waterway and agricultural field under different soil moisture conditions are presented in Fig. 11. $S_i$ values for soils within the grassed waterway decrease with increasing soil moisture until the soil moisture reaches the plastic limit (Fig. 11a). Once the soil moisture is above the plastic limit, $S_i$ values increase and are less dependent on soil moisture content. Similar results were observed for the agriculture field (Fig. 11b). The higher $S_i$ values (proxy for soil erosion rates) for the agriculture field compared to the grassed waterway, suggest that soil particles in the field are more susceptible to erosion and erode more rapidly due to disturbances such as tillage (fall and spring) and harvesting. The field disturbances may also explain the larger spread for $S_i$ values from the field as they effect the stability of the soil particles from time to time resulting in more variable erosion rates.
Best-fit exponential regressions were developed between $S_i$ values and soil moisture for soil moistures lower than the plastic limit (Table 15). Similar to the results for critical shear stress, the exponential curve for $S_i$ values in the agricultural field was flatter compared to that in the grassed waterway, indicating less overall change in $S_i$ values with varying soil moisture for the agriculture field compared to the grassed waterway. The negative powers for both equations confirm that erosion rate (represented by $S_i$ values) decreases as soil moisture increases for both the grassed waterway and agriculture field. The values of $R^2$ for the regression equations between $S_i$ and soil moisture in the grassed waterway and agricultural field suggest that 50% and 40% of the variability in their $S_i$ index values can be explained by the soil moisture.

**Effect of Soil moisture on detachment capacity of soil**

Continuous soil moisture measured in the grassed waterway from 14 June 2013 until 13 June 2014 was used to assess the variation in soil detachment capacity during drying and wetting cycles (Fig. 12). The equation presented in Table 14 for the grassed waterway was substituted into Equation 1 and detachment capacity was estimated for soil moisture content values below plastic limit (Fig. 12). For soil moisture above the plastic limit an average critical shear stress value of 2.6 Pa was substituted into Equation 1. The detachment capacity was estimated for a hypothetical storm that can generate flow critical shear stress of 6 Pa (greater than the maximum critical shear stress measured during the study, 5.63 Pa) in the grassed waterway. We used a constant value for the rill erodibility factor ($K = 0.0079$ s m$^{-1}$) which was obtained from the State Soil Geographic Database (STATSGO) (SCS, 1992) using equations developed by Elliot et al. (1989). While the value of $S_i$ which is a proxy for erosion rate cannot be used interchangeably with $K$, it provides an indication of how soil erodibility will vary with soil moisture. The relationships between $S_i$ and
soil moisture (Table 15) indicate that $S_i$ decreases with increasing soil moisture. Thus detachment capacity should decrease at a faster rate with increasing soil moisture if we also factor in the relationship between $S_i$ and soil moisture. Figure 12 shows that an inverse relationship exists between soil moisture and detachment capacity. Detachment capacity decreases as soil moisture increases and vice versa. This analysis demonstrates the variability in detachment capacity associated with changes in soil moisture.

### 3.5 Summary and Conclusion

Sediment transported from agriculture fields to receiving waters is one of the most concerning problems related to water pollution. Estimation of the amount of soil being eroded and transported is critical. One of the widely accepted methods for this is by determining the critical shear stress and comparing it with the shear stress exerted by the flow. In this study we identified that the critical shear stress which is the driving factor for soil erosion by water can vary significantly with the soil moisture. Therefore we studied the dynamic nature of critical shear stress with soil moisture. Critical shear stress measurements were made in the grassed waterway and agricultural field under different soil moisture conditions for a nested watershed in Pioneer Farm, WI.

The analysis showed that critical shear stress and suspension index are not constant for a soil rather they change with the changes in soil moisture content. While critical shear stress increased with increasing soil moisture, suspension index which is a measure of soil erosion rate decreased with increasing soil moisture. Exponential regression equations were developed for critical shear stress and suspension index in terms of soil moisture. It was also observed that critical shear stress was lower for the disturbed soil in the agriculture field as compared to the undisturbed
soil in grassed waterway. The study highlighted that the dynamic nature of soil properties such as critical shear stress and erosion rate during wetting and drying of soil can be a dictating factor in estimating detachment capacity of the soil and hence the soil erosion.

Results from this study can be used to improve the critical shear stress estimations for varying soil moisture conditions. This could also potentially improve the erosion predictions by different empirical and physically-based models that use critical shear stress for estimating rill and gully erosions.

3.6 References


Table 9. Sampling dates and the number of measurements collected using the CSM in the grassed waterway and the agricultural field.

<table>
<thead>
<tr>
<th>Sampling Date</th>
<th>Number of CSM measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grassed Waterways</td>
</tr>
<tr>
<td>06/14/2013</td>
<td>8</td>
</tr>
<tr>
<td>07/10/2013</td>
<td>8</td>
</tr>
<tr>
<td>08/09/2013</td>
<td>8</td>
</tr>
<tr>
<td>08/16/2013</td>
<td>8</td>
</tr>
<tr>
<td>10/07/2013</td>
<td>8</td>
</tr>
<tr>
<td>10/16/2013</td>
<td>8</td>
</tr>
<tr>
<td>11/21/2013</td>
<td>8</td>
</tr>
<tr>
<td>04/10/2014</td>
<td>8</td>
</tr>
<tr>
<td>04/22/2014</td>
<td>8</td>
</tr>
<tr>
<td>05/20/2014</td>
<td>8</td>
</tr>
<tr>
<td>06/13/2014</td>
<td>8</td>
</tr>
</tbody>
</table>

*There was problem with the functioning of CSM
**The field was being tilled
Table 10. Average silt, sand and clay percentages (n=3) for the grassed waterway and agriculture field (with standard deviation in parentheses) on 10 July 2013.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Grassed waterway</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Silt (%)</td>
<td>Sand (%)</td>
</tr>
<tr>
<td>(0-3.8cm)</td>
<td>77 (1.4)</td>
<td>5.3 (0.9)</td>
</tr>
<tr>
<td>(3.8-7.6cm)</td>
<td>74.7 (0.8)</td>
<td>6.8 (0.4)</td>
</tr>
</tbody>
</table>
Table 11. Average bulk density and organic matter (n=3) for the grassed waterway and agriculture field (with standard deviations in parentheses).

<table>
<thead>
<tr>
<th>Date of sample collection</th>
<th>Depth (cm)</th>
<th>Bulk Density</th>
<th>Organic Matter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Grassed waterway</td>
<td>Field</td>
</tr>
<tr>
<td>10 July 2013</td>
<td>(0 – 3.8)</td>
<td>1.2 (0.07)</td>
<td>0.9 (0.13)</td>
</tr>
<tr>
<td></td>
<td>(3.8 -7.6)</td>
<td>1.2 (0.04)</td>
<td>1.1 (0.09)</td>
</tr>
<tr>
<td>21 November 2013</td>
<td>(0 – 3.8)</td>
<td>1.0 (0.04)</td>
<td>0.9 (0.07)</td>
</tr>
<tr>
<td></td>
<td>(3.8 -7.6)</td>
<td>1.2 (0.04)</td>
<td>1.1 (0.09)</td>
</tr>
<tr>
<td>10 April 2014</td>
<td>(0 – 3.8)</td>
<td>1.0 (0.04)</td>
<td>1.0 (0.03)</td>
</tr>
<tr>
<td></td>
<td>(3.8 – 7.6)</td>
<td>1.0 (0.03)</td>
<td>1.0 (0.02)</td>
</tr>
</tbody>
</table>
Table 12. Atterberg limits (liquid & plastic) along with the plasticity index for soil in the grassed waterway and agricultural field.

