This is to certify that the

dissertation entitled

MODELING SEDIMENT AND PHOSPHORUS LOADING IN
A SMALL AGRICULTURAL WATERSHED

presented by

Da Ouyang

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Crop and Soil Sciences

Major professor

Date 7/31/01

MODELING SEDIMENT AND PHOSPHORUS LOADING IN A SMALL AGRICULTURAL WATERSHED

By

Da Ouyang

AN ABSTRACT OF A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Crop and Soil Sciences

2001

Professor Jon F. Bartholic

ABSTRACT

MODELING SEDIMENT AND PHOSPHORUS LOADING IN
A SMALL AGRICULTURAL WATERSHED

By

Da Ouyang

Agricultural nonpoint source pollution is considered the leading cause for water pollution in the United States. Sediment and phosphorus are two major pollutants that are responsible for water pollutions. While soil erosion degrades soil productivity, it causes water quality problem through sediment and nutrients. Excessive fertilization, particularly from phosphorus, leads to eutrophication which deteriorates surface water quality. Efforts have been made to minimize agricultural nonpoint source pollution by, for example, implementing best management practices. Controlling agricultural nonpoint source pollution requires good information and knowledge on identifying the source areas and quantifying the pollutant loadings. A water monitoring program is helpful but costly. A scientifically based model can provide an alternative approach to provide a quantitative estimation on soil erosion, sediment and nutrient loadings, and to help identify the source areas.

The goal of this research is to investigate various agricultural nonpoint source pollution models, and develop a GIS based and spatially distributed approach to better estimate soil erosion, sediment and phosphorus loading in an agricultural watershed context.

A small agricultural watershed, Marshall Drain Watershed, was selected as the study area. This watershed is approximately 400 acres with 90 percent agricultural land use. It is a subwatershed of the Sycamore Creek watershed, located in Ingham county, Michigan. Agricultural nonpoint source pollution, particularly sediments, has been identified as the major cause of water pollution in the watershed. A multi-year water quality and land use/tillage management monitoring program has been conducted in the watershed from 1990-1997. Data from this monitoring program are used in this study.

A Spatially Explicit Sediment Delivery Model (SEDMOD) and the modified Revised Universal Soil Loss Equation (MRUSLE) are used in this study. These two models are integrated into Sediment and Phosphorus Loading Model (SPLM). It is GIS based and capable of calculating soil erosion, sediment yield and phosphorus loading. The results showed SPLM estimated sediment and phosphorus loading with an improved accuracy compared to other models. Input data required to run the model are minimum and readily available. The results of this research demonstrate the benefits of using a spatially explicit model combined with GIS technology. SPLM allows users to identify the source areas and estimate NPS loadings which may lead to a cost-effective watershed planning and management for minimizing agricultural nonpoint source pollution.

To my wife Sumei and daughter Jessica

ACKNOWLEDGEMENTS

First of all, I want to thank my wife Sumei for her constant support and encouragement, and my parents who have never given up on me even in those difficult years in China. Without their support, urging and understanding, this dissertation would not be possible.

I thank my major advisor and supervisor Dr. Jon Bartholic for supporting me financially and emotionally, and for offering me an opportunity to work full-time at the Institute of Water Research while I was completing my dissertation. I also want to thank my advisory committee members Dr. Richard Harwood, Dr. Delbert Mokma, and Dr. Stuart Gage for their time, patience and guidance throughout my Ph.D. program.

My thanks are extended to John Suppnick at Michigan Department of Environmental Quality, who generously provided me all the water quality monitoring data in this study. I thank Jerry Grigar, State Agronomist at USDA-NRCS, for his many helpful discussions about soil erosion models. I also want to express my appreciation to Bob Hicks at USDA-NRCS Mason Office for sharing his knowledge about the study watershed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 Overview

1.1.1 Problem Statement

Since the 1970s, following the passage of the Clean Water Act (CWA), great progress has been made in controlling point source pollution, especially from industrial facilities and municipal discharges. Nonpoint source (NPS) pollution has now become the leading cause of surface water degradation in the United States. Nonpoint source pollution is generally referred to the pollution resulting from diffuse sources. The single major nonpoint source pollution comes from agricultural cropland. According to the U. S. Environmental Protection Agency's (USEPA) National Water Quality Inventory reported to Congress, agricultural nonpoint source pollution is responsible for the impairment of 60 percent of the impaired river miles and 50 percent of lake acres in the United States (USEPA 1994). Although progress has been made over the past few years, agricultural nonpoint source pollution has been continuously considered as the No. 1 source for water pollution in rivers and lakes according to a series of EPA's 1994, 1996 and 1998 reports for the National Water Quality Inventory (USEPA 1994, 1996, 1998, 2000).

The primary water quality problems from agricultural nonpoint source pollution are sediment and nutrients. Soil erosion not only degrades agricultural productivity, sediment-bound pollutants such as phosphorus also cause the major pollution concern in surface waters. Contribution of nonpoint source pollution from agricultural land use has been estimated at 64% of total suspended sediment and 76% of total phosphorus (Duda and Johnson, 1985). Overenrichment of nutrients in freshwater stimulates algal and rooted aquatic plant growth, and results in oxygen depletion, fish kills, odor problem and consequently eutrophication (Lee, 1971). Eutrophication impairs the use of surface waters for recreation, fisheries, industry and drinking (Sharpley and Meyer, 1994; Sharpley et al. 1994). Environmental and economic impacts for controlling agricultural nonpoint source pollution are tremendous. It is estimated that the economic damage to surface water quality caused by sediment and nutrients from agricultural cropland ranges from 2.2 to 7 billion dollars each year in the United States (Lovejoy et al., 1997).

Soil erosion and sediment delivery are the key processes controlling NPS pollution in agricultural watersheds. Not all soil erosion will be delivered to waterways due to deposition. Actually, only a portion of soil loss from agricultural land is transported to a river. The process of soil erosion involves three steps: detachment of soil particles, transport, and deposition. Soil erosion by water can be categorized into sheet, rill, gully or channel, and stream bank erosion. When raindrops fall on soil surface and detach soil particles, the water runs over the soil surface and removes particles in a thin layer, which causes sheet erosion. Rill erosion occurs where water concentrates to form small channels. Erosion from large channels due to large water concentration causes gully erosion (Foster 1986). Sheet and rill erosion are the main sources of erosion from agricultural land. Widely used soil erosion model, Universal Soil Loss Equation (USLE), was developed primarily for predicting sheet and rill erosion.

Phosphorus is one of the major pollutants from agricultural nonpoint sources. Although there are many forms of phosphorus, the particulate phosphorus or sediment attached phosphorus is the most common form in which phosphorus components move with eroded soil particles. Previous studies suggest that high phosphorus losses from croplands are associated with intensive row crop agriculture, fertilizer additions and tillage, etc. (Nelson, and Logan 1983).

1.1.2 Research Needs

Because of the diffuse nature of NPS pollution, challenges remain in identifying, assessing and controlling NPS pollution. The processes of NPS pollution and effectiveness of various NPS control technologies are not fully understood. While numerous models have been developed in the past three decades, few has been evolved as national standardized procedure for NPS pollution assessment. Among the U.S. government agencies, for example, USEPA and the U.S. Department of Agriculture (USDA) use their own different models/ approaches/ procedures for nonpoint source pollution assessment. Most of nonpoint source pollution models either require extensive input data, or lack of integration of new technologies available today such as geographic information system (GIS) which helps spatial analysis, or lack of necessary accuracy in assessing sedimentation. Especially, for estimating sediment delivery ratio and sediment load, most models are spatially lumped models, which lack capabilities to identify source areas or high risk areas. Developing a spatially distributed approach to better estimate soil erosion and sediment/phosphorus loading with minimum and readily available data sets is needed.

A single storm event loading model for estimating nonpoint source pollution is essential to determine the allocation of pollutant loadings among point and nonpoint sources to meet the Total Maximum Daily Load (TMDL) standard. The federal regulations require the states to identify the waters that require TMDL and rank/prioritize those impaired waters (USEPA 1999). The so-called 303(d) list is the list of impaired waters (stream segments and lakes) that are submitted to USEPA by the states under Section 303(d) of the Clean Water Act. Development of spatially distributed model with an ability to estimate sediment load for single storm events will help to better identify and prioritize the areas with impaired waters.

Some NPS models have been developed for assessing nonpoint source pollution such as Agricultural Nonpoint Source Pollution Model (AGNPS) (Young, et al. 1978), Soil and Water Assessment Tool (SWAT) (Arnold et al. 1996), among others. These models can estimate NPS pollution such as soil loss, sediment, nutrient, and pesticide losses. The major drawbacks for using these models include extensive input data requirement and lack of accuracy for quantitative estimation of nonpoint source pollution in agricultural watersheds. Studies from Michigan Department of Environmental Quality (MDEQ) showed that estimated average annual sediment loading using AGNPS was 88% - 94% higher than the monitored data in their study watershed (Suppnick 1999). In addition, Needham (1999) has concluded from his study that Annualized AGNPS (ANN-AGNPS) is incapable of accurately estimating NPS loadings. Further research is clearly needed to improve the applicability and the accuracy of the modeling approaches.

Walling (1983) pointed out that two major problems existed in the current sediment delivery and soil erosion models: temporal lumping and spatial lumping. Temporal lumping models aggregate the individual storms and attempt to average out the variations among them. Spatial lumping models, on the other hand, provide a single value for the entire watershed without considering the variations on local conditions. In this study, spatially explicit sediment delivery ratio model is integrated with the modified Revised Universal Soil Loss Equation for estimating sediment and phosphorus load, which takes into account the temporal and spatial variations in the watershed.

1.2 Research Objectives

The goal of this research was to investigate various agricultural nonpoint source pollution models, and develop a GIS based and spatially distributed approach to better estimate soil erosion, sediment and phosphorus loading on a watershed basis.

Objectives of this study are (1) to investigate the various NPS models for soil erosion and sediment delivery calculations; (2) to modify the Revised Universal Soil Loss Equation (RUSLE) so that it is suitable to estimate soil erosion for single storm events; (3) integrate the Modified RUSLE (MRUSLE) and Spatially Explicit Sediment Delivery MODel (SEDMOD) for estimating sediment yield and phosphorus loading; and (4) compare and evaluate this integrated spatial modeling approach with other selected models using monitoring data available in the study watershed.

This study provides an alternative modeling approach for assessing NPS pollution and identifying its source areas in agricultural watersheds using existing data. The outcomes of this study may help watershed planners, resource managers and local governmental and federal agencies and field staff to prioritize the critical areas needing technical assistance, and implement best management practices to minimize soil erosion, sediment and nutrient loading and its impacts on water quality.

1.3 Thesis Organization

This thesis is divided into five chapters. Chapter one gives an overview of nonpoint source pollution problems that exist today, research needs and objectives. Chapter two presents the literature review regarding various NSP models including major agricultural NPS models, soil erosion models, sediment delivery ratio models, and sediment yield and phosphorus loading estimation methods. Chapter three describes the methods and data used in this study, including description of the study watershed, data source, and data processing for soil erosion, sediment delivery and phosphorus loading calculations. Chapter four provides the research results as well as discussion on the significance of these results including comparison of results from several different models with the water monitoring data in the study watershed. Chapter five provides with conclusions drawn from this study and commendations for future study.

CHAPTER TWO

LITERATURE REVIEW

A number of models have been developed to calculate the sediment delivery ratio and sediment yield. Many nonpoint source pollution models provide more comprehensive simulations on hydrology, sedimentation, and biological and chemical processes. They can generally be grouped into two catalogs. One is called statistical or empirical models such as the Universal Soil Loss Equation (USLE). These kinds of models are statistically established based on observed data, and are usually easier to use and computationally efficient. The other kinds of models can be called parametric, deterministic, or physically based models, such as Water Erosion Prediction Project (WEPP). These models are developed based on the fundamental hydrological and sedimentological processes. They may provide detailed simulation with many different sub-components, but usually require extensive data input and are not easy to use. The following sections will describe a few agricultural nonpoint source pollution models including both empirically and physically based models. The soil erosion and sediment delivery components used in the NPS models are also reviewed.

2.1 Soil Erosion Models

2.1.1 USLE – Universal Soil Loss Equation

Research on soil erosion and its effect on agricultural productivity started in 1930s. During 1940s and 1950s, research scientists began to develop a quantitative procedure for estimating soil loss in the Corn Belt in the United States. Several factors were introduced to an early soil loss equation, in which slope and practice were primarily considered. A rainfall factor was later added in the erosion equation (Wischmeier and Smith 1978). In 1954, the U.S. Department of Agriculture, Agricultural Research Service (ARS) established the National Runoff and Soil Loss Data Center at Purdue University to locate, assemble, and consolidate all available data throughout the United States. More than 10,000 plot-years of basic runoff and soil loss data were then collected from U.S. federal-state cooperative research projects in 49 U.S. locations. Based on the data assembled at the Data Center and studies conducted by other soil scientists, Wischmeier, Smith, and others developed the Universal Soil Loss Equation (USLE) using six factors. An agriculture handbook describing USLE was published in 1965 (Agriculture Handbook 282) and revised in 1978 (Agriculture Handbook 537) (Wischmeier and Smith 1978). USLE has been widely used as the major conservation planning tool in the United States and other countries in the world.

After undergoing several changes in the form of soil loss equations, Wischmeier and Smith (1978) have established a general format of Universal Soil Loss Equation (USLE) which is the product of six factors:

$$A = R * K * LS * C * P \qquad [2.1.1]$$

Where A = estimated average soil loss in tons per acre per year

R = rainfall-runoff erosivity factor

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

C = cover-management factor

P = support practice factor

2.1.1.1 R factor in USLE

R is the rainfall-runoff erosivity factor, which is a measure of the erosive force of rainfall with a consideration of runoff effect. The energy of a storm is relative to both volume and intensity of rainfall and runoff. R factor for a given time is a sum of the energy-intensity (EI) values from all storms in that time period. The value of EI equals the product of total storm energy (E) times the maximum 30-minute intensity (I_{30}). Rain showers of less than 0.5 in. are omitted from the erosion index computation, unless at least 0.25 in. of rain fell in 15 minutes (Wischmeier and Smith 1978). Average annual values of EI computed from 22-year station rainfall records were used to plot an isoerodent map for R factor in USLE. The isoerodents connect points with equal rainfall erosivity.

Total storm energy (E) used to compute R factor in USLE was calculated from the following equation:

$$E = 916 + 331 \log_{10} I \qquad I <= 3 \text{ in /hr.} \qquad [2.1.2]$$

$$E = 1074 \qquad I > 3 \text{ in/hr.} \qquad [2.1.3]$$

Where E = kinetic energy in foot-tons per acre-inch

I = intensity in inches per hour

Energy-Intensity (EI) for a storm is then computed as follows:

$$EI = E * I_{30} \qquad [2.1.4]$$

Where EI = Energy-Intensity in foot-tons per acre per hour.

I_{30} = maximum 30-min intensity in inches per hour.

2.1.1.2 K factor in USLE

K is the soil erodibility factor, a rate of soil loss per rainfall erosion index unit as measured on a unit plot which is 72.6 ft. long with a uniform slope of 9 slope, in continuous fallow, tilled up and down the slope (Wischmeier and Smith 1978). K represents the effect of soil properties and soil profile characteristics on soil loss. Some soils are more erodible than others. Soil erodibility factor is affected by several factors including soil texture, organic matter, and permeability. It is also interrelated with other factors such as the rainfall-runoff factor and the cover-management factor. Organic matter reduces soil erodibility through increased infiltration (reduced runoff) which reduces the susceptibility of soil to detachment (Grigar and Davis 1995). Different soils have different K values. For example, clay soils have low K values because they are resistant to detachment. Sandy soils are easily detached, but usually have low runoff, and thus may have low K values. Soils with high contents of silt have high K values because they are easily detached and also produce high rates of runoff.

In USLE application, a simple way to determine K factor is to find the value from soil erodibility nomograph developed by Wischmeier and others in 1971. The nomograph represents the influence of five soil and soil-profile parameters on K value: percent modified silt (0.002-0.1 mm), percent modified sand (0.1-2 mm), percent organic matter (OM), and classes for structure and permeability. For soils that have less than 70 percent silt faction, the following equation can be used to approximate the nomograph:

$$K = [2.1 * 10^{-4} (12 - OM)^{1.14} + 3.25 (s - 2) + 2.5 (p - 3)] / 100 \qquad [2.1.5]$$

Where K = soil erodibility factor in ton • acre • h (hundreds of acre • ft-tonf • in) $^{-1}$

M = product of percent modified silt (0.002-0.1 mm) * (% silt + % sand)

OM = percent organic matter

s = soil structure code used in soil classification, and

p = profile-permeability class.

The nomograph is suited particularly well when used for soils with less aggregated and medium-textures surface in the Midwest (Renard, et al 1997).

2.1.1.3 LS factor in USLE

L is the slope length factor and S is the slope steepness factor. L factor and S factor are usually considered together as LS factor to reflect the influence of topography on erosion. L is defined as the horizontal distance from the origin of overland flow to the point where either (1) the slope gradient decreases enough that deposition begins or (2) runoff becomes concentrated in a defined channel (Wischmeier and Smith 1978). Slope length can be measured by pacing or measuring in the field. L factor represents the ratio of soil loss in a particular field to that from the standard plot. It can be expressed as:

$$L = (\lambda / 72.6)^m \qquad [2.1.6]$$

Where L = slope length factor

λ = slope length in ft.

m = variable slope-length exponent.

The value of m varies with percent slope. m equals 0.5 for percent slope >= 5; 0.4 for slopes between 3.5 to 4.5 percent; 0.3 for slopes of 1 to 3 percent; and 0.2 for slopes less than 1 percent (Wischmeier and Smith 1978).