<table>
<thead>
<tr>
<th></th>
<th>Liquid Limit (LL)</th>
<th>Plastic Limit (PL)</th>
<th>Plasticity Index (PI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grassed waterway</td>
<td>40</td>
<td>31</td>
<td>9</td>
</tr>
<tr>
<td>Field</td>
<td>37</td>
<td>30</td>
<td>7</td>
</tr>
</tbody>
</table>
Table 13. Average soil moisture, critical shear stress and suspension index data (with standard deviation in parentheses). Average with different letters represent significantly different means for each parameter (p < 0.0001).

<table>
<thead>
<tr>
<th></th>
<th>All measurements</th>
<th>&lt; PL*</th>
<th>&gt; PL**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grassed waterway</td>
<td>Field</td>
<td>Grassed waterway</td>
</tr>
<tr>
<td>Soil Moisture (%)</td>
<td>27.3\textsuperscript{a} (6.2)</td>
<td>20.8\textsuperscript{b} (8.1)</td>
<td>24.9\textsuperscript{a} (5.2)</td>
</tr>
<tr>
<td>Critical Shear stress(Pa)</td>
<td>3.2\textsuperscript{a} (1.3)</td>
<td>1.9\textsuperscript{b} (0.9)</td>
<td>3.4\textsuperscript{a} (1.1)</td>
</tr>
<tr>
<td>Suspension Index</td>
<td>2.6\textsuperscript{a} (1.7)</td>
<td>4.6\textsuperscript{b} (1.9)</td>
<td>2.2\textsuperscript{a} (1.5)</td>
</tr>
</tbody>
</table>

\* < PL – Soil moisture content below plastic limit
\* > PL – Soil moisture content above plastic limit
Table 14. Relationships between soil moisture (SM) and critical shear stress ($\tau_c$) data with soil moisture less than plastic limit for the grassed waterway and the agricultural field along with their $R^2$ values.

<table>
<thead>
<tr>
<th>Location</th>
<th>Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grassed waterway</td>
<td>$\tau_c = 0.69e^{0.06SM}$</td>
<td>0.69</td>
</tr>
<tr>
<td>Field</td>
<td>$\tau_c = 0.78e^{0.04SM}$</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Table 15. Relationships between soil moisture (SM) and suspension index ($S_i$) for soil moisture less than plastic limit for the grassed waterway and the agricultural field along with their $R^2$ values.

<table>
<thead>
<tr>
<th>Location</th>
<th>Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grassed waterway</td>
<td>$S_i = 13.73e^{-0.08SM}$</td>
<td>0.50</td>
</tr>
<tr>
<td>Field</td>
<td>$S_i = 9.29e^{-0.05SM}$</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Fig. 7 (a) Location of the UW Platteville Pioneer Farm in Southwestern Wisconsin. (b) basin areas delineated in blue and locations for water quality sampling stations indicated by ▲. (c) nested watershed S4 and S5 along with the locations of soil moisture and critical shear stress measurements indicated by ■. (Photos provided by Rendy Mentz, Research Program Manager at Pioneer Farm, WI.)
Fig. 8 Grid (with grid cells (1m X 1m) and sub-cells (0.2m X 0.2m) for critical shear stress measurements in the grassed waterway along with location of the soil moisture probes and data logger
Fig. 9 Average daily soil moisture data collected by the two soil probes (indicated by line graph), average soil moisture (along with the standard deviation) measured using Delta-T probe for the grassed waterway and the agricultural field (indicated by circle markers) along with the precipitation data (indicated by bar graph).
Fig. 10 Effect of soil moisture on critical shear stress of soil within (a) grassed waterway and (b) agriculture field along with their plastic limit (PL), and liquid limit (LL).
Fig. 11 Effect of soil moisture on suspension index of soil within (a) grassed waterway and (b) agricultural field along with their plastic limit (PL), and liquid limit (LL).
Fig. 12 Effect of soil moisture on detachment capacity of soil within the grassed waterway for a hypothetical runoff event generating shear stress of 6 Pa for $K = 0.0079$ s m$^{-1}$. 
Chapter 4

4. Estimating sediment delivery ratios for Grassed Waterways using WEPP

4.1 Abstract

Grassed waterways (GWWs) transport sediment and nutrients from upland source areas to receiving waters. Watershed planners have a critical need to understand GWW sediment delivery to optimally target source area management practices. Better physically-based tools are needed to estimate sediment delivery by GWWs. This study developed several distributed sediment delivery ratio (SDRs) regressions for GWWs using the process-based Water Erosion Prediction Project (WEPP) model. WEPP was calibrated and validated for runoff and sediment yield for a large 30.2 ha and smaller 5.7 ha nested watersheds with a terraces and a common GWW outlet. A crop rotation of corn, oat and alfalfa and fall tillage using chisel plow were employed in the nested watersheds. A hypothetical case without terraces, with corn, oat and alfalfa rotation and chisel plow as fall tillage was also run for the 5.7 ha watershed and the GWW. The length, slope, Manning’s roughness coefficient and infiltration rate for the GWW were varied and sediment delivery ratios (SDRs) calculated for 30 representative storms over a 20 year period of simulated climate. Regressions were developed for the existing (terraced) and hypothetical (without terraces) management scenarios for early (April – July), late (August – October) and full (April – October) growing seasons. Equations developed for the non-terrace watershed had higher $R^2$ values compared to the terraced watershed suggesting that channel and storm parameters were better able to explain the variation in SDR for the non-terraced watershed. This is likely the result of a more direct and greater rainfall/runoff and erosion response for the non-terraced watershed. Manning’s
roughness coefficient was the most significant parameter for predicting SDR for both terraced and non-terraced watersheds.

4.2 Introduction

Sediment eroded from upland areas is carried downstream to receiving waters via rills and gullies. In areas where ephemeral gully erosion is occurring, gullies will likely contribute disproportionately high sediment losses in erosion-prone areas (Laflen, 1985; Thomas et al., 1986; Casali et al., 1998). Constructed grassed waterways (GWWs) are one effective management practice that can prevent gully formation by safely conveying runoff from fields to receiving waters. A properly constructed GWW reduces overland flow runoff velocity, thus allowing sediment to settle prior to exiting the field as well as preventing additional sediment losses from scour. As such GWWs represent an important delivery pathway for sediment and other pollutants from upland source areas to downstream receiving waters.

Upland source-area or targeted management strategies have become increasingly important for allocating limited non-point source control dollars for water quality management of receiving waters. Understanding the sediment delivery process is an essential component for targeted source-area management. One approach to assess sediment delivery through GWWs is to apply process based models. Process-based models are widely used by researchers and managers to provide decision support for management. Watershed models are able to represent processes such as hydrology, hydraulics, plant growth, nutrient dynamics and soil erosion occurring within a hillslope or a watershed. Some of the more widely used hydrologic and water quality models include: the Soil and Water Assessment Tool (SWAT), (Arnold et al., 1998), Hydrologic Simulation
Program-Fortran (HSPF), (Bicknell et al., 1997), Annualized Agricultural Non-Point Source model (ANN-AGNPS) (Bingner and Theurer, 2001) and Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995). These models simulate watershed hydrologic processes by maintaining the water balance of the system while simultaneously simulating other processes such as water routing, sediment transport and nutrients dynamics.

Several studies have used physically-based models such as the WEPP model to investigate the sediment delivery processes in GWWs and assess their effectiveness in reducing the runoff velocity and sediment delivery (Hjelmfelt and Wang, 1997; Lee, 2008; Abaci et al., 2010; Dermisis et al., 2010). These studies found that the sediment delivery efficiency of GWWs depends upon various factors including surface topography, soil, vegetation and storm characteristics. These studies suggest a reduction in runoff volume and sediment yield occurs with increasing GWW length. They also found that the sediment removal efficiency of GWWs is reduced for larger storm events. One major constraint in the application and testing of physically-based models is that they are often data and time intensive. For instance, Munoz-Carpena (1999) developed the physically-based Vegetated Filter Strip Model (VFSMOD) to evaluate the sediment removal performance of vegetative filters. The model requires a significant number of inputs such as hydraulic conductivity, soil water saturation content, and surface retention, among others. Deletic (2001) developed a dynamic mathematical model for runoff and sediment transport to assess the sediment removal efficiency of grassed filter strips and swales. The input data include hydraulic conductivity, soil water saturation content, surface retention and grass density, among others. Therefore watershed planners need alternatives to physically-based models in order to estimate sediment delivery using more readily available inputs.
Alternatives to physically-based models are less data intensive empirical equations. Several studies have developed empirical equations to estimate the sediment delivery ratio (ratio of sediment yield at a point to the gross erosion in the watershed). While upland sheet and rill erosion can be estimated using equations such as the Universal Soil Loss Equation (Wischmeier and Smith, 1978) or the Revised Universal Soil Loss Equation 2 (RUSLE2: USDA, 2003), sediment yield is often not measured (Ouyang, 1997). Measurement of sediment yield is further complicated in real world systems by surface flow entering GWWs and other channels along their entire length, making water and pollutant mass balance calculations prohibitively difficult. Initial attempts to address the sediment delivery issue resulted in the development of several empirical equations: Maner (1958), Roehl (1962), Williams (1975), Vanoni (1975) and Walling (1983). Most of these equations were developed to estimate sediment delivery using soil texture and structure or drainage area and general flow path characteristics with limited process consideration. One disadvantage of empirical equations is that they are limited to the constraints of the data set used in their development, thus limiting their geographical range of application. Because the Williams (1975) approach considers channel length and sediment delivery it is well suited for BMP targeting applications that include Geographic Information Systems (GIS). A short coming however is the lack of robust evaluation of a primary empirical parameter ($\beta$) outside of the model development data set. The need therefore still exists for relationships that use more readily available channel and storm characteristic data to estimate a sediment delivery ratio.

The amount of reliable sediment delivery monitoring data that could be used to develop and validate predictive equations is limited at best. Watershed managers currently have a critical need for sediment delivery estimates from a specific landscape location (e.g. field) to receiving waters. Until appropriate monitoring data become available planners are forced to rely on
previously validated processed-based models that synthesize existing sediment delivery knowledge. Simplified sediment delivery regression equations can be developed based on processes described within more sophisticated models such as WEPP. The simpler regression equations can then be developed to represent the relative distribution of sediment delivery potential across the landscape while considering site specific physical characteristics of the conveyance system. In addition, the regression equations can enhance our understanding of the processes and parameter sensitivity governing sediment delivery.

The overall goal of this study was to develop regression equations for estimating a distributed sediment delivery ratio to support targeted management decisions for watershed planning applications. The specific objectives were to (i) setup, calibrate and validate the process-based WEPP model for a nested agricultural watershed and (ii) use this model to develop simplified sediment delivery equations that use channel and storm event characteristics as input parameters.

4.3 Methodology

4.3.1 Study Area

The study area watershed is located at the University of Wisconsin (UW)-Platteville Pioneer Farm in Lafayette County, southwestern Wisconsin (Fig. 13). The farm occupies a total area of 174 ha and is used to demonstrate and evaluate various agricultural management practices that will help farmers increase production efficiency. The farm has been divided into several small subwatersheds for research purposes. The study watershed contained several fields using a seven year crop rotation of three years corn, one year oats-alfalfa and three years alfalfa. Tillage was performed in the fall using a chisel plow and by a soil finisher during the first week of May prior
to planting. Runoff and water quality have been continuously monitored at paired watershed outlets by the U.S. Geological Survey (USGS) since 2001. The watersheds designated as S4 (30.2 ha) and S5 (5.7 ha) (Fig. 13) were used in this study. These watersheds are nested (S5 is contained within S4), with outlets connected by a single GWW. The watersheds are dominated by silt loam soils (Tama and Ashdale series) with underlying limestone bedrock. These are deep, well drained, and dark colored productive agricultural soils. Historical climate data (average temperature and precipitation) obtained for Southwest Wisconsin from the Wisconsin State Climatology Office for the period of 1895 – 2005 are presented in Table 16.

4.3.2 Watershed Modeling

The Water Erosion Prediction Project (WEPP) hillslope and watershed model is an event based, mechanistic model developed by the United States Department of Agriculture - Agriculture Research Service (USDA-ARS) in 1995 (Flanagan et al., 2010). The model can be used to estimate runoff and sediment yield from small watersheds. It uses the Green-Ampt Mein–Larson method for estimating infiltration and assumes that runoff starts when rainfall for any storm is higher than the infiltration rate and depression storage has been satisfied. An approximation of the kinematic wave model is used to calculate peak discharge. In addition, the model contains a plant growth component and estimates interrill / rill erosion and transport using a steady state sediment continuity equation. Sediment transport capacity is calculated by particle size class based upon the potential sediment load computed using the Yalin sediment transport equation (Yalin, 1963). The WEPP model also contains channel flow and sediment transport routines. Hydrologic elements such as infiltration, depression storage, and runoff for the channels in WEPP are computed using similar methods as for the hillslopes. Erosion processes (detachment, transport and deposition) in
the channel are computed using the steady state sediment continuity equation. A detailed
description of all the processes in WEPP is presented in the WEPP technical documentation

Slope, soil properties, management (tillage and crop rotations) and rainfall data for this
study were obtained from staff at the Pioneer Farm. Watershed hillslope and channel elevation
data for the S4 and S5 watersheds were obtained using a 1 – foot Digital Elevation Model (DEM)
generated using LIDAR. ArcGIS v9.3.1 (ESRI 2009) was used to calculate average slope for the
hillslopes and channels using the DEM data. Direct field slope measurements were used to verify
the GWW slope and cross section. The WEPP soils database was used to determine the main soil
erodibility properties which include interill erodibility, rill erodibility and critical shear stress.

4.3.3 Nested Watersheds Setup

The WEPP model was setup for nested watersheds S4 and S5 (Fig. 13). Watershed S4
contains the smaller watershed S5 within it. The watersheds included both terraced (narrow-based)
and non-terraced fields. The nested watershed was modeled using an approach similar to that
described by McCullough et al. (2008). Each terrace was represented by a hillslope draining into
a channel through an impoundment (Fig. 14a). Watershed S5 was sub-divided into 9 hillslopes,
draining into 9 channels (Fig 14b). These channels are drained to the outlet via a grassed waterway.
The entire S4 watershed (contains S5) and was represented by 37 hillslopes and 45 channels (Fig.
14b). The channel system includes terraced channels draining the hillslopes and directing runoff
to the GWW which in-turn directs the combined runoff to the watershed outlet.
4.3.4 Model calibration and validation

The WEPP model was calibrated at the outlets of both the smaller watershed (S5) and the larger watershed (S4) using observed flow and sediment data collected between 2001 and 2007. It is important to note that data collection stopped for watershed S4 in 2007 and that only years 2003, 2004 and 2007 had sufficient data for calibration and validation. Therefore storm event data during 2003 and 2004 were used for calibration and 2007 for validation. The calibration and validation was performed on an event basis. The goodness of fit was initially evaluated visually using a scatter plot between the observed and predicted values. Model performance was then quantified using the coefficient of determination ($R^2$), Nash Sutcliffe Efficiency (EN) and Root mean square error (RMSE) values. The Parameter Estimation (PEST) tool (Doherty, 2004) was used for input parameter optimization during calibration. A program was developed to convert WEPP output into a format compatible with PEST. This program allowed automated calibration of WEPP using the PEST algorithms.