S factor reflects the influence of slope gradient on erosion. Slope can be estimated in the field by use of a clinometer or similar device, or from contour maps. The LS factor is a ratio of soil loss per unit area from an actual field slope to that from the standard unit plot with 72.6-ft long and 9% slope. Values of LS factor can be found in the LS factor tables. For agricultural landuse, a LS factor table has been developed and is provided in Agricultural handbook 537 for row-cropped agricultural and other moderately consolidated soil conditions with little-to-moderate cover. LS factor in USLE was derived from the equation:

$$LS = (\lambda / 72.6)^m (65.41 \sin^2\theta + 4.56 \sin\theta + 0.065) \qquad [2.1.7]$$

Where θ = angle of slope. λ and m are defined as above.

2.1.1.4 C factor in USLE

C is the cover-management factor. The C factor is used to reflect the effect of cropping and management practices on erosion rates. It is a ratio of soil loss under a specific condition to that from conditions defined in USLE plot, i.e. clean-tilled, continuous fallow. It indicates that how much soil loss can be reduced by different conditions such as land cover, crop sequence, and management practices. C factor is considered the one that can be adjusted by implementing conservation tillage to reduce the overall soil erosion. The soil loss ratios used in USLE to determine C factor was derived from analysis of about 250,000 plot soil loss data. USLE provides a guideline with tabulated data for determining C factor. Tabulated data contain soil loss ratios for various cropping system and management at different crop stages. Because effectiveness of surface cover on soil loss is different over time, six crop-stage periods are used: Period

F (rough fallow); Period SB (seedbed); Period 1 (establishment); Period 2 (development); Period 3 (maturing crop); and Period 4 (residue or stubble). Erosion-index distribution data were also considered to determine C factor for individual crop-stage periods since it affects the effectiveness of management practices on soil erosion (Wischmeier and Smith 1978).

2.1.1.5 P factor in USLE

P factor is the support practice factor, a ratio of soil loss with a specific support practice such as contouring, stripcropping and terracing to that with straight row farming up-and-down slope. P factor considers practices that modify the flow pattern, grade, or direction of surface runoff and reduce the amount and rate of runoff. It does not consider improved tillage practices such as no-till and other conservation tillage, which are considered in C factor (Foster et al., 1997). The following table lists the P values with various slope-length conditions for contouring.

Table 2.1.1 P values and slope-length limits for contouring

Land slope percent	P value	Maximum length (ft.)
1 – 2	0.60	400
3 – 5	0.50	300
6 – 8	0.50	300
9 – 12	0.60	120
13 – 16	0.70	80
17 – 20	0.80	60
21 – 25	0.90	50

(from Agriculture Handbook 537, Wischmeier and Smith, 1978)

2.1.2 RUSLE – Revised Universal Soil Loss Equation

Recent research, computing technology and new information have led to the development of a revised Universal Soil Loss Equation, namely RUSLE. The revised USLE or RUSLE has retained the same form of the equation with same six factors. However, procedures for calculating these factors have been refined. The key changes in RUSLE include deriving some of the main factors such as C and R from sub-factors with 15-day intervals, which better reflects the impact of temporal variations in climate, surface conditions and management practices. K factor in RUSLE also takes into account subsurface rock fragment effects on infiltration, and seasonal variation, which reflects the influence of freeze-thaw process. Complex slope segments are considered in RUSLE and better guideline for determining slope length (L) was provided. RUSLE also gives a detail and better description of conservation practices to calculate P factor. The following sections describe some details for computing the six factors used in RUSLE.

2.1.2.1 R factor in RUSLE

Similar to R factor used in USLE, R factor in RUSLE is also calculated from the sum of energy intensity value (EI). However, a different formula was used to compute E, the kinetic energy.

$$e = e_{max} [1 - a \exp(-b\ i)] \quad [2.1.8]$$

where e = the kinetic energy

e_{max} = a maximum unit energy as intensity approaches infinity;

i = total storm rainfall intensity;

a, b = coefficients.

Brown and Foster (1987) recommended that parameters in the question can be applied as the following equation based on their analysis.

$$e = 1099 [1 - 0.72 \exp(-1.27 i)] \qquad [2.1.9]$$

where e = kinetic energy in ft • tonf • $acre^{-1}$ • in^{-1}

i = total storm rainfall intensity in in • h^{-1}

An average rainfall erosivity R value over a long-term period of time can be calculated:

$$R = [\sum_{i=1}^{j} (EI_{30})_i] / N \qquad [2.1.10]$$

Where $(EI_{30})_i = EI_{30}$ for storm i,

j = number of storms,

N = year period.

2.1.2.2 K factor in RUSLE

RUSLE has considered the effect of rock fragments and seasonal variations in K values. Effects of rock fragments include the rocks' surface coverage that reduces soil erosion, and subsurface component that increases soil erosion due to reduction in water infiltration. Surface cover is counted for in the C factor as surface cover similar to crop residue. The subsurface effect on K value is considered by adjusting permeability classes.

Soil erodibility factor is affected by freeze-thaw cycles. Soils are most susceptible to erosion during thawing periods while soil erodibility gradually decreases during the growing season. The K value at any given date can be calculated based on maximum and minimum K values which need to be first computed from the nomograph and rainfall-runoff erosivity factor R:

$$K_{max} = (3.0 - 0.005\ R)\ K_{nom} \quad [2.1.11]$$

$$K_{min} = K_{max} / (8.6 - 0.019\ R) \quad [2.1.12]$$

Where K_{max}, K_{min} = maximum and minimum K values respectively;

K_{nom} = K value from nomograph;

R = rainfall-runoff erosivity factor.

The time when maximum and minimum K values occur can be determined from the following relationships:

$$t_{max} = 154 - 0.44\ R \quad [2.1.13]$$

$$t_{min} = t_{max} + FF \quad [2.1.14]$$

where t_{max}, t_{min} = julien dates for maximum and minimum K;

R = rainfall-runoff erosivity factor;

FF = frost-free period or growing season in days.

Seasonal K values (K_i) can be calculated from the following relationships which represent two scenarios:

Scenario 1: $t_{max} < t_{min}$

When $t_{max} < t_i < t_{min}$

$$K_i = K_{max}\ (K_{min} / K_{max})\ \wedge\ ((ti - tmax) / \Delta t) \quad [2.1.15]$$

When $t_i < t_{max}$ or $t_i > t_{min}$ when average temperature $T_{av} > 27^\circ$ F:

$$K_i = K_{max} \exp\ [0.009\ (t_i - t_{min} + 365\delta\ )] \quad [2.1.16]$$

Where $\delta = 1$ if $(t_i - t_{min}) \le 0$; $\delta = 0$ if $(t_i - t_{min}) > 0$ and for $T_{av} \le 27^\circ$ F, $K_i = K_{min}$.

Scenario 2: $t_{max} > t_{min}$

When $t_{max} > t_i > t_{min}$,

For average temperature $T_{av} > 27^\circ$ F:

$$K_i = K_{max} \exp [0.009 (t_i - t_{min})] \quad [2.1.17]$$

For average temperature $T_{av} \leq 27°$ F: $K_i = K_{min.}$

When $t_i > t_{max}$ or $t_i < t_{min}$,

$$K_i = K_{max} (K_{min} / K_{max}) \wedge ((T_i - T_{max} + 365\,\delta) / \Delta t) \quad [2.1.18]$$

Where $\delta = 1$ if $(t_i - t_{min}) \leq 0$; $\delta = 0$ if $(t_i - t_{min}) > 0$.

2.1.2.3 LS factor in RUSLE

The topographic LS in RUSLE can be computed for both simple slopes similar to USLE as well as for complex hillsides with a number of slope segments (Renard et al. 1997; McCool et al. 1991). Slope steepness is calculated from slope angles as:

$$S = 10.8 \sin\theta + 0.03 \qquad S < 9\% \quad [2.1.19]$$

$$S = 16.8 \sin\theta - 0.50 \qquad S \geq 9\% \quad [2.1.20]$$

For slopes that are shorter than 15ft., the following equation is used:

$$S = 3.0 (\sin\theta)^{0.8} + 0.56 \quad [2.1.21]$$

Where S = slope steepness factor,

θ = slope angle.

Foster and Wischmeier (1974) suggested that a complex or irregular slope can be broken into a number of segments with similar characteristics. An effective segment of topographic factor LS can be computed from the following equation:

$$LS_i = S_i\, x^m [\, i^{m+1} - (i-1)^{m+1}] \,/\, (7.26)^m \quad [2.1.22]$$

Where LS_i = effective LS for ith segment,

m = slope-length exponent (usually assumed equal to 0.5)

x = length in ft. of each segment.

2.1.2.4 C factor in RUSLE

While USLE calculates the Soil Loss Ratio (SLR) on various crop stages for C factor, RUSLE computes the SLR on a 15-day time step. When a management event occurs during the half-month period, the SLR can be calculated at smaller time segments (Yoder et al. 1997). Soil Loss Ratio (SLR) is calculated based on five subfactors which contain cropping and management variables affecting soil erosion:

$$SLR = PLU * CC * SC * SR * SM \qquad [2.1.23]$$

Where SLR = soil loss ratio

PLU = prior-land-use subfactor,

CC = canopy-cover subfactor,

SC = surface-cover subfactor,

SR = surface-roughness subfactor, and

SM = soil-moisture subfactor.

Prior-land-use subfactor (PLU) represents the effects of crop residual from prior crops and prior tillage practices on soil erosion. It is calculated as:

$$PLU = C_f * C_b * \exp[(-c_{ur} * B_{ur}) + (c_{us} * B_{us} / C_f^{\,Cuf})] \qquad [2.1.24]$$

Where C_f = surface-soil-consolidation factor,

C_b = relative effectiveness of subsurface residue in consolidation,

B_{ur} = mass density of live and dead roots incorporated surface residue in the upper inch of soil (lb/acre-in.),

B_{us} = mass density of incorporated surface residue in the upper inch of soil (lb/acre-in),

C_{uf} = impact of soil consolidation on the effectiveness of incorporated residue,

c_{ur} and c_{us} are calibration coefficients indicating the impacts of the subsurface residues.

Canopy cover subfactor (CC) represents the effects of energy reduction from interception of vegetative canopy. The effect is estimated as:

$$CC = 1 - F_c * \exp(- 0.1 * H) \quad [2.1.25]$$

Where CC = canopy cover subfactor (0 – 1),

F_c = fraction of land surface covered by canopy, and

H = distance that raindrops fall after striking the canopy.

Subsurface cover subfactor (SC) is an important subfactor in determining SLR which represents the effects of subsurface cover such as crop residues, rocks and other materials that reduce the transportation capacity of runoff water (Foster 1982). It can be computed as:

$$SC = \exp [-b * S_p * (0.24 / R_u) 0.08] \quad [2.1.26]$$

Where b = empirical coefficient,

S_p = percentage of land area covered by surface cover, and

R_u = surface roughness.

Surface roughness subfactor (SR) represents the effects of roughness and disturbance of the surface on soil erosion by reducing the flow velocity, and trapping water and sediments. This subfactor is computed as:

$$SR = \exp [-0.66 (R_u - 0.24)] \quad [2.1.27]$$

Soil moisture subfactor (SM) considers the influence of antecedent soil moisture on the infiltration and runoff. SM is equal to 1 when the soil profile is close to the field capacity. Since soil moisture is usually high during the crop season in most of the continental United States, the soil moisture does not need to adjusted in those regions.

After the Soil-Loss Ratio (SLR) is calculated, the C factor is then obtained by summing SLRs for each time interval which is weighted by EI distribution for that time period over the annual EI:

$$C = \left(\sum_{i=1}^{n} SLR_i * EI_i\right) / EI_t \qquad [2.1.28]$$

Where C = C factor in RUSLE,

SLR_i = Soil Loss Ratio for the time period i,

EI_i = percentage of annual EI for the time period i,

n = number of time periods, and

EI_t = sum of the EI percentage for the entire time period.

2.1.2.5 P factor in RUSLE

Support practice factor P in RUSLE represents the effect of specific support practices such as contouring, stripcropping and terracing on soil erosion. It is the ratio of soil loss under those support practices to that with traditional upslope and downslope tillage. Improved tillage practices such as no-till are not taken into account in P factor since they are already considered in C factor (Foster et al. 1997).

For contouring practice, the P factor is calculated by considering ridge height and storm erosivity. The base value of P factor can be calculated as follows:

$$P_b = a\,(s_m - s_c)^b + P_{mb} \qquad s_c < s_m \qquad [2.1.29]$$

$$P_b = c\,(s_c - s_m)^d + P_{mb} \qquad s_c \geq s_m \qquad [2.1.30]$$

$$P_b = 1 \qquad s_c \geq s_e \qquad [2.1.31]$$

Where P_b = base values of the P factor for contouring,

s_m = slope at which contouring has its greatest effectiveness,

s_c = slope for which a value of P_b is desired,

s_e = slope steepness above which contouring is ineffective,

P_{mb} = minimum P value for a given ridge height.

The P factor for contouring is then computed as:

$$P = 1 - (1 - P_b)\,(1 - P_m) / (1 - P_{mb}) \qquad [2.1.32]$$

P factor for stripping practices is calculated from empirical erosion-deposition model (Renard and Foster 1983). It is computed based on the following relationship:

$$P_s = 1 - B / g_p \qquad [2.1.33]$$

Where P_s = value of P factor for contouring,

B = credit for deposition, and

g_p = sediment load at the end of slope that would occur if the strips caused no deposition.

Similarly, P factor for terracing is determined as

$$P = 1 - B\,(1 - P_y) \qquad [2.1.34]$$

Where P = value of P factor for conservation planning,

B = credit for deposition, and

P_y = sediment delivery factor.

2.1.3 MUSLE – Modified Universal Soil Loss Equation

USLE was initially designed to predict soil loss for a long-term annual average soil loss. It is generally not recommended for a short period of time or a single storm event (Wischmeier 1976). In many cases, however, it is important to know the soil loss and sediment delivery in a specific time or a storm event. Several researchers have conducted studies to modify USLE to add its capability to predict sediment yield and soil loss for a single storm event (Foster et al 1977; and Williams and Berndt, 1977). One of the modified versions was developed by Williams and Berndt in 1977 by substituting the rainfall erosivity factor R with a runoff effect term, which can be used to predict sediment yield for a single event:

$$Y = 11.8\,(Q * q_p)^{0.56}\, K\, C\, P\, LS \qquad [2.1.35]$$

Where Y = sediment yield from an individual storm in metric ton,

Q = storm runoff volume in m^3,

q_p = peak runoff rate in m^3/sec,

K = soil-erodibility factor,

LS = slope length and gradient factor,

C = crop management factor, and

P = erosion-control-practice factor.

The model developers suggested that Q represents the energy for the detachment process and q_p defines sediment transport in this modified USLE (MUSLE). And thus introducing storm runoff volume (Q) and the peak runoff rate (q_p) in the model eliminates the need to calculate the sediment delivery ratio in order to estimate sediment yield.

Q and q_p are computed from runoff model from SCS equation:

$$Q = (R - 0.2s)^2 / (R + 0.8s) \qquad [2.1.36]$$

$$q_p = b_1 * Q^{b2} \quad [2.1.37]$$

Where Q = daily runoff,

R = daily rainfall,

s = retention parameter, and

b1, b2 = constants determined from plotting peak and volume values on log paper.

MUSLE was tested on 26 watersheds in Texas using monthly and annually sediment data. It was shown that the accuracy of MUSLE generally increases as watershed area decrease. The model can not be used to determine where deposition occurs since it does not have sediment routing function (Williams and Berndt 1977).

Almost at the same time, Onstad, Foster and Meyer have proposed another version of modification on USLE to predict soil erosion for single storm events (Onstad and Foster 1974; Foster et al. 1977). They also focused on modifying the rainfall erosivity term R factor in USLE. They took into account both storm rainfall factor and storm runoff (runoff volume and peak rate) in erosivity factor. The energy term is given as a function of rainfall and runoff energy:

$$W = 0.5\, R_{st} + 15\, Q\, q_p^{\ 1/3} \quad [2.1.38]$$

Where W = energy term which substitutes R factor,

R_{st} = storm rainfall factor, EI units,

Q = storm runoff volume, in.

q_p = storm peak runoff rate, in. per hour.

It was assumed that detachment is evenly divided by rainfall and runoff. It considers the detachment and transport capacities for each compartment (calculating unit) of the watersheds.

Foster et al. (1977) proposed a similar form of erosivity term based on runoff erosivity and runoff ersovity:

$$R_m = 0.5\, R_{st} + 0.5\, \alpha\, V_u\, \sigma_{pu}^{\;1/3} \qquad [2.1.39]$$

Where R_m = modified R factor,

R_{st} = storm energy (EI_{30}),

α = coefficient,

V_u = runoff volume,

σ_{pu} = peak runoff rate

The study showed that the modified USLE improved the soil loss estimation for specific storms compared to USLE. They split USLE into two separate terms to reflect different sources: rill erosion and interrill erosion, which also contributed to improvement of accuracy. They suggested that research is needed to define a better relationship to computer runoff erosivity than the one they suggested (Foster et al. 1977).

Young et al. (1987) used another modified version of USLE in Agricultural Nonpoint Source Pollution Model (AGNPS) which is a model for a single storm event. The modified USLE takes slope shape into consideration and introduced a slope shape factor (SSF). The slope shape factors represent the difference of concave and convex slopes, and were determined from the chart developed by Wischmeier and Smith (1978). Soil erosion from single storm events is calculated from the following equation which is used in AGNPS.

$$E = EI * K_s * L_f * C_f * P_f * SSF \qquad [2.1.40]$$

Where E = soil loss in tons/acre;

EI = rainfall energy-intensity in hundred foot-ton inch/acre hour;

K_s = soil erodibility factor in ton-acre hour/hundred-acre foot-ton inches;

L_f = slope-length factor;

L_f = slope-steepness factor;

C_f = cover and management factor;

P_f = support practice factor, and

SSF = a calculated factor to adjust for slope shape.