4.3.5 Channel sediment delivery

The calibrated and validated WEPP model was subsequently used to represent only field S5 and the GWW. In order to focus on the sediment delivery processes occurring in the GWW, the hillslopes in watershed S4 that contribute directly to the GWW along its length were removed from the model leaving watershed S5 connected directly to the outlet of S4 via the GWW (Fig. 15).

The channel was assumed to have a non-eroding cross section. The bottom width was 7.3 m (determined from field measurements). Rest of the channel parameters were obtained from the
study by McCullough et al., 2008 in which they successfully represented channels as GWWs. As described in the study sediment delivery in the channel is significantly affected by two parameters in WEPP: channel shape and channel control section at the outlet. So we used a GWW configuration similar to that used by McCullough et al., 2008 representing the channel outlet control section shape as triangular, using the normal flow option. The inverse slope of channel bank (ratio of half of channel width by the vertical depth) was considered as 19.99 m/m (default in WEPP). Because the focus of the study was on sediment loss during delivery we assumed that all GWW were properly designed and maintained, thus minimizing the occurrence of scour within the channel itself. To prevent scour during the WEPP model runs the channel critical shear was set to a very high value (100 Pa).

A literature review was conducted to identify those parameters for GWWs most sensitive to sediment delivery. Channel length, slope, surface roughness, infiltration and travel time have the greatest effect on sediment delivery through a GWW (Briggs et al. 1999; Chow et al. 1999; Hjelmfelt and Wang, 1999; Dermisis et al. 2010). Two executable files were developed using the FORTRAN programming language to run WEPP multiple times using various combinations of channel length, infiltration, Manning’s roughness coefficient, and slope. These executables files automatically adjust the values of one variable at a time while holding the other variables constant and subsequently run the model for various channel parameter combinations.

The channel parameters were varied over the ranges specified in Table 17. It is important to note that WEPP uses two different values for Manning’s roughness coefficient: Manning’s roughness coefficient for the bare soil and total Manning’s roughness coefficient for the bare soil and vegetation. The values presented in Table 17 correspond to the total Manning’s roughness coefficient for channel vegetation as the Manning’s roughness coefficient for the bare soil was not
changed during the model runs. Model documentation for WEPP (Flanagan and Nearing, 1995) states that the total Manning’s roughness coefficient for a vegetated channel should always be greater than for the bare soil. The range for Manning’s roughness coefficient was obtained from the CREAMS manual (Knisel, 1980) for grass cover in good condition (0.08) to very dense (0.30), with the assumption that cover is erect and as deep as flow. While Manning’s roughness values can go even higher for high flows where the vegetation is submerged (Kinsel, 1980), 0.3 was a reasonable upper limit for the small watershed in our study. The channel lengths and slopes were chosen to cover a typical range of grassed waterways used in Wisconsin.

After calibration and validation, the model was run for 20 years of climate data generated using the WEPP climate generator (CLIGEN V 4.3) program. The program generates climate data for areas where climate data such as precipitation, temperature, solar radiation, and wind velocity are not available. The CLIGEN precipitation data were used because the observed data did not provide the range of rainfall values desired to produce robust regressions. The WEPP model generated the runoff and sediment yield at the inlet of the GWW and at the outlet using the aforementioned combinations for channel conditions. Sediment delivery was calculated using the sediment yield estimates at the channel outlet and at the outlet of the S5 watershed using a representative subset of 30 storms selected from the 20 year model simulation period. The 30 storm events were selected to represent the frequency distribution of rainfall depths expected for the area. These storms where further characterized based on their occurrence during the growing seasons: early growing season (April – July), late growing season (August- October) and full growing season (April – October). Table 18 summarizes the median and range of storms selected and corresponding runoff volumes used in the simulation. The 8,125 WEPP output values were stored in a data base for subsequent processing and statistical analysis.
4.3.6 Generalized hypothetical scenario

Soil erosion by sheet and rill erosion is reduced by terraces as they trap and deposit the eroded sediment (Foster and Highfill, 1983), which is not representative for most Wisconsin agricultural landscapes. In order to obtain a more typical land management scenario a watershed similar to S5 but without terraces was setup using WEPP. The area and crop rotation of the S5 watershed was retained and divided into 6 different hillslopes with a slope length of around 60 m and watershed slope of 3%. All hillslopes drained towards a single outlet channel which was connected to the GWW.

4.3.7 Statistical Analysis:

All statistical tests were performed using the Statistical Analysis System (SAS 9.3; SAS Institute Inc, Cary, NC) software. A brief description of the tests is presented below.

Multicollinearity: Before performing stepwise regression the independent variables were tested for multicollinearity. This test identifies the variables that are highly correlated. The coefficient of correlation is calculated between each pair of independent variables. Correlation coefficients close to 1 or -1 indicate significant correlation between the tested variables. The problem of multicollinearity can be eliminated by removing one of the variables.

Multiple regression: Stepwise multiple regression analysis was performed on the output data generated from the WEPP model runs for the actual and hypothetical cases (with and without terraces), respectively. The analysis was performed using the following variables: sediment delivery ratio (SDR), GWW length (L) (km), GWW slope (S) (%), Manning’s roughness
coefficient (N) for GWW, infiltration rate (I) (mm/hr), total runoff entering GWW (R) (mm), rainfall depth (P) (mm), duration of storm (D) (hr) and peak runoff rate (PR) (m³/s). Stepwise regression analysis is a combination of various alternating forward selection and backward elimination processes. The objective of the analysis is to identify the parameters which result in the highest R² for the model. During the forward selection one independent variable is entered at each step which increases the value of R². During backward elimination a variable is eliminated at each subsequent step. Although either the forward selection or backward elimination can be used as alternatives in place of stepwise regression, we used the stepwise process as it tests various combinations of variables in order to achieve the best possible combination for the final regression model.

We considered three different time periods for the regression analysis: full growing season (April – October), early growing season (April – July) and late growing season (August – October). The early growing season was considered from planting until the crop reaches full canopy cover. The late season includes the time period when the crop is fully developed until harvest. The full growing season combined both time periods. The summary of storms used during all 3 simulation time periods is presented in Table 18.

### 4.4 Results and Discussion

#### 4.4.1 Calibration and Validation

*Runoff and sediment yield simulation – watershed S5 outlet*

The observed and simulated storm event flow and sediment yield during the calibration (2003-2004) and validation (2007) periods at the outlet of watershed S5 are shown in the Figure
16. It is evident from the figures that the model was able to simulate total runoff and sediment yield reasonably well. Table 19 presents the model performance statistics for predicted versus observed runoff and sediment yield during calibration and validation. The $R^2$ values above 0.8 and $E_N$ values above 0.7 for runoff simulation suggests that model was doing a good job predicting runoff during both calibration as well validation period. It was interesting to see that the model performance measures ($R^2$ and $E_N$) for simulating sediment yield were higher than runoff during the calibration period, but RMSE values show that the model was performing better for runoff volume in terms of residual error. The $R^2$ and $E_N$ values were heavily influenced by the 93 mm extreme rainfall event that occurred on April 30, 2004. This event resulted in significantly greater runoff and sediment yield (5000 kg) than any other event in the data set and in-turn biased the model statistics toward higher $R^2$ and $E_N$ values. We therefore included the statistics for model performance measures without the large April 30$^{th}$ event in parenthesis (Table 19).

*Runoff and sediment yield simulation – watershed S4 outlet*

Figure 17 presents observed and simulated runoff and sediment yield during the calibration (2003-2004) and validation (2007) period for the outlet of watershed S4. Visual comparison along with the statistical measures presented in Table 19 suggest that WEPP again did an adequate job of simulating runoff and sediment yield for the larger S4 watershed. It is also evident that the extreme event on 30 April 2003 likely influenced the high $R^2$ and $E_N$ values. It is also interesting to note that the WEPP model parameters selected by the PEST software for calibration did not differ much from the model default values suggesting that the default input parameter values from the soil database in WEPP are reasonable.
4.4.2 Statistical analysis

Statistical analysis of the SDR and channel characteristics was performed on the dataset generated by WEPP for the GWW connecting the outlet of watershed S5 and watershed S4. This section presents the results from the multicollinearity and regression analyses performed on the dataset.