Variables in this equation EI, K_s, L_f, C_f, and P_f are defined as same as USLE. The slope shape factors were calculated based on gradients for the upper third, the middle third, and the lower third segments on a 75-foot slope.

Because a different shape of a slope affects the erosion/deposition process, a slope shape factor is introduced in this equation. An upwardly concave slope may trap runoff water and sediment, which transports less sediment than upwardly convex slope (Figure 2.1.1).

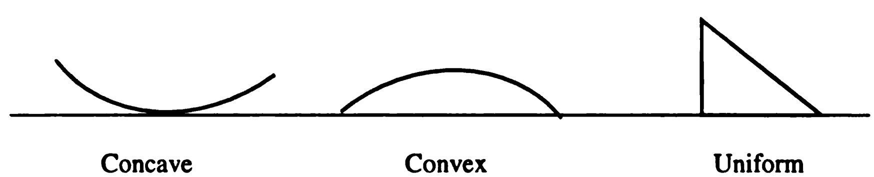

Figure 2.1.1 Examples of three typical slope shapes

In this modified USLE, slope shape factor has a multiplication factor of 1.00, 1.30, and 0.88 for uniform, convex and concave slope respectively.

2.1.4 WEPP – Water Erosion Prediction Project

Different from USLE and RUSLE which are empirical models, the Water Erosion Prediction Project (WEPP) is a continuous simulation computer program which predicts soil loss and sediment deposition from overland flow on hillslope, soil loss and sediment deposition from concentrated flow in small channels, and sediment deposition in impoundments (USDA 1995). WEPP not only has a component to calculate soil erosion, it also contains several other components including stochastic weather generator, a hydrology component, a daily water balance component, a plant growth and residue decomposition component, and an irrigation component.

WEPP can be used for different scales: hillslope profiles (tens of meters) and small watersheds (hundreds of meters). For hillslope profiles, WEPP predicts the soil particle detachment by raindrop impact and transport by sheet flow on interrill areas, and soil particle detachment, transport and deposition by concentrated flow in rill areas. As an extension of the WEEP hillslope model, the WEPP watershed model is capable of identifying zones of sediment deposition and detachment within constructed channels and representing the effects of agricultural management practices on erosion and deposition processes.

Erosion model used for hillslope in WEPP is a steady-state sediment continuity equation which represents the movement of sediment in a rill:

$$\frac{dG}{dx} = D_f + D_i \qquad [2.1.41]$$

where x = distance downslope in meters,

G = sediment load in $kg \cdot s^{-1} \cdot m^{-1}$

D_f = rill erosion rate in $kg \cdot s^{-1} \cdot m^{-2}$

D_i = interrill sediment delivery to the rill in $kg \cdot s^{-1} \cdot m^{-2}$

A positive value of rill erosion D_f represents detachment while a negative value represents deposition. The soil loss computed from this equation is expressed in soil loss per unit land area. Sediment load and sediment transport capacity are calculated on a unit rill width basis. Sediment transport capacity is calculated using the following equation:

$$T_c = k_t \tau_f^{3/2} \quad [2.1.42]$$

Where T_c = transport capacity,

k_t = transport coefficient ($m^{0.5} \cdot s^2 \cdot kg^{-0.5}$), and

τ_f = hydraulic shear acting on the soil (Pa).

Sediment load is calculated as the load per unit time:

$$G = G_* T_{ce} [w / R_s] \quad [2.1.43]$$

Where G = sediment load in $kg \cdot s^{-1}$ per unit width,

G_* = sediment load that is normalized to the transport capacity at the end of the uniform slope,

T_{ce} = transport capacity at the end of the uniform slope,

w = rill width in meters,

R_s = spacing of the rill in meters.

The total sediment load for the entire storm event is the product of sediment load per unit time (G) and effective storm runoff duration.

WEPP is written in ANSI FORTRAN 77 and running under MS-DOS operating system. The windows version is currently under beta test.

2.2 Soil Erosion Modules in Agricultural NPS Models

2.2.1 AGNPS – Agricultural Nonpoint Source Pollution Model

Agricultural Nonpoint Source Pollution Model (AGNPS) developed by Young et al. (1987) is a process-based single event model, used to simulate sediment and nutrient transport from agricultural watersheds. This model uses a distributed approach which divides a watershed into uniform square areas or cells. Input data of approximately 22 parameters are required for each cell. Outputs from AGNPS include volume and peak runoff, sediment yield, sediment-attached and soluble nitrogen and phosphorus, COD (soluble chemical oxygen demand yield). Results are provided in a summarized report and detailed information for each cell. Sediment and nutrient transport are broken down into five particle size classes: clay, silt, small aggregates, large aggregates, and sand.

AGNPS has four basic components: hydrology; erosion; sediment transport; and transport of nitrogen, phosphorus, and chemical oxygen demand. The model can be used to compare the effects of various management practices such as cropping system, and fertilizer application method and timing on water quality within a watershed. As described in the previous section, a modified USLE was used to simulate the soil erosion for a single event. Methods described in Technical Release 55 (TR-55) published by the Soil Conservation Service (SCS, 1986) is used in the hydrology module to calculate overland runoff and peak flow.

Sediment routing through the watershed is modeled on a per-cell and per particle size basis from the headwaters to its outlet. Simulation of sediment transportation and deposition is derived from the steady state continuity equation:

$$Q_s(x) = Q_s(0) + Q_{sl}\,\Delta x / L_r - \int_0^x D(x)\ W\,dx \qquad [2.2.1]$$

Where $Q_s(x)$ = sediment discharge at the downstream end of the channel reach in pounds per second,

Q_s (0) = sediment discharge at the upstream end of the channel reach in pounds per second,

Q_{sl} = lateral sediment inflow rate in pounds per secound,

x = downslope distance in feet,

Lr = reach length in feet,

D(x) = sediment deposition rate at point x in pounds per second-square foot, and

W = channel width in feet.

Deposition is computed as:

$$D(i) = V_{ss} / [\, q * (q_s - g_s) \,] \qquad [2.2.2]$$

Where D (i) = sediment deposition rate at point i between points x and 0 in pounds per second-square foot,

V_{ss} = particle fall velocity in feet per second,

Q = runoff rate in cubic feet per second-foot,

q_s = sediment flow rate in pounds per second-foot, and

g_s= effective sediment transport capacity in pounds per second-foot.

Effective sediment transport capacity (g_s) is calculated from the modified stream power equation (Young et al., 1987):

$$g_s = \eta * \kappa * \tau * V_c^2 / V_{ss} \qquad [2.2.3]$$

where η = effective transport factor,

κ = transport capacity factor,

τ = shear stress in pounds per square foot, and

V_c = average channel velocity in feet per second.

Sediment discharge is calculated for the period when eroded sediment moves from the upland to the channel, and the period when sediment moves within the channel.

Sediment attached nutrient load is calculated from a submodel used in CREAMS (The Chemical, Runoff, and Erosion from Agricultural Management Systems) (Frere et al., 1980):

$$SED' = SOIL * SED * ER * 0.892 \qquad [2.2.4]$$

Where SED' = N or P transported by the sediment in pounds per acre,

SOIL = N or P concentration in the soil,

SED = sediment yield in kilograms per hectare, and

ER = enrichment ratio for N or P.

The current version of AGNPS program is v5.0 which is written in FORTRAN running on DOS operating system. In order to run the program, the following parameters for each cell are required: cell number, cell division, receiving cell number, receiving cell division, flow direction, SCS curve number, land slope (%), slope shape, slope length (ft.), overland Manning's n, USLE K factor, C factor, P factor, surface condition constant, COD factor, soil texture, fertilizer indicator, pesticide indicator, point source indicator, additional erosion source, and impoundment indicator.

2.2.2 Ann-AGNPS – Annualized Agricultural Nonpoint Source Pollution Model

Annualized Agricultural Nonpoint Source Pollution model (Ann-AGNPS) is an extension of AGNPS from simulating a single storm event to a yearly basis. It is a batch-process, and continuous simulation model for surface runoff pollutant loading. Ann-AGNPS is capable of simulating amounts of water, sediment, chemicals (nutrients and pesticides) leaving from one area (cell) and their movement to another location within the watershed on a daily basis.

The Revised Universal Soil Loss Equation (RUSLE) replaced the USLE in Ann-AGNPS for soil erosion module. Upstream runoff volume and weighted rainfall including rainfall, snowmelt, and irrigation are used to calculate runoff curve number. Sediment loads are calculated for within bank flow and out of bank flow from three sediment sources: sheet and rill erosion, gully erosion, and bed and bank erosion. Similar to AGNPS, the sediment is routed by five particle classes: clay, silt, small aggregate, large aggregate, and sand. Sediment attached and soluble compounds for nitrogen, phosphorus, and organic carbon are also modeled. A decay function is used based on the reach travel time, and water temperature.

Ann-AGNPS is still under development. Few studies using Ann-AGNPS have been reported or published. Needham (1994) used Ann-AGNPS with a geographic information system (GIS) interface. He concluded that the Ann-AGNPS model can not accurately predict quantitative contributions for NSP pollutions. It is only capable of providing qualitative assessment in identifying and ranking the contributing areas.

2.2.3 SWAT – Soil and Water Assessment Tool

Soil and Water Assessment Tool (SWAT) developed by the USDA and Texas A & M University (Arnold et al., 1996) is a physically based and continuous time model that provides daily simulation on impacts of management on water, sediment and agricultural chemicals. SWAT has five major components: hydrology, weather, sedimentation, crop growth model, and nutrients.

SWAT uses a weather generator which simulates daily precipitation, daily maximum and minimum air temperature, solar radiation, wind speed, and relative humidity. Hydrology module simulates surface runoff, percolation, lateral surface flow, groundwater flow, evapotranspiration, and snow melt. The hydrology model is based on the water balance model:

$$SW_t = SW + \sum_{i=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i) \quad [2.2.5]$$

Where SW = soil water content – 15-bar water content,

t = time in days,

R = daily precipitation (mm),

Q = daily runoff (mm),

ET = daily evapotranspiration (mm),

P = daily percolation (mm), and

QR = return flow (mm).

Runoff volume is calculated using the SCS curve number equation (USDA-SCS, 1972) and peak runoff rate is calculated from the modified Rational formula or the SCS TR-55 method (USDA-SCS 1986). The Modified Universal Soil Loss Equation developed by Williams and Berndt (1977) is used to calculate sediment yield for each sub-basin. This equation is described in previous section.

Nitrogen (organic N) transported with sediment is calculated using a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978):

$$YON = 0.001\,(Y)\,(CON)\,(ER) \quad [2.2.6]$$

Where YON = organic N runoff at the sub-basin outlet in kg/ha,

CON = concentration of organic N in the top soil layer in g/t,

Y = sediment yield in t/ha, and

ER = enrichment ratio.

Similarly, phosphorus (P) transport by sediment is calculated a loading function:

$$YP = 0.01\ (Y)\ (C_p)\ (ER) \quad [2.2.7]$$

Where YP = sediment phase of P loss in runoff in kg/ha,

C_p = concentration of P in the top soil layer in g/t,

Y = sediment yield in t/ha, and

ER = the enrichment ratio.

A GIS interface in Geographic Resources Analysis Support System (GRASS) has been developed for SWAT input and output. The program is run in the Unix operating system. Windows version of SWAT has also been developed. Like other physically based models, SWAT requires tremendous input data sets to run the model, including crop, nutrient, pesticide, irrigation data as well as lake water quality data, and information about ponds and reservoirs.

2.2.4 EPIC – Erosion-Productivity Impact Calculator

Erosion-Productivity Impact Calculator (EPIC) developed in 1980s (Williams et al., 1984) is a continuous simulation model that can be used to assess the impact of management practices on agricultural production, and soil and water resources. There are 10 major components in EPIC model: weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control. EPIC model can be used for a field-size area, up to 100 hectares in which weather, soils, and management systems are assumed to be homogeneous.

Erosion model used in EPIC simulates the erosion caused by rainfall, runoff, and irrigation. It provides three versions of soil loss equations: original Universal Soil Loss Equation (Wischmeier and Smith 1978) using energy-intensity term (EI) substitutes R factor for single events, modified USLE developed by Williams (1975), and by Onstad and Foster (1975).

Among many equations used in the model, rainfall energy (in metric units) is calculated using the following equation:

$$RE = \Delta R \,(12.1 + 8.9 \log(\Delta R / \Delta t)) \qquad [2.2.8]$$

Where RE = rainfall energy, and

ΔR = rainfall amount in mm during a time Δt interval in hours.

The USLE rainfall energy factor EI is then computed by multiplying the energy term by the maximum 0.5-hour rainfall intensity:

$$EI = R\,[12.1 + 8.9\,(\log r_p - 0.434)]\,(r_{0.5}) / 1000 \qquad [2.2.9]$$

Where EI = energy-intensity,

R = daily rainfall amount in mm,

r_p = peak rainfall rate in mm/h, and

$r_{0.5}$ = maximum 0.5-hour rainfall intensity in mm/h.

EPIC model requires users to have considerable amount of technical knowledge to install and maintain the model. In addition, extensive data collection and conversion to EPIC format may be required in order to run the model.

2.3 Sediment Delivery Ratios (SDR)

By definition, sediment delivery ratio (SDR) is the ratio of the amount of sediment that actually leaves an area to the total soil loss in that area. The expression for computing sediment delivery ratio can be written in the following form:

$$SDR = SY / E \qquad [2.3.1]$$

where SDR = sediment delivery ratio

SY = sediment yield

E = gross erosion per unit area above a measuring point.

Water quality monitoring including sediment measurement is expensive and time consuming. In most cases, sediment yield is not measured, but estimated from soil erosion and sediment delivery ratio. The following sections describe some models/approaches used to estimate sediment delivery ratios.

2.3.1 Drainage area and SDR (SDR curves):

Relationships between SDR and other factors have been established as curves. Watersheds with large drainage area and fields with long distances to streams have low sediment delivery ratios. This is because large areas have more chances to trap soil particles, thus the chance of soil particles reaching the water channel system is low. Some researchers suggested that SDR is closely related to the power of -0.2 to the drainage area or the distance to the stream, others suggested the power of -0.1 and -0.3 in the function (Gianessi et al., 1986; and Roehl 1962). Figure 2.3.1 shows that a relationship can be established between sediment delivery ratio and drainage area while Figure 2.3.2 shows another relationship between sediment delivery ratio and distance from field boundary to a stream.

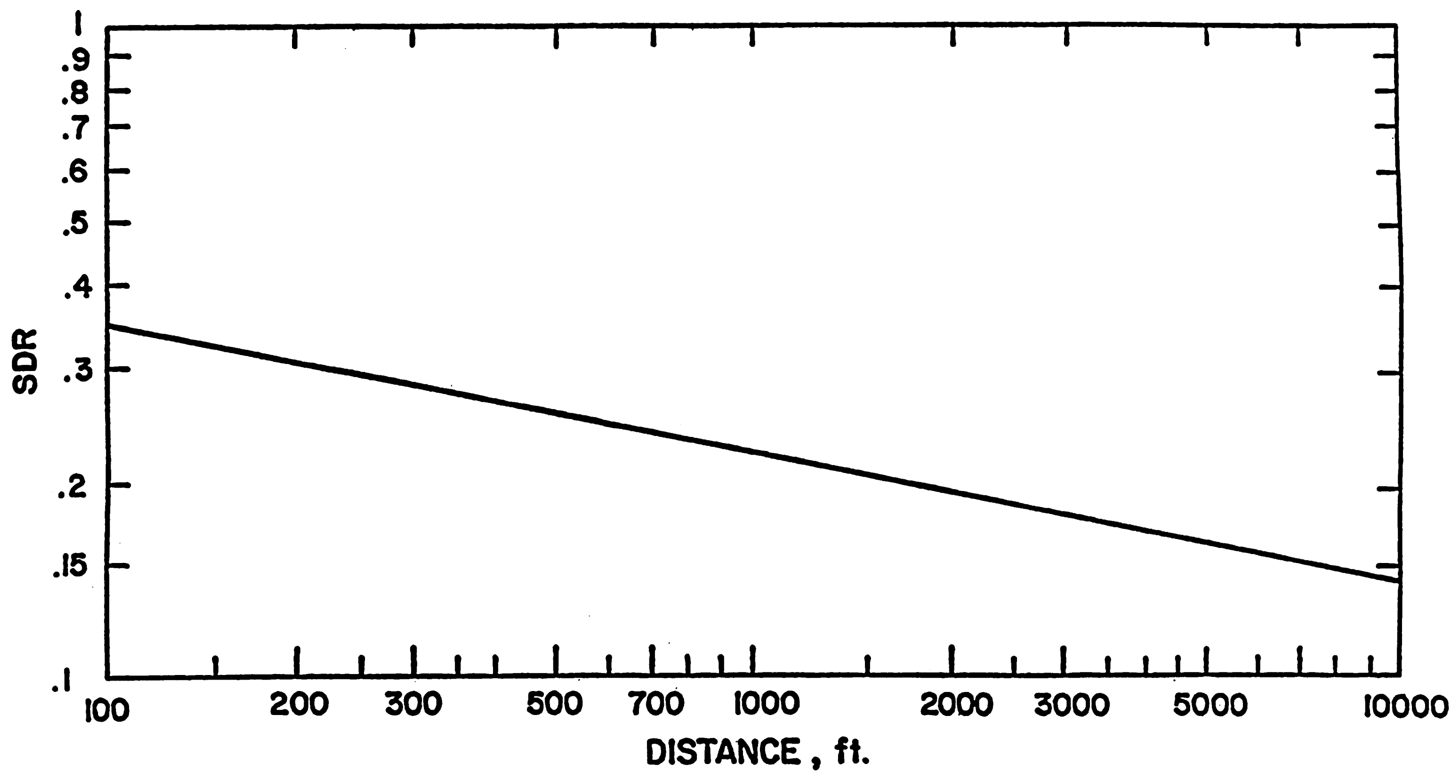

Figure 2.3.1 **Relationship between sediment delivery ratio for a field based on the distance of the field boundary to a stream. (from Walter and Black, 1982)**

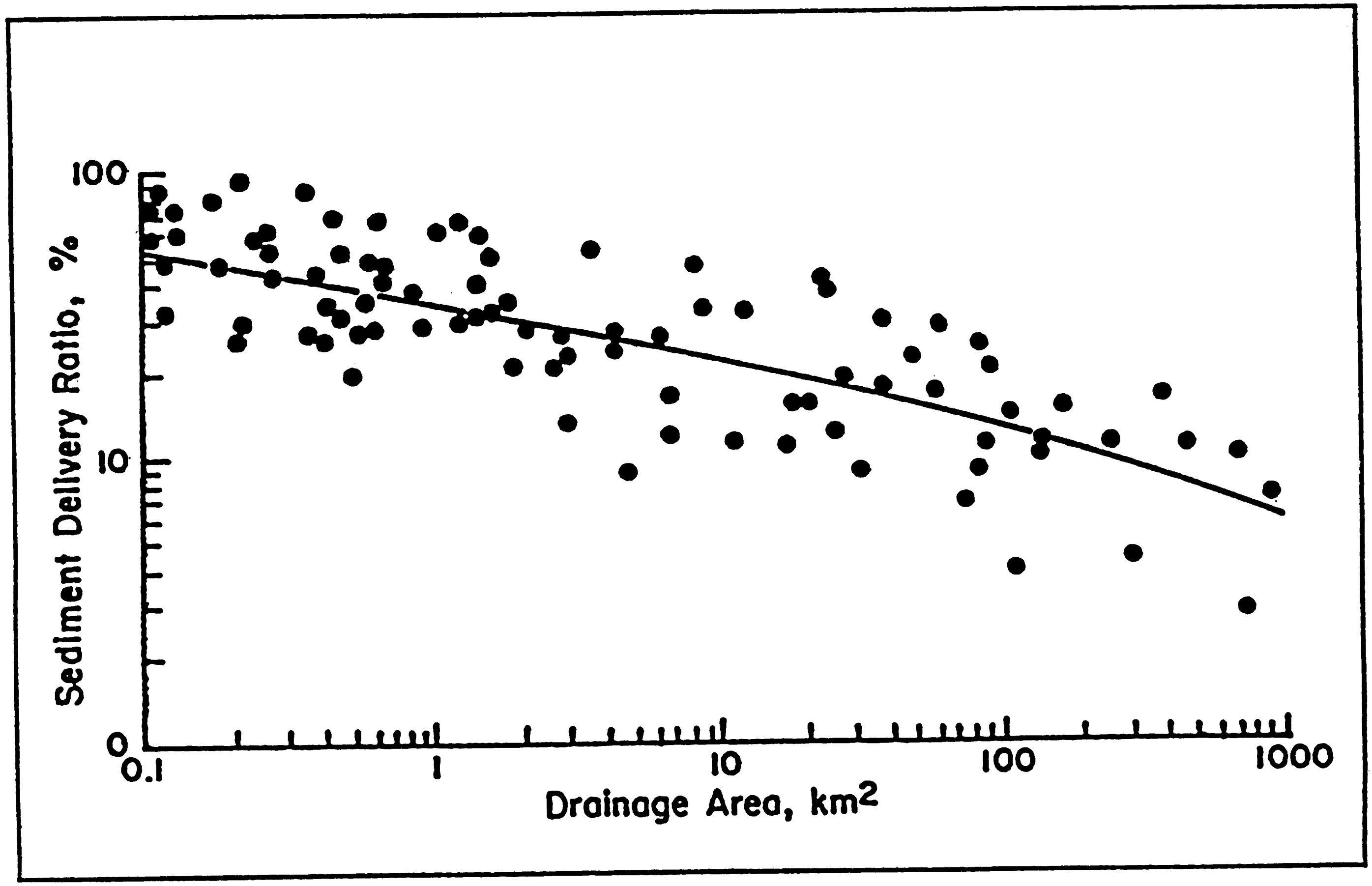

Figure 2.3.2 **Relationship between the delivery ratio and watershed size. (from Roehl, 1962)**

The relationships have been generalized as curves called SDR curves. The SDR curves include SDR vs. drainage area and SDR vs. distance. The drainage area method is most often and widely used in estimating the sediment delivery ratios in previous research.

Renfro (1975) developed an equation relating SDR with drainage area. It is based on Maner's (1962) equation and the sediment yields observed in 14 watersheds in the Blackland Prairie Area in Texas. The model shows a good relationship between SDR and drainage area ($R^2 = 0.92$). The model can be written as follows:

$$\log(SDR) = 1.7935 - 0.14191 \log(A) \qquad [2.3.2]$$

where A = drainage area in km^2

Vanoni (1975) used data from 300 watersheds throughout the world to develop a model by the power function. This model is considered a more generalized one to estimate sediment delivery ratio.

$$SDR = 0.42\ A^{-0.125} \qquad [2.3.3]$$

where A = drainage area in square miles.

The USDA SCS (1979) developed a SDR model based on the data from Blackland Prairie, Texas. A power function was derived from the graphed data points:

$$SDR = 0.51\ A^{-0.11} \qquad [2.3.4]$$

where A = drainage area in square miles.

Haith and Tubbs (1981) suggested a similar equation for sediment delivery ratio based on watershed area:

$$TS_k = 0.47\ A^{-0.125} \qquad [2.3.5]$$

Where TS_k = transport factor, or sediment delivery ratio, and

A = watershed area in square kilometers.

2.3.2 Rainfall-runoff and SDR

Water is the vehicle for sediment transport. Rainfall and runoff are the driving forces of sediment delivery. A humid watershed usually has a higher SDR due to more rainfall. SDR is also associated with rainfall pattern. A longer duration rainfall event with less intensity has a lower SDR than a short rainfall event with higher intensity. Land use/land cover is another factor affecting SDR. A watershed with good vegetation cover has a low SDR because vegetation slows down the runoff rate and allows the eroded soil particles to deposit. The rainfall factor of the USLE reflects the energy used in soil detachment while the runoff factor used in the Modified USLE (MUSLE) reflects the energy used in both sediment transport and detachment.

A SDR model which is used in the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1996) takes runoff factor into account. The primary form of the SDR model is

$$SDR = (q_p / r_{ep})^{0.56} \qquad [2.3.6]$$

where q_p = peak runoff rate in mm/hr.

r_{ep} = peak rainfall excess rate in mm/hr

= peak rainfall rate(r_p)- the average infiltration rate(f).

The average infiltration rate in mm/hr can be estimated by the following equation

$$f = (R - Q) / DUR \qquad [2.3.7]$$

where R = rainfall in mm.

Q = runoff volume in mm.

DUR = duration of a rainfall event in hr.

$= 4.605\ (R / r_p)$

Therefore, SWAT-SDR model can be re-written as follows:

$$SDR = ((q_p / r_p) / (0.782845 + 0.217155\ Q / R))^{0.56} \quad [2.3.8]$$

This model is developed for estimating sediment delivery for a single event. The factors q_p and r_p are peak runoff and peak rainfall in mm/hr for an event, respectively. Factors Q and R are runoff and rainfall volumes in mm for an event, respectively. Other units such as in/hr and inch(es) can be used, and can be canceled if used consistently. In this study, this model was used to estimate SDR based on long-term average rainfall and runoff data.

2.3.3 Drainage Area-Runoff and SDR

Dency and Bolten (1976) suggested general watershed sediment yield equations relating deposits in 800 reservoirs to drainage area size and mean annual runoff. The equations are

$$S = 1280\ Q^{0.46}\ (1.43 - 0.26 \log A) \quad \text{for areas where runoff is less than 2 in.} \quad [2.3.9]$$

$$S = 1958\ e^{-0.055}\ Q\ (1.43 - 0.26 \log A) \quad \text{for other areas.} \quad [2.3.10]$$

where S = sediment yield (tons per square mile per year)

Q = runoff (in.),

A = watershed area (square miles).

2.3.4 Slope, gradient, and relief-length ratio and SDR:

SDR is affected by topographic features of the watershed. A watershed with short and steep slopes will deliver more sediment to a channel than a watershed with a long and flat landscape. Shape of a watershed also affects SDR. A narrow watershed may have a high SDR. The feature of watershed shape can be expressed by relief-length ratio. Relief of a watershed is defined as the difference of the elevations in the watershed divide and outlet. Watershed length is the distance of the two points measured parallel to the main stem drainage from the watershed divide to the point of sediment yield measurement (SCS, 1971). Relief-length ratio is used as a physiographic characteristic which affects sediment delivery ratio.

Williams and Berndt (1972) used slope of the main stream channel to predict sediment delivery ratio. The model is written as:

$$SDR = 0.627\ SLP^{0.403} \qquad [2.3.11]$$

Where SLP = % slope of main stream channel.

Maner's studies (1958) suggested that SDR was better correlated with relief and maximum length of a watershed expressed as relief-length ratio (R/L) than with other factors. Renfro 1975 modified the model ($R^2 = 0.97$) as follows:

$$\log(SDR) = 2.94259 + 0.82362 \log(R/L) \qquad [2.3.12]$$

where R = relief of a watershed, defined as the difference in elevation between the average elevation of the watershed divide and the watershed outlet.

L = maximum length of a watershed, measured approximately parallel to mainstream drainage.

Williams (1977) found the sediment delivery ratio is correlated with drainage area, relief-length ratio, and runoff curve numbers. He developed a model based on sediment yield data for 15 Texas basins. The model is expressed as follows:

$$SDR = 1.366 \times 10^{-11} (DA)^{-0.0998} (ZL)^{0.3629} (CN)^{5.444} \qquad [2.3.13]$$

where DA = drainage area in km^2,

ZL = relief-length ratio in m/km,

CN = long-term average SCS curve number.

2.3.5 Particle size and SDR

SDR is also affected by texture of the sediment materials. Texture of the eroded materials is associated with sources of erosion. Coarse materials are usually produced by streambank and gully erosion, while fine materials are often from sheet and rill erosion. Less energy is needed to transport fine particles (i.e. silt and clay) than coarse materials (i.e. sands). Thus, sands are more likely deposited in the transport process, while eroded silt and clay particles are more easily transported downstream. As a result, sediment containing high clay content will have a high delivery ratio.

Walling (1983) suggested that sediment delivery ratio may be calculated from proportions of clay in the sediment and in the soil.

$$SDR (\%) = C_{soil} (\%) / C_{sed} (\%) \qquad [2.3.14]$$

where C_{soil} (%) = content of clay in the soil (%).

C_{sed} (%) = content of clay in sediment (%).

2.3.6 Loading Coefficients and SDR

A more simplistic approach to estimate sediment delivery ratio as well as nutrient loading is to use a loading coefficient based on the type of land use. Delwiche and Haith (1983) have established a loading function for predicting runoff, sediment, and nutrient losses from complex watersheds. The function was based on input data including watershed landuse, soil information, daily precipitation and temperature records and rainfall erosivities. They proposed several separate models for different types of land uses: urban, cropland, forest, and barnyard. These models provide predicted runoff, sediment load, and nutrient load for each runoff event and for each source in a watershed. The model for cropland runoff was given as follows:

$$LS_{kt} = 0.001\ Cs_{tk}\ X_{kt}\ TS_k\ A_k \qquad [2.3.15]$$

Where LS_{kt} = solid compound of nutrient export from area k on day t,

Cs_{tk} = nutrient concentration in sediment in mg/kg,

X_{kt} = soil loss in tons/ha,

TS_k = solid phase transport factor or delivery ratio,

A_k = area of source k, and

0.001 = conversion factor.

The term for soil loss (X_{kt}) is computed using USLE modified by Haith and Tubbs (1981) for single storm events. The transport factor or sediment delivery ratio is defined by the equation described in the previous section.

Based on Wisconsin watershed data, Novotny and Chesters (1989) estimated sediment delivery ratios for various land uses (Table 2.3.1).

Table 2.3.1 Estimated sediment delivery ratios for various land uses

Land use	**Impervious Area (%)**	**Sediment Delivery Ratio (%)**
Agriculture	< 5	1 – 30
Developing construction	< 5	20 – 50
Low density residential, unsewered	< 20	< 10
Parks	< 10	< 3
Medium density residential, partially sewered	30 - 50	30 – 70
Medium density residential, sewered	30 - 50	70 – 100
Commercial high density residential, sewered	> 50	100

As variations may exist even in the same type of land use, it needs to refine the sediment delivery ratio for a specific watershed. The above table shows that the sediment delivery ratio from agricultural land range 1% to 30%. This range may be too great to apply to a specific watershed to estimate sediment delivery ratio quantitatively. However, it may provide a general comparison between different land uses.

Rast and Lee (1983) did an extensive literature review regarding nutrient export coefficients for nonpoint source loading to the lakes. They collected data for generalizing nutrient export coefficients from various previous studies and government research documents. It is reported that phosphorus export coefficient is from 0.03 to 0.07 (g P / $m^2 \cdot yr$) from agricultural and rural areas.

2.3.7 Spatially Distributed SDR

Most empirical models for sediment delivery ratios are spatially lumped models. That is, one single value of sediment delivery ratio is applied to the entire watershed. Spatial diversity on local topographic, land use, and soil conditions are not taken into consideration in the most SDR models. Variations on those factors are assumed to be averaged out within the watershed. On the other hand, spatially distributed sediment delivery ratio models take into account the local conditions that affect sediment delivery process. Spatially Explicit Delivery MODel (SEDMOD) is one of few spatially distributed SDR models available today. This model was newly developed in late 1990s and has not been widely tested for many different watersheds.

SEDMOD is implemented with Arc/Info GIS and can be used to calculate a site-specific delivery ratio for nonpoint source pollutants (Fraser, et al., 1998; Fraser, 1999). It takes into account six important parameters that affect sediment transport. These six parameters are flow-path slope gradient, flow-path slope shape, flow-path hydraulic roughness, stream proximity, soil texture, and overland flow. SEDMOD uses a cell-based model with GRID in Arc/Info GIS. A raster GIS layer or a grid is first created for each of six parameters to represent their effects on sediment transport process. A linear weighting model was used to estimate the delivery potential which created a composite raster GIS layer. The delivery potential (DP) is expressed as a percentage.

$$DP = SG_r\, SG_w + SS_r\, SS_w + SR_r\, SR_w + SP_r\, SP_w + ST_r\, ST_w + OF_r\, OF_w \qquad [2.3.16]$$

Where DP = Delivery Potential

SG = Flow-Path Slope Gradient,

SS = Flow-Path Slope Shape,

SR = Flow-Path Surface Roughness,

SP = Stream Proximity,

ST = Soil Texture,

OF = Overland Flow Index, and

for the subscript letter r and w:

XX_r = Normalized rating for parameter XX, ranging from 0 – 100, and

XX_w = Relative weight of parameter XX, ranging from 0 – 1.

The weights assigned to these six parameters are normalized so they sum to 1. The composite layer for delivery potential has a range of 0 – 100. The composite layer is then scaled to have a mean value same as that predicted using a spatially lumped sediment delivery model proposed by American Society of Civil Engineers (ASCE, 1975). ASCE suggested that sediment delivery ratio varies approximately with –1/8 th power of drainage area, i.e.

$$DR_a = c\,A^{\,b} \qquad [2.3.17]$$

Where DR_a = Delivery Ratio in percentage,

c = A constant for a "small watershed" as a "point erosion source" with 100% delivery ratio,

A = Drainage area in square miles, and

b = A constant, -1/8

SEDMOD assumed that an average sized 22 meters long plot, usually designed for Universal Soil Loss Equation (USLE), as a "point erosion source." Average percentage delivery ratio for a watershed is calculated as follows:

$$DR = DP + (DR_a - \mu(DP)) \qquad [2.3.18]$$

Where DR = Final delivery ratio layer, expressed in percentage,

DP = Delivery potential from composite layer,

DR_a = Spatially lumped delivery ratio,

$\mu(DP)$ = Mean value of delivery potential

The delivery ratios for individual cells in this adjusted layer have values distributed around the average delivery ratio, which reflects the magnitude of the six delivery parameters. It gives a spatially distributed delivery ratio index for a watershed, instead of one delivery ratio for the entire watershed if using spatially lumped model alone.

A number of parameters are required to run SEDMOD. These parameters include local topographic and soil conditions which are described below.

2.3.7.1 Slope Gradient

Digital Elevation Model (DEM) and a stream network grid were used to derive this parameter. SEDMOD calculates slope gradient averaged over each cell's unique flow-path to the stream. Mean flow-path gradient was used in a power function to calculate SEDMOD slope parameter.

2.3.7.2 Slope Shape

A convex slope with decreasing slope (divergence) has a greater sediment delivery ratio than uniform slope and concave slope. A concave slope with increasing slope (convergence) has greater deposition than convex slope. SEDMOD uses DEM data to derive the slope shape parameter from the profile curvature, which is derived from the coefficients of a 3x3 cell polynomial surface. Flow-path curvature values were normalized from 0 for extremely concave to 100 for extremely convex.