Multicollinearity analysis:

As indicated in Table 20, the peak runoff rate (PR) and total runoff (R) volume are highly correlated ($R^2 = 0.99$). Since total runoff volume is typically easier to estimate than peak runoff rate, the peak runoff rate was eliminated from the predictive regression equation. All the other combinations showed lack of strong correlation ($R^2 \leq 0.49$).

Stepwise regression analysis:

Multiple regression equations were developed to predict sediment delivery ratio (SDR) for both the existing and hypothetical scenarios using the following independent variables: length, slope, Manning’s roughness coefficient, infiltration rate, rainfall volume, total runoff volume and storm duration. The results from the stepwise regression for the full, early and late growing season are presented below. All variables included were significant in explaining the model at the significance level of $p < 0.15$. The BoxCox transformation was used to find the best transformation for SDR.

The best fit regressions for the GWW from the outlet of watershed S5 with terraces for the full, early and late growing season time periods are equations 1, 2 and 3 respectively:

$$ SDR = (-0.017L) + (-0.12N) + (0.0035S) + (-0.0005I) + (0.0004P) + (0.00004R) + (-0.0011D) + 0.92 \quad R^2 = 0.35 $$

(1)
\[
SDR = (-0.005L) + (-0.09) + (0.003S) + (-0.0002I) + (0.001P) + (0.00003R) + (-0.004D) + 0.91 \quad R^2 = 0.38 \quad (2)
\]

\[
SDR = (-0.058L) + (-0.17N) + (0.004S) + (-0.001I) + (-0.003P) + (0.01R) + (-0.01D) + 1.17 \quad R^2 = 0.44 \quad (3)
\]

The best fit regressions for the GWW from the outlet of the hypothetical management scenario watershed without terraces, with corn, oat and alfalfa rotation and fall tillage using chisel plow for the full, early and late growing season time periods are 4, 5 and 6:

\[
SDR = (-0.15L) + (-1.93N) + (0.11S) + (-0.0009I) + (-0.002P) + (0.003R) + (0.02D) + 0.83 \quad R^2 = 0.60 \quad (4)
\]

\[
SDR = (-0.18L) + (-2.1N) + (0.11S) + (-0.001I) + (-0.009P) + (0.009R) + (0.04D) + 0.98 \quad R^2 = 0.67 \quad (5)
\]

\[
SDR = (-0.18L) + (-2.1N) + (0.11S) + (-0.001I) + (-0.009P) + (0.009R) + (0.04D) + 0.80 \quad R^2 = 0.49 \quad (6)
\]

Where, \(L\) – length (km), \(N\)- Manning’s roughness coefficient, \(S\) – Slope (%), \(I\) – infiltration rate (mm/hr), \(P\) – total rainfall (mm), \(R\) – total runoff (mm) and \(D\) – storm duration (hr).

Equations 4 and 5 for the GWW from the non-terraced watershed exhibited better \(R^2\) values, compared to their counterparts for the terraced watershed. This suggests that the channel and storm parameters were better able to explain the variation in SDR for the non-terraced case during the full and early growing season than the other cases. One possible explanation for this is the fact that non-terraced watershed had a more direct rainfall / runoff response than did the terraced watershed in which the SDR values were consistently high over all rainfall events. This is illustrated by the difference in the range of SDR values between the terraced and non-terraced watersheds summarized in Table 18. Terraced fields behave differently in terms of sediment delivery to their outlets because much of the upland sediment is trapped by the terraces resulting in reduced sediment yield compared to non-terraced fields. The non-terraced watershed produced an average sediment yield of 4.2 t/acre, while the average from the terraced watershed was only
0.2 t/acre over the 20 year simulation period. The deposition occurring in the terraces removed larger particles favoring a finer particle size distribution reaching the GWW which was more easily and consistently transported. This is illustrated in Table 18 by the smaller range in SDR for the terraced compared to non-terraced system.

It was interesting to note that the SDR equations for the late growing season had similar $R^2$ values of 0.44 and 0.49 for equations 3 and 6, respectively. In addition, the $R^2$ values for the terraced watershed were all similar while for the non-terraced watershed the $R^2$ for the late season (0.49) was much lower than the early season (0.67) and full season (0.60). This could be explained by reduced runoff volume and sediment yield during later growing season as the plant canopy develops compared to the early season. Greater canopy density results in a reduced direct runoff response to rainfall and in-turn reduced statistical predictive power. This is likely the same mechanism operating in the terraced watershed and is supported by the reduced late season runoff volume and range in Table 18. In addition, all of the equations show that the SDR decreases with increasing channel length, Manning’s roughness coefficient, and infiltration and increases with increased slope. Higher Manning’s roughness coefficient decreases flow velocity, increasing hydraulic resonance time which favors sedimentation as do longer channel lengths. Steeper slopes will deliver more sediment as steeper slopes increase flow velocity and transport energy, while increased infiltration removes water and sediment from the channel, decreasing delivery.

For both the terraced and non-terraced cases, Manning’s roughness coefficient was the most significant predictor of SDR. The physical and temporal variability inherent with Manning’s roughness coefficient further complicates delivery calculations. For the early growing season and the non-terraced watershed (highest $R^2$), the most significant SDR channel physical parameters were Manning’s roughness coefficient, followed by length, followed by slope then infiltration.
While infiltration rate directly affects the runoff and hence sediment delivery, in the model there is no direct relationship between infiltration rate and sediment delivery, thus rendering it least important. For the channel from the terraced watersheds runoff was the most significant hydrologic parameter. This was expected as terraces can reduce runoff significantly, resulting in lower sediment yield, and therefore making it the most sensitive parameter.

It is important to note that these equations were developed assuming that GWWs do not act as a sediment source. In other words only deposition occurs in the channel and there is no scouring. These equations are also limited to ephemeral GWWs and are not applicable to perennial channels. The regressions are also not applicable to channels containing wetland vegetation due its high roughness and flow retardance. The Manning’s roughness coefficient for wetland vegetation can reach values up to 0.7 (Hall and Freeman, 1994) depending on the stem density and flow conditions. In our case the upper limit for the Manning’s roughness coefficient was 0.3, which is below the range for wetland vegetation.

4.5 Summary and Conclusion

Accurate estimation of sediment delivery from the upland areas through GWWs is important to effectively target management practices. This study used the WEPP model to develop regression equations for estimating sediment delivery through a GWW connecting upland areas to the receiving waters. WEPP was calibrated and validated for runoff and sediment yield at the outlets of two nested watersheds in Southwestern WI. The model was able to predict runoff and sediment yield accurately at both watershed outlets. The calibrated and validated model was used to represent a GWW connecting the smaller (5.7 ha) nested watershed to the larger watershed outlet. The channel length, slope, Manning’s roughness coefficient and infiltration rate were varied
over specified ranges in order to estimate their effect on the sediment delivery ratio (SDR). The model was run for 20 years of climate data producing an 8,125 point data set that included terraced and non-terraced watersheds. Both the watersheds followed corn, oat and alfalfa rotation with chisel plow as fall tillage. Thirty storms covering a representative range of magnitudes of the storms of Southwestern WI were selected from the 20 year output.