2.3.7.3 Stream Proximity

Due to the deposition process, sediments are less likely transported to a water body from sites far away from a stream than from sites near the stream. SEDMOD uses an exponential decay function to estimate the stream proximity parameter. The decay function is based on a 50 percent sediment reduction for every 100 meters distance.

$$\text{Proximity factor} = e^{-0.00639D} \qquad [2.3.19]$$

Where D = distance to a stream, in meters

2.3.7.4 Overland Flow

SEDMOD uses a topographically based moisture index (Beven and Kirkby, 1979) to derive the overland flow parameter. It provides a relative measure of soil saturation for each cell that may be subject to overland flow conditions. The index was computed as follows in Arc/Info GRID:

$$MI = Ln[A/(C\, T_i \tan \alpha)] \qquad [2.3.20]$$

Where MI = Moisture Index,

A = Contributing area,

C = Grid cell length,

T_i = Local depth integrated soil hydraulic conductivity, and

$\tan \alpha$ = Local slope gradient.

The index shows that sites with large contributing area, low soil transmissivity, small slope gradient are more likely to become saturated and generate overland flow.

2.3.7.5 Soil Texture

Clay content (%) in the upper soil horizon was used as a factor in the SEDMOD to represent differences in transport of soil particles with different size. Compared to sandy soils, clay and silt soil particles are more easily detached and transported by moving water. Fine textured soil particles may also carry higher concentration of nutrients such as phosphorus than course particles (Nelson and Logan, 1983). An enrichment ratio is used to calculate the percentage of soil fraction in transported sediment to that in parent soil.

2.3.7.6 Surface Roughness

Surface coverage (vegetation/residues) can reduce surface runoff and sediment delivery. The surface roughness is determined as a hydraulic roughness coefficient or Manning's n that reflects the effect of surface conditions on the erosion and transport of sediment.

2.4 Soil Erosion, Sediment Yield and Phosphorus Loading

Sediment yield is different from soil erosion in that sediment yield is only a portion of gross soil erosion, that is, erosion minus deposition. Soil erosion calculated from the Universal Soil Loss Equation or Revised USLE does not consider deposition and only for soil loss from sheet and rill erosion. Sediment yield can be estimated from soil erosion and sediment delivery ratio:

$$SY = A * SDR \qquad [2.4.1]$$

Where SY = sediment yield,

A = soil loss, and

SDR = sediment delivery ratio in percent.

SDR can be calculated from various models described in previous sections. Soil loss can be calculated from USLE or RULSE. Modified USLE (MUSLE) developed by Williams (1977) was attempted to eliminate the need to calculate sediment delivery ratio and can be used to estimate sediment yield directly for single storms.

Two sediment delivery ratio models including SEDMOD, a spatially distributed sediment delivery ratio model is used for estimate sediment delivery ratios. Four soil erosion models including the use of modified RUSLE which considers temporal variation with 15-day time intervals for single storm events are used for soil erosion. Together, sediment delivery ratio and soil erosion are used to calculate sediment yield. The results are compared with ground truth monitoring data.

Phosphorus loading is calculated based on sediment yield and phosphorus content in sediment (PC). The phosphorus load is calculated as:

$$PL = SY * PC \qquad [2.4.2]$$

Where PL = phosphorus load,

SY = sediment yield, and

PC = phosphorus content in sediment.

Phosphorus content in sediment can be determined from the monitored sediment and phosphorus loading data.

2.5 Phosphorus Index

In addition to the method for estimating phosphorus loading based on sediment and phosphorus content, some other methods have been developed in previous studies for assessing phosphorus losses from agricultural runoff. USDA-NRCS has developed a phosphorus indexing tool to assess phosphorus loss from agricultural land (Lemunyon and Gilbert, 1993; Stevens et al., 1993). Phosphorus Index uses a number of parameters including soil, hydrology, and land management that affect phosphorus availability, retention, management, movement, and uptake. A weighting factor is assigned to each site characteristic parameters to determine the site vulnerability for phosphorus loss:

Table 2.5.1 Site characteristics and weighting factors used in Phosphorus Index

Site characteristics	Weighting factors
Soil erosion	1.5
Irrigation erosion	1.5
Runoff class	0.5
Soil P test	1.0
P fertilizer application rate	0.75
P fertilizer application method	0.5
Organic P source application rate	1.0
Organic P source application method	1.0

A phosphorus loss rating value is given to each site characteristic. It reflects the level of the severity with each site characteristic for phosphorus loss. Five levels are used in the ratings: none, low, medium, high, and very high with a value of 0, 1, 2, 4, 8, respectively. For example, the following ratings are used for Soil Erosion:

Table 2.5.2 Phosphorus loss ratings for soil erosion used in Phosphorus Index

Soil Erosion	Phosphorus Loss Rating
None (0)	0
Low (< 5 tons/acre)	1
Medium (5 –10 tons/acre)	2
High (10 –15 tons/acre)	4
Very High (> 15 tons/acre)	8

The site vulnerability for phosphorus loss is calculated by multiplying the weighting factor and rating values to get the weighted value for each site characteristic, and then summing the weighted values. Site vulnerability is assessed by comparing the weighted value with site vulnerability chart provided below:

Table 2.5.3 Site Vulnerability for Phosphorus Loss

Total of weighted rating values	Site vulnerability
< 8	Low
8 – 14	Medium
15 – 32	High
> 32	Very High

This phosphorus assessment tool (Phosphorus Index) provides an easy-to-use method for assessing agricultural phosphorus loss. However, cautions must be used when applying it on specific sites as the weighting factors and ratings are arbitrarily assigned although they are based on professional judgment. Furthermore, phosphorus index does not provide a quantitative estimate for phosphorus loading. It may provide the first tier analysis for phosphorus loss assessment.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of Study Watershed

A small agricultural watershed, Marshall Drain Watershed, was selected as the study area (Figure 3.1.1). Note that most images in this dissertation are presented in color. Marshall Drain is a sub-watershed of Sycamore Creek watershed. It is located in Vevay township, south of Mason, Ingham County, Michigan. Marshall Drain subwatershed drains to Sycamore Creek which is a tributary to the Red Cedar River flowing into the Grand River, and discharges eventually into Lake Michigan. The drainage area for the Marshall Drain watershed is approximately 400 acres with 90% agricultural lands. Total acreage of the entire Sycamore Creek watershed is 67,740 acres, of which about 70% are agricultural landuse (Suppnick 1999). Problems identified in the Sycamore Creek Watershed from previous studies (USDA 1990) are sediment from soil erosion, phosphorus, nitrate and pesticides, which cause sedimentation and turbidity problems, nuisance algae growth, and groundwater contamination. Sycamore Creek watershed was on the 303(d) list due to low dissolved oxygen problem, and was required to develop a Total Maximum Daily Load (TMDL) to reduce the sediment load by one half (Suppnick 1999).

Sycamore Creek watershed has been selected as a Section 319 project in Michigan. Section 319 of the Clean Water Act was enacted by Congress in 1987, as a national program specifically aimed at controlling NPS pollution. USEPA developed the Section 319 National Monitoring Program which funded 22 projects in 18 states for consistently monitoring water quality and land management for 6 to 10 years. Sycamore Creek watershed is one of the watersheds for water quality monitoring program funded by Section 319 grants. Water quality and land management monitoring data collected in Sycamore Creek watershed during 1990-1997 were used in this study.

In an earlier study conducted in Sycamore Creek watershed, it was estimated that about 75% of the cropland is considered as critical soil erosion areas (within a one-half mile distance of a stream or drain). Approximately 1,800 acres exceed 12 tons/acre and 13,000 acres range from 8 to 10 tons/acre of soil loss per year (USDA 1990). Prior analysis of water samples from the stream indicated that concentration of suspended solids, total phosphorus and nitrate increased dramatically during runoff events. Phosphorus concentrations during wet weather ranged from 0.04-0.71 mg/L in Sycamore Creek (USDA, 1990). It is considered that phosphorus levels in surface waters greater than 0.01 mg/L (10 ug/l) have been associated with increased algae growth in streams and rivers (Foth and Ellis 1997). The pollutants including sediments and phosphorus are primarily from agricultural land and thus agricultural nonpoint source pollution is a major concern in the watershed. In a TMDL case study conducted in Sycamore Creek watershed, it was further identified that among the pollutants, sediments are most responsible to water quality degradation (USEPA 1992).

The reasons Marshall Drain sub-watershed in Sycamore Creek Watershed was chosen as the study area include:

1. The watershed is predominated by agriculture with 90% of agricultural land use. This is an ideal watershed for studying nonpoint source pollutions in an agricultural watershed context.

2. Water quality is an environmental concern in the watershed. Because of water quality problem, this watershed is on the 303(d) list which requires the development of Total Maximum Daily Load (TMDL) for pollution reduction.
3. Nonpoint source pollution, particularly sediment, is the major cause of impaired water quality. No point source discharge and no bank erosion occurs in the watershed. Therefore, this avoids the complication of multiple discharges for assessing agricultural nonpoint source pollution.
4. The Water Quality Monitoring project has conducted intensive water quality measurements since 1990 by the Michigan Department of Environmental Quality (MDEQ). Land use and tillage management monitoring data have also been collected by the Natural Resources Conservation Service (NRCS), U.S. Department of Agriculture (USDA) during the same period of time. This provides an excellent data set for agricultural NPS modeling.

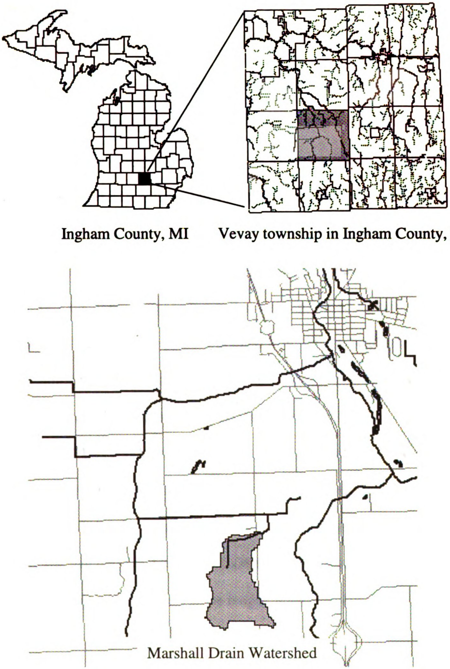

Figure 3.1.1 Study area – Marshall Drain Watershed in south of Mason, Ingham County, Michigan

3.2 Data Collection

3.2.1 GIS Data Layers

Most agricultural NPS models require extensive data inputs. Even with an aid of Geographical Information System (GIS), there are quite a few data layers that need to be created before the model can be run. Fortunately, using Sediment and Phosphorus Loading Model (SPLM) which is built on SEDMOD and the modified RUSLE requires minimum data sets. All GIS data layers used in this study are readily available or can be easily created. Digital base maps used include roads, streams, county boundary and soils. The data were obtained from Michigan Resource Information System (MIRIS). Soil clay content and soil erodibility factor K obtained from USDA-NRCS were added to soil data layer by joining the tabular data with the GIS coverage. Soil data layer was calibrated by Center for Remote Sensing, Michigan State University.

Digital Elevation Model (DEM) data with 30-meter resolution was obtained from the U.S. Geological Survey (USGS). These data were used to generate watershed boundary using Arc/Info command WATERSHED which creates a watershed boundary similar to that manually drawn from USGS topographic map. DEM was also used to calculate the slope steepness and slope length, both of which are needed for estimating soil erosion.

For land use and tillage management, a GIS coverage file with cells of approximately 10 acres in size was created using Arc/Info commands GENERATE and FISHNET. Land use and tillage management data were added to this data layer according to the monitoring data in Table 3.2.4.

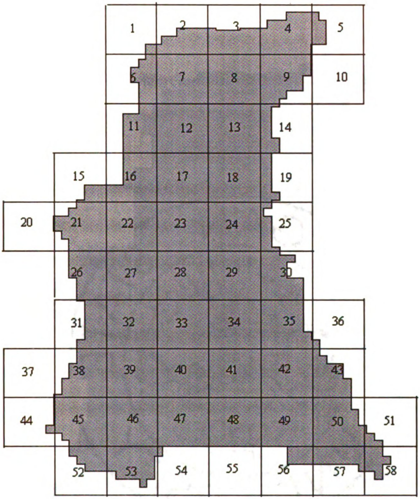

Figure 3.2.1 10-acre grid cells in Marshall Drain Watershed

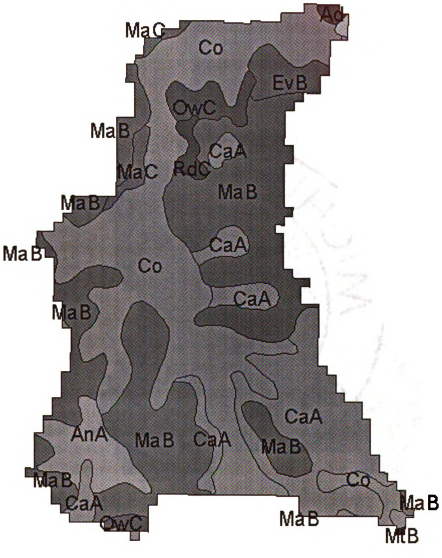

Figure 3.2.2 Soils in Marshall Drain Watershed

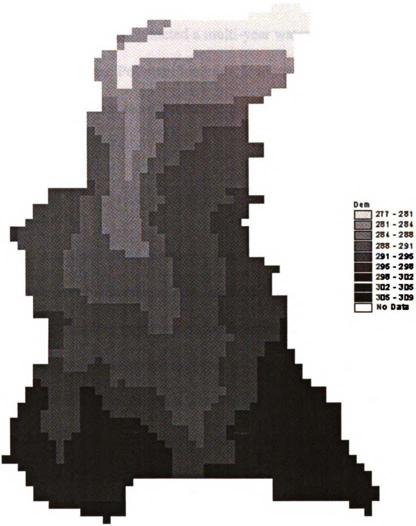

Figure 3.2.3 Digital Elevation in Marshall Drain Watershed

3.2.2 Monitoring Data

This study used data collected from previous projects conducted in Sycamore Creek Watershed. From 1990 to 1997, the Michigan Department of Environmental Quality, Surface Water Quality Division conducted a multi-year water quality monitoring program in Sycamore Creek watershed. Pollutant loadings, land use and land cover, and rainfall intensity had been measured and recorded for the spring season from after snow melt until crop canopy (Suppnick, 1999).

3.2.2.1 Spring Storm Monitoring

Spring storms were monitored using automatic samplers, bubbler flow meters and recording rain gages in the three subwatersheds. Automatic samplers were used to collect samples during runoff events. Sampling began each year from March or April when frost was out of the ground and freezing weather was minimal to July or August when crop canopy had a complete ground coverage. Samples were collected every 30 minutes to 6 hours after a 1-2 inch increase in stage. More samples were collected during the first part of the storm than the end of the storm.

3.2.2.2 Spring Grab Sampling

Grab samples were also collected during the spring storm sampling period from March/April to July/August each year (1990-1997). Grab samples were collected on a regular basis every week except that the first three years grab samples were collected occasionally during non-runoff conditions.

3.2.2.3 Sample Analysis

Because of laboratory expenses, not all collected samples were used for laboratory analysis. About 8 samples (some up to 22 samples) for each storm were kept for analysis.

At least one sample was used for the rising limb of the hydrograph and near the hydrograph peak, and at least two samples for the descending limb of the hydrograph. More samples were used for periods with higher suspended solid loads. Samples were submitted to laboratory for analysis within 24-48 hours after storm events. Samples were analyzed by the Michigan Department of Environmental Quality Laboratory in Lansing, Michigan. Chemical analysis included suspended solids, total phosphorus, ortho-phosphorus, Kjeldahl nitrogen, ammonia nitrogen, nitrite, nitrite plus nitrate, chemical oxygen demand (COD) and turbidity.

Total pollutant load for each storm was estimated from the interval method (Richards and Holloway, 1987) as follows. Bedload was not included in the calculation.

$$L = \sum c_i * q_i * t_i * k \qquad [3.2.1]$$

Where L = storm load (kg);

c = pollutant concentration (mg/l);

q = instantaneous flow associated with the sample (l/sec);

t = time increment for the interval (minutes);

k = unit conversion constant; and

i = individual sample

Table 3.2.1 Monitored runoff, sediment and phosphorus data in Marshall Drain Watershed

Date (mm/dd/yy)	Peak Flow (CFS)	Runoff Volume (in)	Runoff Volume (Cubic ft.)	Suspended Solids (ton)	Total Phosphorus (kg)
4/20/90	2.28	0.05	69317	0.000	0.000
5/4/90	0.45	0.01	8711	0.002	0.018
5/17/90	2.28	0.05	75287	0.082	0.378
3/27/91	3.82	0.08	125730	1.280	3.180
4/4/91	0.53	0.00	6000	0.000	0.000
4/9/91	2.76	0.05	72220	0.562	1.420
4/15/91	2.64	0.04	56865	0.144	0.490
4/19/91	2.98	0.06	88749	0.292	1.090
4/23/91	1.52	0.02	23589	0.043	0.199
4/24/92	9.3	0.26	405000	3.940	10.100
7/14/92	1	0.03	41300	0.050	0.220
4/19/93	16	0.32	488508	13.073	28
5/4/93	0.64	0.00	5637	0.016	0.060
6/7/93	2.1	0.06	84710	0.138	0.580
6/14/93	0.47	0.00	5499	0.012	0.050
6/19/93	11.4	0.18	273000	5.654	12.750
4/12/94	4.93	0.08	116225	0.035	0.220
4/30/94	1.05	0.01	8202	0.027	0.150
7/20/94	0.49	0.00	2688	0.114	0.240
4/26/95	1.28	0.01	20427	0.054	0.220
7/4/95	0.48	0.01	14418	0.005	0.050
5/10/96	4.07	0.06	86039	0.647	2.400
5/21/96	3.63	0.02	32168	0.179	1
6/18/96	26.5	0.44	670000	10.846	21.9
4/5/97	3.75	0.06	96123	0.051	0.460
5/5/97	1.27	0.01	16124	0.034	0.150
5/19/97	2.89	0.03	39436	0.051	0.270
6/23/97	1.69	0.02	31462	0.032	0.190

3.2.2.4 Rainfall Monitoring

To get more accurate rainfall data in the watershed, a Belfort rain gauge was installed in the watershed. The rain gauge was calibrated and checked to determine that it operated appropriately. Recorded rainfall data were used to calculate rainfall intensity, and EI (Energy-Intensity), one factor to calculate soil erosion. Monitored rainfall and intensity in Marshall Drain Watershed are listed in Table 3.2.2.

Table 3.2.2 Monitored rainfall and intensity, and EI in Marshall Drain Watershed

Date (mm/dd/yy)	Total rainfall (in)	Max. 30-min. intensity (in/30 min.)	EI
4/20/90	0.65	0.08	0.58
5/4/90	0.50	0.13	0.76
5/17/90	0.78	0.20	1.93
3/27/91	0.85	0.47	6.20
4/4/91	0.35	0.05	0.18
4/9/91	0.82	0.45	6.18
4/15/91	0.72	0.14	1.67
4/19/91	0.83	0.10	0.94
4/23/91	0.40	0.24	1.26
4/24/92	1.60	0.39	5.90
7/14/92	1.15	0.35	6.00
4/19/93	1.6	0.17	3.593
5/4/93	0.37	0.24	1.524
6/7/93	1.61	0.30	6.337
6/14/93	0.45	0.30	2.254
6/19/93	2.14	0.65	17.60
4/12/94	0.90	0.18	1.89
4/30/94	0.48	0.07	0.347
7/20/94	0.97	0.22	8.69
4/26/95	0.64	0.075	0.50
7/4/95	0.83	0.10	10.50
5/10/96	1.14	0.70	4.98
5/21/96	0.9	0.25	3.35
6/18/96	3.18	0.34	14.7
4/5/97	0.50	0.07	0.40
5/5/97	0.56	0.13	0.86
5/19/97	0.61	0.25	2.07
6/23/97	0.57	0.30	2.72

3.2.2.5 Landuse and Tillage Management Data

Landuse and tillage management practices were recorded by staff of the Natural Resources Conservation Service of the U.S. Department of Agriculture. The data cover the same period for water monitoring from 1990-1997. The 10-acre grids were created in the watershed to reflect the landuse and tillage practices used in those years (Figure 3.2.4). The monitoring data are listed in the following tables (Table 3.2.3 and Table 3.2.4).

Table 3.2.3 Land Use and Tillage Monitoring Results (in acres) for Marshall Drain watershed (1990-1997)

Landuse/Tillage management	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**
B	0	0	190	0	0	0	0	10
C	140	210	20	150	110	0	0	0
NB	0	0	40	0	180	110	170	110
NC	0	0	0	30	0	150	130	20
NW	0	0		110	0	30	20	170
P	170	80	90	80	80	80	60	50
WH	70	80	30	0	0	0	0	0
WO	20	20	20	20	20	20	0	0
R							10	30
G	0	10	10	10	10	10	10	10

P=established Pasture, meadow, hay, alfalfa
C=Conventional till corn
NC= No-till corn
WH= Wheat
NW = No-till Wheat
Wo= Woods
G= Active gravel mining
NB = No-till Soybeans
R= Low Density Residential development
B= Conventional till Soybeans

Table 3.2.4 Monitored land use and tillage practices by 10-acre grid cells

Cell #	Land Use and Tillage Practices							
	1990	1991	1992	1993	1994	1995	1996	1997
1	P	G	G	G	G	G	G	G
2	P	G	G	G	G	G	G	G
3	P	P	P	P	P	P	P	P
4	P	P	P	P	P	P	P	P
5	P	P	P	P	P	P	P	P
6	P	G	G	G	G	G	G	G
7	P	G	G	G	G	G	G	G
8	P	P	P	P	P	P	P	P
9	P	P	P	P	P	P	P	P
10	P	P	P	P	P	P	P	P
11	P	P	P	P	P	P	P	P
12	P	P	P	P	P	P	P	P
13	P	P	P	P	P	P	P	P
14	P	P	P	P	P	P	P	P
15	Wh	C	B	C	NB	NC	NB	NWh
16	Wh	C	B	C	NB	NC	NB	NWh
17	P	P	P	P	P	P	NB	NWh
18	P	Wh	NB	C	NB	NC	NB	NWh
19	P	Wh	NB	C	NB	NC	NB	NWh
20	Wh	C	B	C	NB	NC	NB	NWh
21	Wh	C	B	C	NB	NC	NB	NWh
22	P	P	B	P	P	P	NB	NWh
23	P	Wh	B	C	NB	NC	NB	NWh
24	P	Wh	B	C	NB	NC	NB	NWh
25	P	Wh	B	C	NB	NC	NB	NWh
26	Wh	C	B	C	NB	NC	NB	NWh
27	Wh	C	B	C	NB	NC	NB	NWh
28	Wh	C	B	C	NB	NC	NB	NWh
29	P	Wh	B	C	NB	NC	NB	NWh
30	P	Wh	B	C	NB	NC	NB	NWh
31	Wh	C	P	C	NB	NC	NB	NWh
32	Wh	C	P	C	NB	NC	NB	NWh
33	Wh	C	P	C	NB	NC	NB	NWh
34	P	Wh	NB	C	NB	NC	NB	NWh
35	P	Wh	NB	C	NB	NC	NB	NWh
36	P	Wh	NB	C	NB	NC	NB	NWh
37	Wo	Wo	Wo	Wo	Wo	Wo	NWh	R
38	Wo	Wo	Wo	Wo	Wo	Wo	NWh	R
39	Wo	Wo	Wo	Wo	Wo	Wo	R	R
40	C	C	B	NWh	C	NB	NC	NC

41	C	C	B	NWh	C	NB	NC	R
42	P	P	P	P	P	P	P	B
43	P	P	P	P	P	P	P	B
44	C	C	B	NWh	C	NB	NWH	NC
45	C	C	B	NWh	C	NB	NWH	NC
46	C	C	WH	NC	NB	NWH	NC	NB
47	C	C	B	NWh	C	NB	NC	NB
48	C	C	B	NWh	C	NB	NC	NB
49	C	C	C	NWh	C	NB	NC	NB
50	C	C	C	NWh	C	NB	NC	NB
51	C	C	C	NWh	C	NB	NC	NB
52	C	C	NB	C	NC	B	WH	NC
53	C	C	WH	NC	NB	NWH	NC	NB
54	C	C	B	NWh	C	NB	NC	NB
55	C	C	C	NWh	C	NB	NC	NB
56	C	C	C	NWh	C	NB	NC	NB
57	C	C	C	NWh	C	NB	NC	NB
58	C	C	C	NWh	C	NB	NC	NB

P=established Pasture, meadow, hay, alfalfa
C=Conventional till corn
NC= No-till corn
WH= Wheat
NWH= No-till Wheat
NA= No-till Alfalfa (year of planting)

Wo= Woods
G= Active gravel mining
GI= Inactive gravel mining
R= Low Density Residential development
B= Conventional till Soybeans
NB = No-till Soybeans

3.3 SEDMOD Model

Basic GIS data layers required by SEDMOD are generally readily available. Basic data layers include clay content, DEM, and land use/land cover. Optional data layers include streams which can be derived from DEM if not available, and saturated soil transmissivity in inches per hr. A number of secondary data layers are derived from the basic data layers.

Vegetation roughness is derived from land cover. The roughness layer is created by reclassifying the landuse/land cover layer using Manning's roughness obtained from literature. Table 3.3.1 lists the roughness coefficients for some field conditions. More detail data about Manning's roughness values are included in the appendix. DEM is used to derive a number of data layers including slope and slope shape, and cell travel distance. Soil moisture index is derived from DEM and soils.

When the secondary data layers are generated, raster data layers for the six parameters used in SEDMOD are then created in Arc/Info GRID to compute the sediment delivery ratio layer in the watershed. The calculations are based on data processing with GRID, which uses an algorithm for cell-based raster data layers. GRID is a powerful tool used for spatial modeling.

Soil clay content data layer is created using ArcView GIS by joining the soil clay content in tabular data (Table 3.3.2) with the digital soil coverage file. Percentage of clay in the upper soil horizon is used as a factor to represent the differences in particle size transport (Fraser 1999).

Table 3.3.1 Manning's roughness values for various field conditions (Engman, 1985)

Field condition		Manning's Roughness value
Fallow	Smooth, rain packed	0.01-0.03
	Medium, freshly disked	0.1-0.3
	Rough turn plowed	0.4-0.7
Cropped	Grass and pasture	0.05-0.15
	Clover	0.08-0.25
	Small grain	0.1-0.4
	Row crops	0.07-0.2

Table 3.3.2 Percent of soils and clay content in Marshall Drain Watershed

Soil Name (Soil Symbol)	Percent (%) of land	Clay (%)
Colwood (Co)	45	5-26
Marlette (Ma)	38	10-18
Capacn (Ca)	5	10-18
Aubbeenaubbee (An)	4	8-15
Owosso (Ow)	3	5-18

3.4 Modified RUSLE (MRUSLE)

Inherited from USLE, RUSLE was designed to estimate the average annual soil loss. However, it can be modified to estimate soil loss for single events (Onstad and Foster, 1974; Foster, 2000). Modification of RUSLE is similar to that for USLE made by Onstad and Foster (1974) which modified the USLE's R factor by accounting for both rainfall and runoff effects on erosion. The modified RUSLE can be expressed as follows:

$$ERO = (EI)_m * K * LS * SLR * P \qquad [3.4.1]$$

Where ERO = loss erosion for a single storm event, tons/acre,

$(EI)_m$ = Modified Erosion Index term with consideration of rainfall and runoff effects,

K = soil erodibility factor,

LS = slope length-steepness factor,

SLR = soil loss ratio, and

P = support practice factor.

The modified Erosion Index term is calculated using the following equation:

$$(EI)_m = a * EI + b * Q * q_p \qquad [3.4.2]$$

where $(EI)_m$ = energy term with consideration of rainfall and runoff effects,

EI = Energy-Intensity,

Q = storm runoff volume, in.

q_p = storm peak runoff rate, cubic ft. per second (CFS), and

a, b = coefficients. (a = 0.0475 and b = 0.825 were used in the study watershed)

In addition to the modified RUSLE, other forms of modification are also calculated for comparison purpose. They include equation [2.1.38] proposed by Onstad and Foster (1974) which accounts for both rainfall and runoff effects, and equation [2.1.40] developed by Young et al. (1978) which is used in AGNPS and adjusted by a slope shape factor. The original USLE's EI term without modification is also used in soil erosion calculations and used to compare with other models.

3.4.1 Slope Shape Factor

The slope shape factor (SSF) in AGNPS' modified USLE is used to reflect the difference of slope shapes affecting net erosion/deposition at a specific location. Average empirical multiplier coefficients are used in AGNPS' modified USLE equation: 1.30 for convex slopes meaning the erosion is 30% more than the uniform slopes; and 0.8 for concave slopes meaning that erosion is 20% less than the uniform slopes due to the deposition that may occur in that type of slopes. Concave and convex slopes are determined using a command of Arc/Info GIS called CURVATURE with the digital elevation model data (DEM). Slope curvature is calculated as the second derivative of the surface, i.e. the change of rate in the slope gradient or the slope of the slope. It affects the acceleration/deceleration of water flow, which influences erosion/deposition process (Moore et al. 1991; Zeverbergan and Thorne 1987).

Running CURVATURE command on DEM data will get a new grid with the information of slope curvature. A positive value indicates a convex slope and a negative value indicates a concave slope while the zero value means no change on slope, i.e. an uniform slope. After the curvature layer is created, a slope shape factor layer is generated by assigning the slope shape factor multiplier to grid cells. Then the slope shape factor layer is used to adjust USLE for estimating soil loss.

3.4.2 LS factor calculation

L factor and S factor are usually considered together to combine the effect of slope-steepness and slope-length, which basically reflects the terrain on a given site. For this study, a model developed by Moore and Burch (1985) is used to compute LS factor. They developed an equation to compute length-slope factor:

$$LS = (As / 22.13)^m \ (\sin \beta / 0.0896)^n \qquad [3.4.3]$$

where: m = 0.4 – 0.6 and n = 1.2 – 1.3.

LS = computed LS factor.

As = specific catchment area, i.e. the upslope contributing area per unit width of contour (or rill), in m^2 / m. It is calculated in Arc/Info using the function called FLOWACCUMULATION multiplied by the squared cell size and divided by the cell size.

For 30 meter resolution DEM grids, As can be calculated as:

$$As = \text{calculated flowaccumulation} * 30 * 30 / 30 \quad (\text{for cell size} = 30\ m) \qquad [3.4.4]$$

β = slope angle in degrees. It is calculated in Arc/Info using the function called SLOPE with option PERCENTRISE which is 100 times Tan β. Then β is calculated using "Atan" function in Arc/Info.

$$\tan \beta = \text{slope (in percentrise)} / 100 \qquad [3.4.5]$$

$$\beta = \text{Atan} (\tan \beta)$$

LS factor is calculated with Arc/Info GIS which creates a separate LS factor data layer for the modified RUSLE.

3.4.3 Other factors in Modified RUSLE

The following table lists the main soils in the watershed with soil name, soil symbol, K factor and soil loss tolerance level T. According to the official definition of soil loss tolerable level, T value is defined as the maximum amount of soil loss in tons per acre per year, which can be tolerated and still permit a high level of crop productivity to be sustained economically and indefinitely (Wischmeier and Smith, 1978; Renard, et al. 1997).

Table 3.4.1 K and T values for soils in Marshall Drain Watershed

Soil Name (Soil Symbol)	K	T
Colwood (Co)	0.28	5
Marlette (Ma)	0.24	5
Capacn (Ca)	0.32	5
Aubbeenaubbee (An)	0.24	5
Owosso (Ow)	0.24	5

RUSLE computerized program is used to calculate the soil loss ratio (SLR) sub-factor. The option “Time varying scenario” was chosen. So that it is computed for the soil loss ratio sub-factor in half-month time period. The SLR values for the half-month period when the storm event occurred are used. SLR is calculated for each crop rotation in the study watershed. An example of the output of SLR is listed in the following table for the two-year crop rotation with Corn-Soybean. More results are listed in the appendix.

SLR is calculated using the equation [2.1.23] based on the five sub-factors: the prior-land-use subfactor (PLU), the canopy-cover subfactor (CC), the surface-cover subfactor (SC), the surface-roughness subfactor (SR), and the soil-moisture subfactor (SM). After the SLR is calculated for the all crop rotations, it is then joined with the GIS coverage to create a new data layer for C factor in the watershed. Since different crops were grown in the watershed each year, a separate C factor data layer is created for each year for each 10-acre grid cells.