Equations developed showed that channel parameters such as length, Manning’s roughness coefficient and slope along with storm characteristics were able to explain the variation in SDR. Regressions were developed for the early (Apr – Jul), late (Jul. – Oct.) and full (Apr. – Oct.) growing season time periods. The SDR regression for the non-terraced watershed draining into the GWW during the early growing season time period resulted in the best predictive regression ($R^2 = 0.67$) range of 0.49 – 0.67, while the $R^2$ values for the terraced watershed were lower (0.35 – 0.44). This could be explained by the fact that non-terraced watershed had a more direct rainfall / runoff response than did the terraced watershed. Terraced fields behave differently in terms of sediment delivery to their outlets because much of the upland sediment is trapped by the terraces resulting in reduced sediment yield. For both the terraced and non-terraced cases, Manning’s roughness coefficient was the most significant predictor of SDR.

One of the biggest limitations while developing sediment delivery equations is the lack of reliable sediment delivery monitoring data that could be used to develop and validate predictive equations. While we relied on a validated process-based model for generating sediment delivery ratios, it is a short term solution. Additional monitoring data is required to develop and verify predictive sediment delivery equations.
4.6 References


Table 16. Average monthly temperature and precipitation for Southwest Wisconsin for the period from 1895 – 2005 along with the annual averages (http://www.aos.wisc.edu/~sco/clim-history/division/4707-climo.html).

<table>
<thead>
<tr>
<th></th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>-8.7</td>
<td>-6.5</td>
<td>0.0</td>
<td>7.8</td>
<td>14.2</td>
<td>19.5</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>26.9</td>
<td>27.9</td>
<td>50.0</td>
<td>76.5</td>
<td>96.5</td>
<td>112.8</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>22.1</td>
<td>20.8</td>
<td>16.2</td>
<td>9.8</td>
<td>1.5</td>
<td>-5.7</td>
<td>7.6</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>103.1</td>
<td>97.0</td>
<td>97.0</td>
<td>59.2</td>
<td>52.3</td>
<td>31.8</td>
<td>831.1</td>
</tr>
</tbody>
</table>
Table 17. Channel and climate parameters and ranges used in the WEPP model simulations for grassed waterways.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope (%) (S)</td>
<td></td>
<td>1.0 – 5.0</td>
</tr>
<tr>
<td>Length (km) (L)</td>
<td></td>
<td>0.15 – 1.0</td>
</tr>
<tr>
<td>Manning’s roughness coefficient (N)</td>
<td></td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Infiltration rate (mm/hr) (I)</td>
<td></td>
<td>0.025 – 25</td>
</tr>
</tbody>
</table>
Table 18. Precipitation, runoff and SDR medians and ranges for the early, late and full growing season time periods used in the WEPP model simulations for grassed waterways.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Early Season</th>
<th>Late Season</th>
<th>Full Season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Range</td>
<td>Median</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>48.1</td>
<td>5.1 - 104.7</td>
<td>54.3</td>
</tr>
<tr>
<td>Runoff (mm)</td>
<td>19.5</td>
<td>0.04 – 73.6</td>
<td>26.7</td>
</tr>
<tr>
<td>Duration (hr)</td>
<td>3.6</td>
<td>0.95 – 9.6</td>
<td>4.9</td>
</tr>
<tr>
<td>SDR (terraced)</td>
<td>0.96</td>
<td>0.74 – 1.00</td>
<td>0.93</td>
</tr>
<tr>
<td>SDR (non-terraced)</td>
<td>0.59</td>
<td>0.02 – 1.00</td>
<td>0.67</td>
</tr>
</tbody>
</table>
Table 19. Model performance statistics for runoff and sediment yield at S5 and S4 watershed outlets during calibration and validation at Pioneer Farm. Model performance statistics without the storm on 20 April 2004 are in ( ).

<table>
<thead>
<tr>
<th></th>
<th><strong>S5 Watershed</strong></th>
<th></th>
<th><strong>S4 Watershed</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>calibration</td>
<td>validation</td>
<td>Calibration</td>
<td>validation</td>
</tr>
<tr>
<td></td>
<td>runoff</td>
<td>Sediment yield</td>
<td>runoff</td>
<td>Sediment yield</td>
</tr>
<tr>
<td><strong>R2</strong></td>
<td>0.91 (0.71)</td>
<td>0.98 (0.76)</td>
<td>0.81</td>
<td>0.74</td>
</tr>
<tr>
<td><strong>Ens</strong></td>
<td>0.82 (0.64)</td>
<td>0.88 (0.71)</td>
<td>0.72</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>RMSE</strong></td>
<td>70.6 (39.34)</td>
<td>461.3 (126.3)</td>
<td>82.1</td>
<td>150.2</td>
</tr>
</tbody>
</table>
Table 20. Pearson correlation coefficient ($R^2$) values for paired explanatory independent variables from the multicollinearity test.

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>N</th>
<th>S</th>
<th>I</th>
<th>P</th>
<th>R</th>
<th>PR</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1.00</td>
<td>0.02</td>
<td>-0.03</td>
<td>0.01</td>
<td>-0.01</td>
<td>0.09</td>
<td>0.10</td>
<td>0.01</td>
</tr>
<tr>
<td>N</td>
<td>0.02</td>
<td>1.00</td>
<td>0.12</td>
<td>-0.05</td>
<td>0.05</td>
<td>0.22</td>
<td>0.25</td>
<td>0.12</td>
</tr>
<tr>
<td>S</td>
<td>-0.03</td>
<td>0.12</td>
<td>1.00</td>
<td>0.05</td>
<td>-0.08</td>
<td>-0.29</td>
<td>-0.23</td>
<td>-0.14</td>
</tr>
<tr>
<td>I</td>
<td>0.01</td>
<td>-0.05</td>
<td>0.05</td>
<td>1.00</td>
<td>0.04</td>
<td>-0.09</td>
<td>-0.10</td>
<td>-0.02</td>
</tr>
<tr>
<td>P</td>
<td>-0.01</td>
<td>0.05</td>
<td>-0.08</td>
<td>0.04</td>
<td>1.00</td>
<td>0.49</td>
<td>0.44</td>
<td>0.10</td>
</tr>
<tr>
<td>R</td>
<td>0.09</td>
<td>0.22</td>
<td>-0.29</td>
<td>-0.09</td>
<td>0.49</td>
<td>1.00</td>
<td>0.99</td>
<td>0.24</td>
</tr>
<tr>
<td>PR</td>
<td>0.10</td>
<td>0.26</td>
<td>-0.23</td>
<td>-0.10</td>
<td>0.45</td>
<td>0.99</td>
<td>1.00</td>
<td>0.24</td>
</tr>
<tr>
<td>D</td>
<td>0.01</td>
<td>0.12</td>
<td>-0.14</td>
<td>-0.02</td>
<td>0.10</td>
<td>0.24</td>
<td>0.24</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Fig. 13 Location of the Pioneer Farm in southwestern Wisconsin along with the study site watersheds S5 and S4 and grassed waterway drainage network at the Pioneer Farm.
Fig. 14 WEPP flow path representation of watersheds (a) S5 and (b) S4 at the Pioneer Farm; (H = hillslope, C = Channel).
Fig. 15 WEPP flow path representation for the S5 watershed outlet channel at the Pioneer Farm.
Fig. 16 Comparison between observed and simulated storm event runoff and sediment yield during the calibration (a and b) and validation (c and d) periods for watershed S5 at Pioneer Farm.
Fig. 17 Comparison between observed and simulated storm event runoff and sediment yield during the calibration (a and b) and validation (c and d) periods for watershed S4 at Pioneer Farm.
Chapter 5

5. Conclusions

5.1 Synthesis

The study was conducted to improve understanding and prediction of sediment yield from agricultural watersheds to receiving waters through a conveyance mechanism (such as a grassed waterway) using ANN models, field experiments and physically-based models. ANN models were developed for estimating runoff and sediment yield from upland agricultural watersheds. Relationships were developed between soil moisture and critical shear stress to improve estimates of soil erosion from agricultural fields and grassed waterways. Finally, regression equations were developed to estimate sediment delivery from agricultural watersheds (source areas) to receiving watersheds. The major overall conclusions of the study were:

(1) ANN models can be used to accurately estimate runoff and sediment yield from agricultural watersheds. In addition to watershed and storm characteristics, input parameters representing management practices are important in developing the models.