Table 3.4.2 An example for calculated SLR in half-month intervals for Corn-Soybean rotation with the prior year condition

Dates	% Residue Cover	PLU	CC	SC	SR	SM	SLR	% EI
10/15/1	25	0.643	1	0.463	0.536	1	0.159	0.2
10/16 - 10/31/1	24	0.654	1	0.478	0.555	1	0.173	2
11/1 - 11/15/1	22	0.672	1	0.503	0.593	1	0.201	2
11/16 - 11/30/1	21	0.682	1	0.519	0.632	1	0.224	1
12/1 - 12/15/1	20	0.686	1	0.525	0.666	1	0.24	1
12/16 - 12/31/1	20	0.686	1	0.527	0.694	1	0.251	0
1/1 - 1/15/2	20	0.684	1	0.527	0.714	1	0.258	0
1/16 – 1/31/2	20	0.682	1	0.526	0.73	1	0.262	1
2/1 - 2/15/2	20	0.68	1	0.526	0.744	1	0.266	1
2/16 – 2/28/2	20	0.678	1	0.526	0.756	1	0.27	1
3/1 - 3/15/2	20	0.677	1	0.529	0.77	1	0.276	1
3/16 – 3/31/2	19	0.681	1	0.54	0.79	1	0.291	2
4/1 - 4/15/2	18	0.69	1	0.559	0.812	1	0.313	2
4/16 – 4/30/2	16	0.704	1	0.588	0.834	1	0.345	3
5/1 - 5/4/2	15	0.715	1	0.613	0.847	1	0.371	1.1
5/5 - 5/14/2	6	0.74	0.983	0.814	0.883	1	0.523	2.7
5/15/2	2	0.733	0.967	0.925	0.889	1	0.582	0.3
5/16 – 5/31/2	2	0.732	0.938	0.933	0.897	1	0.574	7
6/1 - 6/4/2	2	0.719	0.908	0.942	0.906	1	0.557	2.4
6/5 - 6/15/2	1	0.693	0.761	0.969	0.889	1	0.454	6.6
6/16 – 6/30/2	1	0.625	0.51	0.974	0.904	1	0.281	9
7/1 - 7/15/2	1	0.538	0.35	0.98	0.918	1	0.17	9
7/16 – 7/31/2	0	0.505	0.267	0.984	0.93	1	0.124	10
8/1 - 8/15/2	0	0.512	0.267	0.987	0.941	1	0.127	10
8/16 – 8/31/2	0	0.518	0.297	0.99	0.95	1	0.144	9
9/1 - 9/15/2	0	0.522	0.399	0.992	0.958	1	0.198	7
9/16 – 9/30/2	0	0.524	0.487	0.994	0.965	1	0.245	6
10/1 - 10/14/2	0	0.524	0.487	0.994	0.969	1	0.246	2.8
10/15/2	93	0.527	1	0.04	0.971	1	0.021	0.2
10/16 - 10/31/2	92	0.534	1	0.041	0.973	1	0.021	2
11/1 - 11/15/2	54	0.44	1	0.195	0.457	1	0.039	2
11/16 - 11/30/2	53	0.452	1	0.2	0.502	1	0.045	1
12/1 - 12/15/2	52	0.457	1	0.202	0.544	1	0.05	1
12/16 - 12/31/2	52	0.459	1	0.201	0.578	1	0.053	0
1/1 - 1/15/3	51	0.458	1	0.2	0.604	1	0.055	0
1/16 – 1/31/3	51	0.457	1	0.2	0.624	1	0.057	1
2/1 - 2/15/3	51	0.456	1	0.199	0.641	1	0.058	1

2/16 – 2/28/3	51	0.455	1	0.198	0.657	1	0.059	1
3/1 - 3/15/3	51	0.455	1	0.199	0.676	1	0.061	1
3/16 – 3/31/3	50	0.462	1	0.203	0.702	1	0.066	2
4/1 - 4/15/3	48	0.474	1	0.211	0.732	1	0.073	2
4/16 – 4/30/3	46	0.493	1	0.226	0.762	1	0.085	3
5/1 - 5/14/3	43	0.519	1	0.247	0.788	1	0.101	3.7
5/15/3	28	0.515	1	0.399	0.824	1	0.169	0.3
5/16 – 5/31/3	26	0.536	0.97	0.423	0.837	1	0.184	7
6/1 - 6/14/3	23	0.572	0.862	0.468	0.859	1	0.198	8.4
6/15/3	17	0.573	0.791	0.57	0.825	1	0.213	0.6
6/16 – 6/30/3	16	0.59	0.692	0.595	0.84	1	0.204	9
7/1 - 7/15/3	14	0.606	0.466	0.637	0.864	1	0.155	9
7/16 – 7/31/3	12	0.59	0.205	0.674	0.883	1	0.072	10
8/1 - 8/15/3	12	0.597	0.144	0.672	0.901	1	0.052	10
8/16 – 8/31/3	24	0.621	0.215	0.44	0.916	1	0.054	9
9/1 - 9/15/3	43	0.642	0.486	0.228	0.93	1	0.066	7
9/16 – 9/30/3	45	0.656	0.67	0.214	0.942	1	0.089	6
10/1 - 10/9/3	41	0.662	0.703	0.249	0.948	1	0.11	1.8
10/10 - 10/14/3	70	0.671	1	0.089	0.951	1	0.057	1

Note:

SLR = PLU * CC * SC * SR * SM

SLR = Soil loss ratio; PLU = the prior-land-use subfactor;
CC = the canopy-cover subfactor; SC = the surface-cover subfactor;
SR = the surface-roughness subfactor, and SM = the soil-moisture subfactor.

3.5 Integration of SEDMOD and Modified RUSLE

The spatially explicit sediment delivery model SEDMOD has its own menu driven interface written in Arc Marco Language (AML) which is run in Arc/Info environment. Because this model only calculates the sediment delivery, a soil erosion model with the modified Revised Universal Soil Loss Equation is added. This integrated model (Sediment and Phosphorus Loading Model – SPLM) is capable of computing sediment delivery ratio, soil erosion for single storm events, sediment yield and phosphorus loading if the phosphorus content in sediment is known. Results from this integrated model are compared with other combinations of sediment delivery ratio model and soil erosion models in the next chapter.

The integrated model SPLM is built on SEDMOD and the modified RUSLE. Data required to run SEMOD and the modified RUSLE are then required to run SPLM. The data layers and structure of SPLM are shown in Figure 3.5.1. Some factors such as C factor in soil erosion model are computed using the RUSLE program. A GIS data layer for C factor is then created by joining the tabular data with a coverage file for the watershed. Slope length and slope steepness factor (LS) is computed from DEM data layer directly.

Because SPLM is run under Arc/Info GIS, input data sets in common data format such as DEM and soils which are readily available can be used. The results can be used for a variety of spatial analysis and representation. The integration for SPLM is also written in AML and can be run in Arc/Info environment.

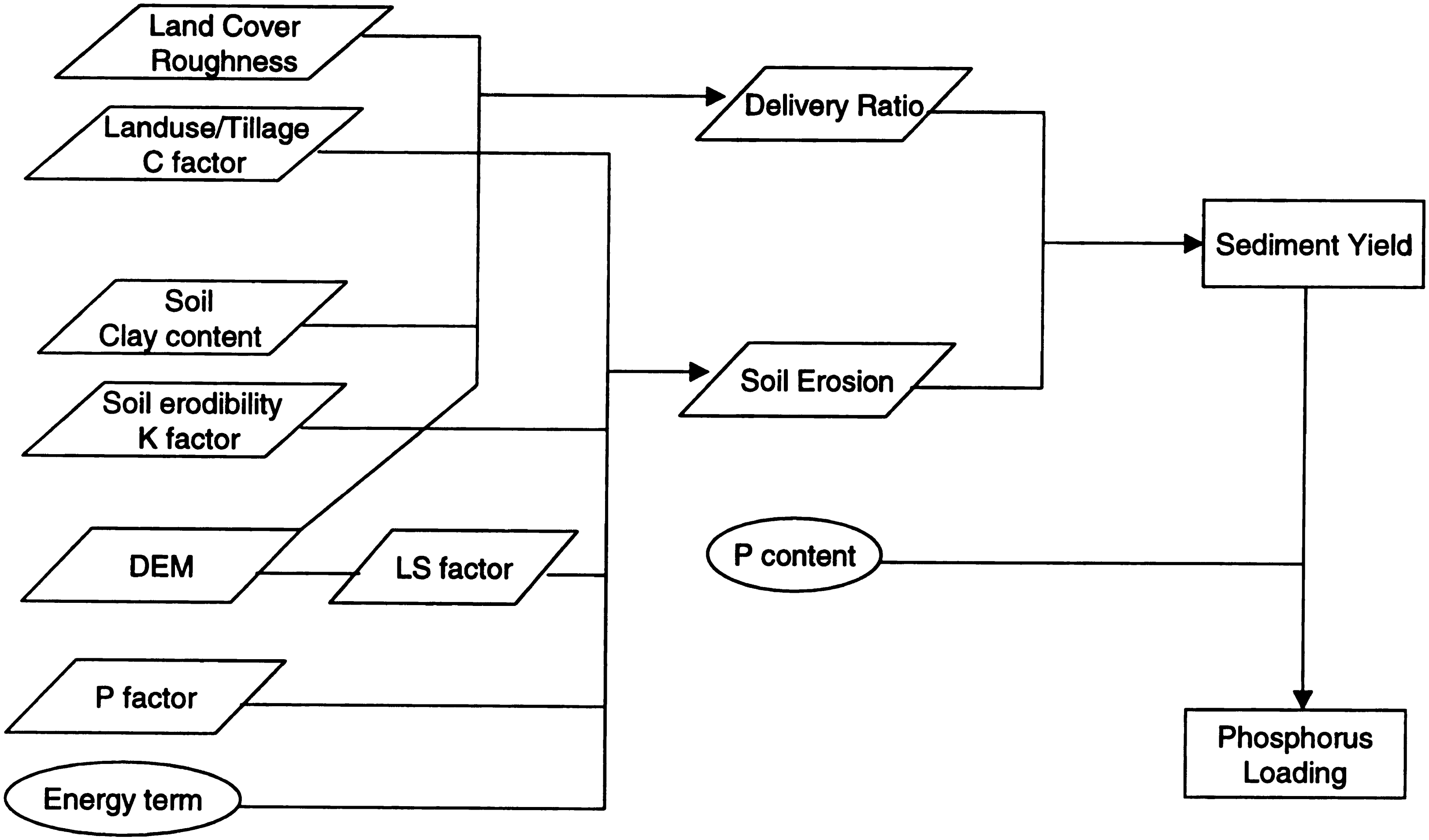

Figure 3.5.1 Integrated Sediment and Phosphorus Loading Model (SPLM)

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Sediment Delivery Ratios

Two models were used to estimate sediment delivery ratio in Marshall Drain Watershed. One is the newly developed spatially distributed model SEDMOD; the second was the spatially lumped empirical model equation [2.3.4]. The reason for choosing equation [2.3.4] for comparison is that it was found in a pervious study conducted in Saginaw Bay watershed of Michigan, that this model provides more accurate results than other spatially lumped statistical models that were tested in the study watershed (Ouyang and Bartholic 1997).

Sediment delivery ratios were calculated for 1991 – 1997 using SEDMOD, which reflected the spatial variations and year-to-year different land uses. Table 4.1.1 lists the maximum, minimum and mean sediment delivery ratios over the grid cells in the watershed. Although these statistical data for sediment delivery ratio are similar over the years, there are some spatial variations of sediment delivery ratios in watershed due to the changes in land use. Figure 4.1.1 shows that sediment delivery ratios in the study watershed based on 1993 and 1996 data. The spatial distribution of sediment delivery ratios are slightly different from year to year due to land use change. Higher delivery ratios give indications of areas that have potential to contribute more sediment.

Sediment delivery ratios were also calculated using an empirical model with drainage-area-based SDR [2.3.4] which is a spatially and temporally lumped model. According to the equation, the calculated sediment delivery ratio is about 0.537 which is relatively high due to the small size of the watershed in which sediments have a short distance to travel to water systems.

Table 4.1.1 The Maximum/Minimum/Mean values of sediment delivery ratios over Marshall Drain Watershed area (1991-1997)

	1991	1992	1993	1994	1995	1996	1997
Min.	0.23	0.25	0.25	0.24	0.22	0.21	0.21
Max.	1.00	1.00	1.00	1.00	1.00	1.00	0.99
Mean	0.365	0.364	0.364	0.364	0.365	0.365	0.365

4.2. Soil Erosion

Four models were used to calculate soil erosion. They are the original form of USLE with EI term substituting R factor for the single events (equation [2.1.1]); modified USLE used in AGNPS (equation [2.1.40]); modified USLE by Onstad and Foster (1974) with a modified energy term W (equation [2.1.38]); and modified RUSLE (MRUSLE), equation [3.3.1]. Soil erosion estimated from these four models for 25 storm events are listed in Table 4.2.1.

The results show the original USLE gave a higher estimate for soil erosion than the other three models, followed by AGNPS which is adjusted by a slope shape factor (SSF). The Onstad-Foster model and MRULSE estimated soil erosion with an average of 8.5 tons per acre per storm and 4 tons per acre per storm, respectively. The original USLE predicts soil erosion ranging from 0.43 to 68.24 tons per acre for storm events with an average of 14.39 tons per acre per storm, while AGNPS estimates soil erosion with an average soil loss of 13.28 tons per acre per storm.

Because no direct measurements were made for soil erosion from the fields in the Marshall Drain watershed, soil erosions estimated from these four models were carried into the comparisons made for sediment yield which the monitored data is available.

Figure 4.2.1 shows the soil erosion in two major storms occurring in 1993 and 1996.

Table 4.2.1 Estimated soil erosion from four single event models

Date	MRUSLE (tons)	Onstad-Foster (tons)	AGNPS (tons)	USLE (tons)
3/27/91	1.106	6.710	11.439	12.394
4/4/91	0.025	0.231	0.398	0.431
4/9/91	0.960	7.715	13.657	14.798
4/15/91	0.383	2.245	3.691	3.999
4/19/91	0.616	2.097	2.856	3.098
4/23/91	0.261	2.193	3.829	4.152
4/24/92	5.650	9.936	13.333	14.438
7/14/92	0.731	7.266	13.103	14.276
4/19/93	42.082	32.677	31.657	34.528
5/4/93	0.839	8.669	16.756	17.194
6/7/93	3.178	26.511	46.516	50.765
6/14/93	0.869	9.072	16.545	18.054
6/19/93	9.740	37.225	62.571	68.240
4/12/94	0.413	1.247	1.811	1.959
4/30/94	0.036	0.315	0.548	0.592
7/20/94	0.281	2.953	5.456	5.903
4/26/95	0.105	0.771	1.273	1.383
7/4/95	0.854	8.947	16.419	17.844
5/10/96	1.209	7.587	13.110	14.154
5/21/96	0.750	5.872	10.462	11.309
6/18/96	29.156	28.281	38.701	41.770
4/5/97	0.389	0.721	0.675	0.730
5/5/97	0.089	0.775	1.374	1.473
5/19/97	0.247	1.715	3.000	3.204
6/23/97	0.175	1.566	2.830	3.023

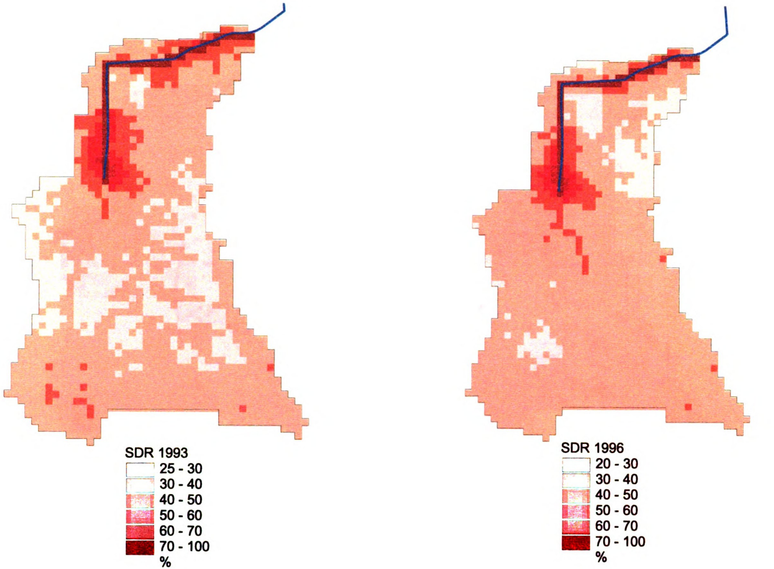

Figure 4.1.1 Estimated Sediment Delivery Ratios in Marshall Drain Watershed (based on 1993 and 1996 data)

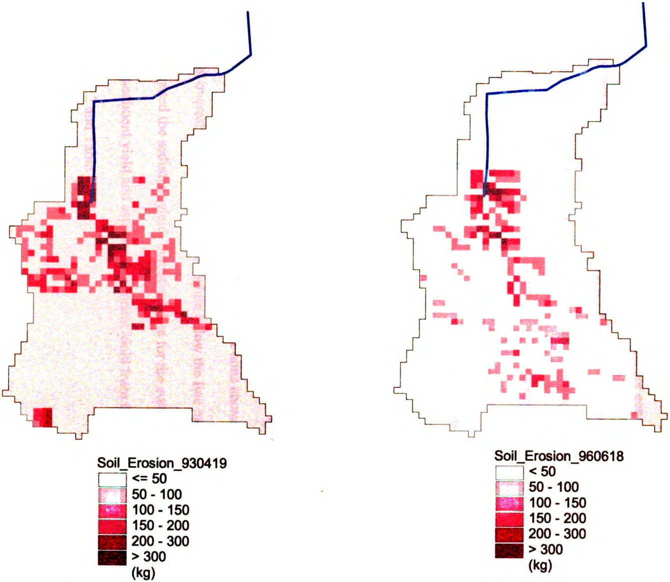

Figure 4.2.1 Estimated Soil Erosion in Marshall Drain Watershed

4.3 Sediment Yield

Sediment yield was calculated using the form of equation [2.4.1], i.e. the product of soil erosion and sediment delivery ratio. The results are generated from a combination of using two sediment delivery ratio models and four soil erosion models, which produce 8 estimates for sediment yield for each storm event. The integrated model, Sediment and Phosphorus Loading Model (SPLM) is based on spatially explicit sediment delivery ratio mode SEDMOD and the Modified RUSLE (MRUSLE). The outcomes of SPLM are compared with results from other 7 combinations of sediment delivery ratio models and soil erosion models.

Table 4.3.3 lists the monitored sediment yield and its estimation based on four soil erosion models and spatially distributed SDR model (SEDMOD). Table 4.3.4 lists the results from the four soil erosion models and an empirical SDR model [2.3.4].

The model results and monitoring data are plotted on Figure 4.3.1- 4.3.3. The line shown on the figure is 1:1, or a perfect fitting line. Points above the 1:1 line indicate that the model overestimated sediment yield while below the line means the model underestimated the sediment yield. Statistical data for the correlation between the measured sediment yield and estimated sediment yield from these 6 models are included in Table 4.3.2 and Table 4.3.3.