(2) Critical shear stress of soil within grassed waterways and agricultural fields is not constant but rather changes with soil moisture, and

(3) Sediment delivery ratios for grassed waterways can be estimated using channel characteristics such as length, Manning’s roughness coefficient, slope and infiltration along with storm characteristics.
5.2 Dynamic critical shear stress in WEPP

Critical shear stress equations developed in Chapter 3 can be used to improve prediction of erosion and sediment yield by physically-based models such as WEPP. In this section, an example is presented to show the effect of changes in antecedent moisture content on critical shear stress and subsequently on sediment yield generated by using the equations developed in Chapter 3 in conjunction with WEPP.

The WEPP model was run for S4 watershed for a single storm on 13 April 2014 that produced precipitation of 64.3 mm. The model resulted in runoff volume of 145.8 m$^3$ and sediment yield of 154.6 kg for the default values of model parameters. The moisture content during the storm increased from 19.3 to 31.7% in the grassed waterway (Table 21). Soil moisture in the field during the storm was estimated using the plot between the observed soil moisture measurements in the grassed waterway and agricultural field from Chapter 3 (Fig. 18). The critical shear stress equations developed for the agricultural field and the grassed waterway (Chapter 3) were used to estimate critical shear stress for minimum, maximum and average soil moisture contents on that day. WEPP model was run again using each of the three critical shear stress values separately. The results showed that while the use of average soil moisture resulted in sediment yield of 154.6 kg (same as default), sediment yield estimates can vary from 25.6 kg to 517.5 kg depending on soil moisture content. This example shows that antecedent soil moisture affect sediment yield significantly.

A single storm was used to illustrate the effect of moisture content on sediment yield because continuous simulation of longer periods would require continuous adjustment of critical shear stress as soil moisture changes; a substantial programming effort to change the WEPP codes.
Similar adjustments could be made in other physically-based models in order to simulate dynamic changes in sediment yield generation during a storm.

5.3 Comparison of WEPP and ANN

The performances of the WEPP and ANN models in predicting runoff and sediment yield was compared for the nested watersheds S4 and S5. Figures 19 and 20 presents the observed and predicted runoff and sediment yields, respectively for years 2003 and 2004. The scatter plots in Figure 19 show that both models did a good job of predicting runoff for the S5 and S4 watersheds. Figure 20 shows that both models also predicted sediment yield for the watersheds reasonably well. However, the ANN model predicted negative sediment yield for events with lower observed sediment yield. Since it is not physically possible to have sediment yield below zero, this exemplifies one of the flaws of the ANN model which does not consider physical processes. This shows that while both models can be used for estimating runoff and sediment yield for the watershed, it is imperative to use process-based models in studies where detailed understating of sediment transport is required.

Model performances were further tested using statistical measures such as $R^2$, $E_{NS}$, and RMSE (Table 22). The ANN model was able to simulate runoff and sediment yield more accurately (Higher $R^2$ and $E_{NS}$; lower RMSE) as compared to the WEPP model for the smaller S5 watershed. For the larger S4 watershed, WEPP did slightly better than ANN in simulating runoff and sediment yield. This could be attributed to the fact that most of the watersheds that were used for training the ANN models were more similar to the smaller watershed S4 (in terms of drainage area). Overall all performance measures supported the visual finding that both models can be used to effectively estimate runoff and sediment yield.
5.4 Conclusions

Results from the first chapter showed that ANN models can be used to accurately predict runoff and sediment yield from agricultural watersheds that consists of BMPs such as terraces, strip cropping and grassed waterways. The sensitivity analysis for the BMP parameters, indicated that (i) runoff is most sensitive to length of the grassed waterway and channel density and (ii) upland management such as cropping and tillage are the most sensitive parameters for sediment yield model. The models developed in this study can be used to make decisions for cost-effective selection of BMPs to improve water quality.

The results from the study of the effect of antecedent soil moisture on critical shear stress (Chapter 3) indicated that critical shear stress varies with the changes in soil moisture content. Critical shear stress increases with increase in soil moisture until the soil moisture content reached the plastic limit. The results also highlighted that critical shear stress is lower for disturbed soil in the agricultural field compared to the more undisturbed soil in the grassed waterway. The exponential relationships developed between critical shear stress and soil moisture can be used to improve estimation of detachment capacity and hence soil erosion during varying soil moisture conditions.

Regression equations developed during this study (Chapter 4) showed that variation in sediment delivery ratios for grassed waterways can be explained by channel parameters such as length, Manning’s roughness coefficient and slope along with the storm characteristics. Regression equations for the grassed waterway draining the non-terraced watershed during the early growing season (April - July) had the best predictive regression ($R^2 = 0.67$) compared to other time periods ($R^2$ ranged from 0.49 to 0.67) and for the grassed waterway draining the terrace watershed $R^2$ ranged from 0.35 to 0.44. The higher $R^2$ values for the non-terraced compared to terraced
watershed could be attributed to the fact that the non-terraced watershed had a more direct rainfall / runoff response than did the terraced watershed leading to higher range of SDR values. Manning’s roughness coefficient was the most sensitive parameter for the SDR equations for both terraced and non-terraced cases.

5.5 Future Research

Chapter 2 focused on development of ANN models for agricultural watersheds with BMPs that can predict runoff and sediment yield. The study was limited to watersheds with a narrow slope range (5% to 6.2%). Future research could be conducted to develop models for watersheds representing a broader range of slopes which might result in slope being included as an important input parameter. The study could also be extended to include watersheds with varying soil types. This could help in developing a more robust model applicable to more watersheds.

In Chapter 3 we developed relationships between soil moisture and critical shear. As highlighted in the chapter, soil moisture can affect the detachment capacity and hence soil erosion significantly. However, most of physically-based models used to estimate sediment yield do not take into account the direct effect of soil moisture variation on this soil physical parameter. Future studies may focus on incorporating these relationships into the physically-based models in order to improve their predictive quality.

We developed equations for estimating sediment delivery ratios for channels connecting upland agricultural areas to the receiving waters in Chapter 4. While we used the WEPP model to obtain the dataset for developing these equations, future studies may be conducted to monitor
isolated channel systems for obtaining observed sediment delivery data. Future studies can also focus on using these equations along with other nutrient management tools like SNAP-Plus for estimating the delivery of nutrient such as phosphorus and other chemicals from the upland source areas into the receiving waters. In future this study can be extended to other physiographic regions of Wisconsin.
Table 21. Effect of varying critical shear stress on runoff and sediment yield generated by WEPP due to variation in soil moisture on 13 April 2014.

<table>
<thead>
<tr>
<th></th>
<th>Soil Moisture (Field) (%)</th>
<th>Critical Shear from Table 14 (Field) (Pa)</th>
<th>Soil Moisture (GWW) (%)</th>
<th>Critical Shear from Table 14 (GWW) (Pa)</th>
<th>Runoff (m$^3$)</th>
<th>Sediment Yield (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>13.0</td>
<td>1.5</td>
<td>19.3</td>
<td>2.2</td>
<td>145.8</td>
<td>517.5</td>
</tr>
<tr>
<td>Max</td>
<td>23.6</td>
<td>2.8</td>
<td>31.7</td>
<td>4.6</td>
<td>145.8</td>
<td>25.6</td>
</tr>
<tr>
<td>Average</td>
<td>19.6</td>
<td>2.2</td>
<td>27.0</td>
<td>3.5</td>
<td>145.8</td>
<td>154.6</td>
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Table 22. Model performance statistics for runoff and sediment yield at S5 and S4 watershed outlets using WEPP and ANN.

<table>
<thead>
<tr>
<th></th>
<th>Watershed S4</th>
<th></th>
<th>Watershed S5</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Runoff</td>
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Fig. 18 Comparison between observed soil moisture in the grassed waterway and agricultural field.

\[ y = 0.8487x - 3.3068 \]

\[ R^2 = 0.6623 \]
Fig. 19 Comparison of observed and simulated runoff using WEPP and ANN models for (a & b) watershed S4 and (c & d) watershed S5, respectively.
Fig. 20 Comparison of observed and simulated sediment yield using WEPP and ANN models for (a & b) watershed S4 and (c & d) watershed S5, respectively.
## Appendix A: Storm Event Data

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## Appendix B: Crop Growth Records

### Pioneer Farm Crop Growth

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</tr>
</tbody>
</table>

Field 26

<table>
<thead>
<tr>
<th>Date</th>
<th>Operation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/6/2004</td>
<td>Tillage</td>
<td>Soil Finisher</td>
</tr>
<tr>
<td>4/8/2004</td>
<td>Plant</td>
<td>Oats, Alfalfa; Morain, Dekalb 134</td>
</tr>
<tr>
<td>8/14/2004</td>
<td>Harvest</td>
<td>Oats, no yield reported</td>
</tr>
<tr>
<td>10/5/2004</td>
<td>Harvest</td>
<td>Alfalfa, 1.1 dry tons/ac</td>
</tr>
<tr>
<td>5/31/2005</td>
<td>Harvest</td>
<td>Alfalfa, 2.5 dry tons/ac</td>
</tr>
<tr>
<td>6/28/2005</td>
<td>Harvest</td>
<td>Alfalfa, 1.9 dry tons/ac</td>
</tr>
<tr>
<td>8/3/2005</td>
<td>Harvest</td>
<td>Alfalfa, 1.6 dry tons/ac</td>
</tr>
<tr>
<td>5/22/2006</td>
<td>Harvest</td>
<td>Alfalfa, no yield reported</td>
</tr>
<tr>
<td>7/4/2006</td>
<td>Harvest</td>
<td>Alfalfa, no yield reported</td>
</tr>
<tr>
<td>8/4/2006</td>
<td>Harvest</td>
<td>Alfalfa, no yield reported</td>
</tr>
<tr>
<td>9/23/2006</td>
<td>Harvest</td>
<td>Alfalfa, no yield reported</td>
</tr>
<tr>
<td>5/8/2007</td>
<td>Tillage</td>
<td>Chisel Plow</td>
</tr>
<tr>
<td>5/9/2007</td>
<td>Tillage</td>
<td>Soil Finisher</td>
</tr>
<tr>
<td>5/9/2007</td>
<td>Plant</td>
<td>Corn, Dekalb 5263, 30 inch rows, 32000 seeds/ac</td>
</tr>
<tr>
<td>9/25/2007</td>
<td>Harvest</td>
<td>Corn, no yield reported</td>
</tr>
<tr>
<td>5/4/2008</td>
<td>Tillage</td>
<td>Soil Finisher</td>
</tr>
<tr>
<td>5/9/2008</td>
<td>Plant</td>
<td>Corn</td>
</tr>
<tr>
<td>10/26/2008</td>
<td>Harvest</td>
<td>Corn</td>
</tr>
<tr>
<td>10/31/2008</td>
<td>Tillage</td>
<td>Chisel Plow</td>
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</table>
### Discovery Farm Crop Growth

#### Field 160 A

<table>
<thead>
<tr>
<th>Date</th>
<th>Operation</th>
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</tr>
</thead>
<tbody>
<tr>
<td>4/29/2004</td>
<td>Plant</td>
<td>Corn, Trelay 8P373, 30 inch rows, 32000 seeds/ac</td>
</tr>
<tr>
<td>9/14/2004</td>
<td>Harvest</td>
<td>Corn, 180 bu/ac</td>
</tr>
<tr>
<td>5/6/2005</td>
<td>Plant</td>
<td>Soybean, Trelay 2222RR, 15 inch rows, 175000 seeds/ac</td>
</tr>
<tr>
<td>9/23/2005</td>
<td>Harvest</td>
<td>Soybean, 66 bu/ac</td>
</tr>
<tr>
<td>4/24/2006</td>
<td>Plant</td>
<td>Corn, Trelay SP941, 30 inch rows, 32000 seeds/ac</td>
</tr>
<tr>
<td>9/28/2006</td>
<td>Harvest</td>
<td>Corn, 205 bu/ac</td>
</tr>
<tr>
<td>5/2/2007</td>
<td>Plant</td>
<td>Corn, Trelay SP941, 30 inch rows, 32000 seeds/ac</td>
</tr>
<tr>
<td>9/20/2007</td>
<td>Harvest</td>
<td>Corn, 200 bu/ac</td>
</tr>
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</table>

#### Field 160 B

<table>
<thead>
<tr>
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<th>Operation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/6/2004</td>
<td>Plant</td>
<td>Soybean, Trelay 2222RR, 15 inch rows, 175000 seeds/ac</td>
</tr>
<tr>
<td>9/25/2004</td>
<td>Harvest</td>
<td>Soybean, 62 bu/ac</td>
</tr>
<tr>
<td>4/28/2005</td>
<td>Plant</td>
<td>Corn (Silage), Trelay SP941, 30 inch rows, 32000 seeds/ac</td>
</tr>
<tr>
<td>9/5/2005</td>
<td>Harvest</td>
<td>Corn (Silage), 10 dry tons/ac</td>
</tr>
<tr>
<td>4/26/2006</td>
<td>Plant</td>
<td>Corn (Silage), Trelay SP941, 30 inch rows, 32000 seeds/ac</td>
</tr>
<tr>
<td>9/15/2006</td>
<td>Harvest</td>
<td>Corn (Silage), 9.5 dry tons/ac</td>
</tr>
<tr>
<td>5/5/2007</td>
<td>Plant</td>
<td>Soybean, Trelay 2222RR, 15 inch rows, 175000 seeds/ac</td>
</tr>
<tr>
<td>9/29/2007</td>
<td>Harvest</td>
<td>Soybean, 70 bu/ac</td>
</tr>
</tbody>
</table>

#### Field 160 C

<table>
<thead>
<tr>
<th>Date</th>
<th>Operation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/29/2004</td>
<td>Plant</td>
<td>Corn, Trelay 8P373, 30 inch rows, 32000 seeds/ac</td>
</tr>
<tr>
<td>9/14/2004</td>
<td>Harvest</td>
<td>Corn, 180 bu/ac</td>
</tr>
<tr>
<td>5/6/2005</td>
<td>Plant</td>
<td>Soybean, Trelay 2222RR, 15 inch rows, 175000 seeds/ac</td>
</tr>
<tr>
<td>9/23/2005</td>
<td>Harvest</td>
<td>Soybean, 66 bu/ac</td>
</tr>
<tr>
<td>4/24/2006</td>
<td>Plant</td>
<td>Corn, Trelay SP941, 30 inch rows, 32000 seeds/ac</td>
</tr>
<tr>
<td>9/28/2006</td>
<td>Harvest</td>
<td>Corn, 205 bu/ac</td>
</tr>
<tr>
<td>5/2/2007</td>
<td>Plant</td>
<td>Corn, Trelay SP941, 30 inch rows, 32000 seeds/ac</td>
</tr>
<tr>
<td>9/20/2007</td>
<td>Harvest</td>
<td>Corn, 200 bu/ac</td>
</tr>
</tbody>
</table>