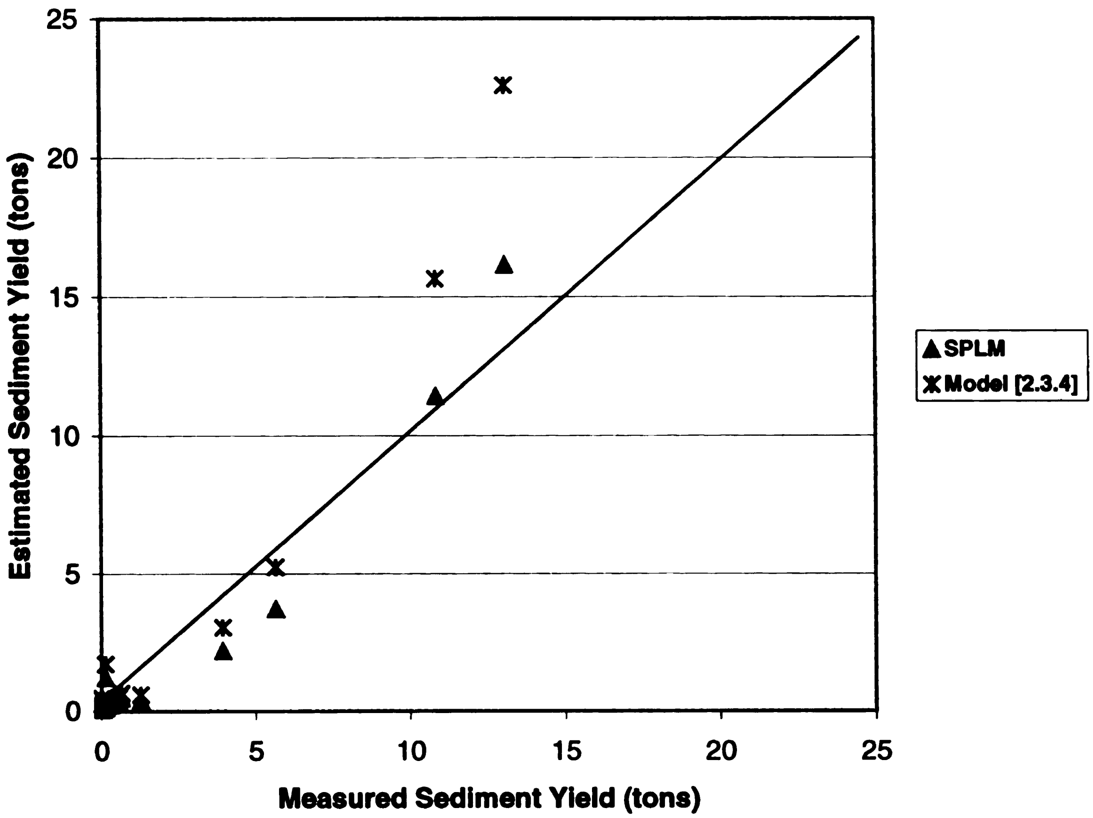

Figure 4.3.1 Monitoring sediment load and estimated sediment load from the modified RUSLE with SEDMOD (SPLM) and SDR Model [2.3.4]

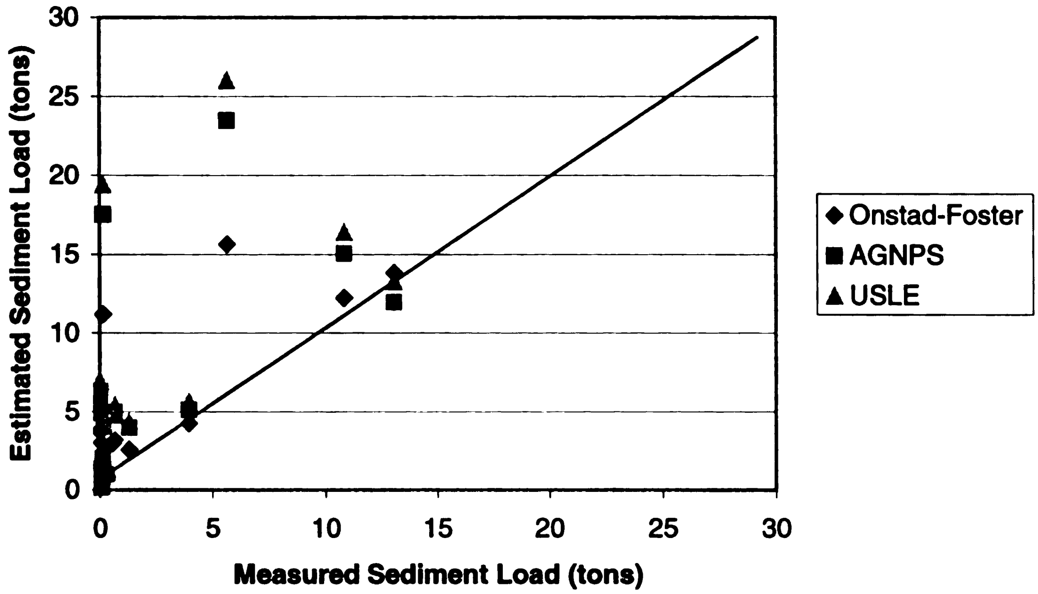

Figure 4.3.2 Measured sediment load and estimated from SEDMOD for delivery ratio, and three soil erosion models.

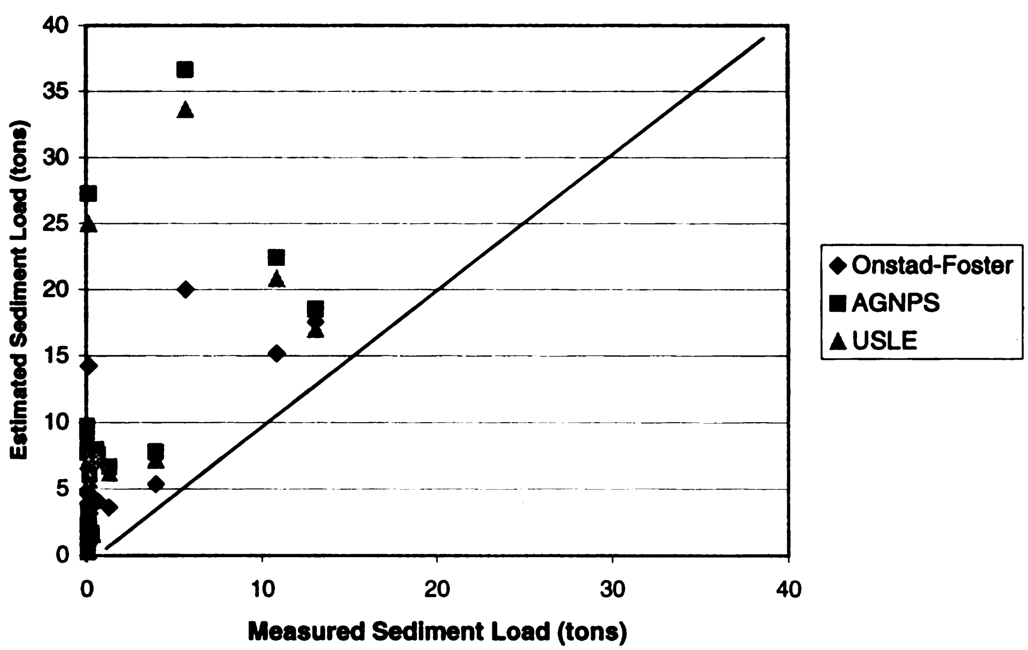

Figure 4.3.3 Measured sediment load and estimated from Equation [2.3.4] for delivery ratio, and three soil erosion models.

Figure 4.3.1 shows the results using the modified RUSLE for soil erosion, and SEDMOD and Equation [2.3.4] for sediment delivery ratios. Statistical data in Table 4.3.1 show that the modified RUSLE with SEDMOD (i.e. SPLM) has the best results with the highest R square (0.95) and the lowest standard error (0.85). With the modified RULSE, empirical sediment delivery ratio model [2.3.4] also has a fairly good fit with monitoring data with a R square of 0.95, but has a higher standard error (2.87). Onstad-Foster version of modified USLE model has R square of 0.62 with SEDMOD which is similar to that with Equation [2.3.4]. AGNPS version of modified USLE which takes into account a slope shape factor does not make much difference with the original USLE, both of which have a poor correlation between the monitoring data and modeling results. They have generally overestimated the sediment yield with both sediment delivery ratio models (Figure 4.3.2 – 4.3.3). It indicates these models have systematic errors.

From the results in this watershed, it is shown that SPLM (the modified RUSLE combined with SEDMOD) provides the most accurate estimates.

To compare the model results and monitoring data, we also used one of the most useful methods to evaluate the modeling results, which is called Model Efficiency (ME). Model efficiency was first used by Nash and Sutchliffe (1970) and later used by many researchers in water related modeling (Green and Stephenson, 1986; Risse et al. 1993; and Rapp et al. 2001). The model efficiency is defined as follows:

$$ME = 1 - \frac{\sum_{i=1}^{n}(Q_{mi} - Q_{ci})\hat{}2}{\sum_{i=1}^{n}(Q_{mi} - \overline{Q_m})\hat{}2} \qquad [4.3.1]$$

Where ME = model efficiency,

Q_{mi} = measured value of event i,

Q_{ci} = computed valued of event i,

$\overline{Q_m}$ = mean of the measured values, and

n = number of events.

The higher the ME value, the better results a model provides. A model provides perfect results when ME is 1. The ME values for the four soil erosion models with two sediment delivery ratio models are listed in Table 4.3.2.

Table 4.3.1 Model Efficiencies (ME)

	SEDMOD				Eq. [2.3.4]			
	MRULSE	Onstad-Foster	AGNPS	USLE	MRULSE	Onstad-Foster	AGNPS	USLE
ME	0.93	-0.05	-1.98	-2.77	0.58	-1.03	-5.97	-7.47

The model efficiency for SPLM is highest (ME=0.93) when SEDMOD is used with the modified RUSLE (MRUSLE). It is better than Eq. [2.3.4] when it is used with the modified RUSLE (ME = 0.58) and also better than other models. This is consistent with statistical analysis data that SPLM (using SEDMOD with the modified RUSLE) has the highest correlation coefficient (R^2 = 0.95) and the lowest standard error (SE = 0.85).

Figure 4.3.4 shows the sediment yield on cell-by-cell basis for two major storms in 1993 and 1996. The results are from SPLM (i.e. SEDMOD and the modified RUSLE). The output map illustrates the high sediment contributing areas in the watershed. By identifying the high contributing areas, it helps prioritize the implementation of Best Management Practices (BMPs) to reduce soil erosion. Equation [2.3.4] is a spatially lumped model and does not have the capability to provide spatial representation of sedimentation. SPLM by integrating SEDMOD, a spatially distributed sediment delivery ratio model, with the modified RUSLE, provides a new alternative modeling approach which is able to identify the risk areas with an improved accuracy.

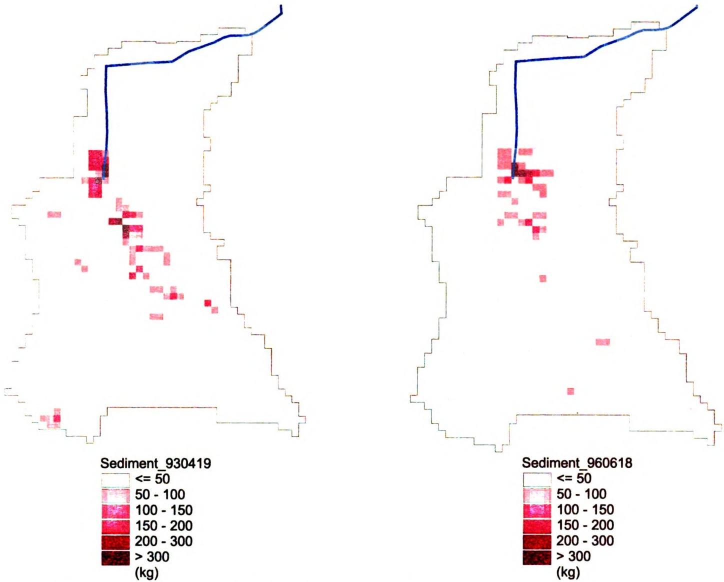

Figure 4.3.4 Estimated Sediment in Marshall Drain Watershed

Table 4.3.2 Monitored sediment yield and its estimation based on spatially distributed SDR model (SEDMOD) and four soil erosion models

Date	Monitored Sediment Yield (tons)	SPLM (tons)	Onstad-Foster (tons)	AGNPS (tons)	USLE (tons)
3/27/91	1.280	0.385	2.573	3.961	4.311
4/4/91	0	0.009	0.088	0.138	0.150
4/9/91	0.562	0.334	2.957	4.727	5.145
4/15/91	0.144	0.133	0.860	1.277	1.390
4/19/91	0.292	0.219	0.820	1.006	1.099
4/23/91	0.043	0.093	0.858	1.348	1.473
4/24/92	3.940	2.190	4.247	5.102	5.597
7/14/92	0.050	0.276	3.022	4.885	5.385
4/19/93	13.073	16.140	13.818	11.961	13.242
5/4/93	0.016	0.322	3.672	5.962	6.606
6/7/93	0.138	1.215	11.176	17.522	19.406
6/14/93	0.012	0.332	3.824	6.232	6.903
6/19/93	5.654	3.708	15.624	23.480	25.979
4/12/94	0.035	0.156	0.518	0.676	0.738
4/30/94	0.027	0.013	0.124	0.195	0.212
7/20/94	0.114	0.104	1.210	2.007	2.193
4/26/95	0.054	0.042	0.339	0.502	0.551
7/4/95	0.005	0.332	3.835	6.314	6.937
5/10/96	0.647	0.462	3.200	4.981	5.415
5/21/96	0.179	0.289	2.499	4.007	4.365
6/18/96	10.846	11.423	12.216	15.056	16.364
4/5/97	0.051	0.161	0.328	0.276	0.301
5/5/97	0.034	0.030	0.286	0.456	0.493
5/19/97	0.051	0.076	0.581	0.921	0.985
6/23/97	0.032	0.055	0.537	0.879	0.940
R^2		0.95	0.62	0.37	0.37
Standard Error		0.85	2.87	4.86	5.38

Table 4.3.3 Monitored sediment yield and its estimation based on spatially lumped SDR model (equation [2.3.4]) and four soil erosion models.

Date	Monitored Sediment Yield (tons)	Modified RUSLE (tons)	Onstad-Foster (tons)	AGNPS (tons)	USLE (tons)
3/27/1991	1.280	0.594	3.603	6.143	6.656
4/4/1991	0	0.013	0.124	0.214	0.231
4/9/1991	0.562	0.516	4.143	7.334	7.947
4/15/1991	0.144	0.206	1.206	1.982	2.147
4/19/1991	0.292	0.331	1.126	1.534	1.664
4/23/1991	0.043	0.140	1.178	2.056	2.230
4/24/1992	3.940	3.034	5.336	7.160	7.753
7/14/1992	0.050	0.393	3.902	7.036	7.666
4/19/1993	13.073	22.598	17.548	17.000	18.542
5/4/1993	0.016	0.451	4.655	8.998	9.233
6/7/1993	0.138	1.707	14.236	24.979	27.261
6/14/1993	0.012	0.467	4.872	8.885	9.695
6/19/1993	5.654	5.230	19.990	33.601	36.645
4/12/1994	0.035	0.222	0.670	0.973	1.052
4/30/1994	0.027	0.019	0.169	0.294	0.318
7/20/1994	0.114	0.151	1.586	2.930	3.170
4/26/1995	0.054	0.056	0.414	0.684	0.743
7/4/1995	0.005	0.459	4.805	8.817	9.582
5/10/1996	0.647	0.649	4.074	7.040	7.601
5/21/1996	0.179	0.403	3.153	5.618	6.073
6/18/1996	10.846	15.657	15.187	20.782	22.430
4/5/1997	0.051	0.209	0.387	0.362	0.392
5/5/1997	0.034	0.048	0.416	0.738	0.791
5/19/1997	0.051	0.133	0.921	1.611	1.721
6/23/1997	0.032	0.094	0.841	1.520	1.623
R^2		0.95	0.61	0.36	0.36
Standard Error		1.20	3.66	6.94	7.56

4.4 Phosphorus Loading

Once the sediment yield was calculated, one could estimate phosphorus loading based on sediment load and phosphorus-to-sediment ratio or phosphorus content in sediment. A previous study has shown that sediment attached phosphorus is the major form in phosphorus loading (Nelson and Logan, 1983). Figure 4.4.1 shows the sediment load and total phosphorus load from the monitoring data in the study watershed. It is illustrated that a good linear relationship exists between phosphorus loading and sediment loading ($R^2 = 0.99$). Thus, the phosphorus content in sediment, or a phosphorus-to-sediment ratio can be obtained from the slope of the line. Based on the monitoring data in the study watershed, the phosphorus-to-sediment ratio is about 2.13 kg phosphorus per ton sediment. The results of phosphorus loading estimated from this method (equation [2.4.2]) are listed in Table 4.4.1 and Table 4.4.2.

Since phosphorus loading is based on the sediment yield and phosphorus content in sediment, its accuracy relies on the accuracy from both factors. Similar to the model efficiency for estimating sediment yield, SPLM has the highest model efficiency (ME = 0.91), followed by the case when the modified RUSLE is used with Eq. [2.3.4] which has the model efficiency of 0.54.

Figure 4.4.2 shows that monitoring phosphorus loading and estimated phosphorus loading along with the 1:1 line. Points are distributed in the both sides of the 1:1 line, indicating that the model does not systematically overestimate or underestimate the phosphorus loading. The correlation coefficient for SPLM is 0.936 with the standard error of 2.12. It is better than the modified RUSLE with Eq. [2.3.4] which has a correlation efficient of 0.935 and standard error of 2.95. Results from other models are plotted on Figures 4.3.3 and 4.3.4, which show the similar trends as sediment loads.

The advantage of using SPLM based on SEDMOD with the modified RUSLE is that not only can it provide more accurate results, it also provides the spatial representation for helping identify the high contributing areas. This information can help prioritize the efforts for more efficient nonpoint source pollution control.

Similarly to results of sediment yield, SPLM based on SEDMOD with the modified RUSLE provides more accurate results than other models tested in this study. Figure 4.4.5 shows phosphorus loading in two major storms in 1993 and 1996. The output map helps identify the potential high phosphorus contributing areas in the watershed.

The fact that phosphorus load is highly correlated with sediment load suggests that management practices that are used to control sediment may control phosphorus loading as well.

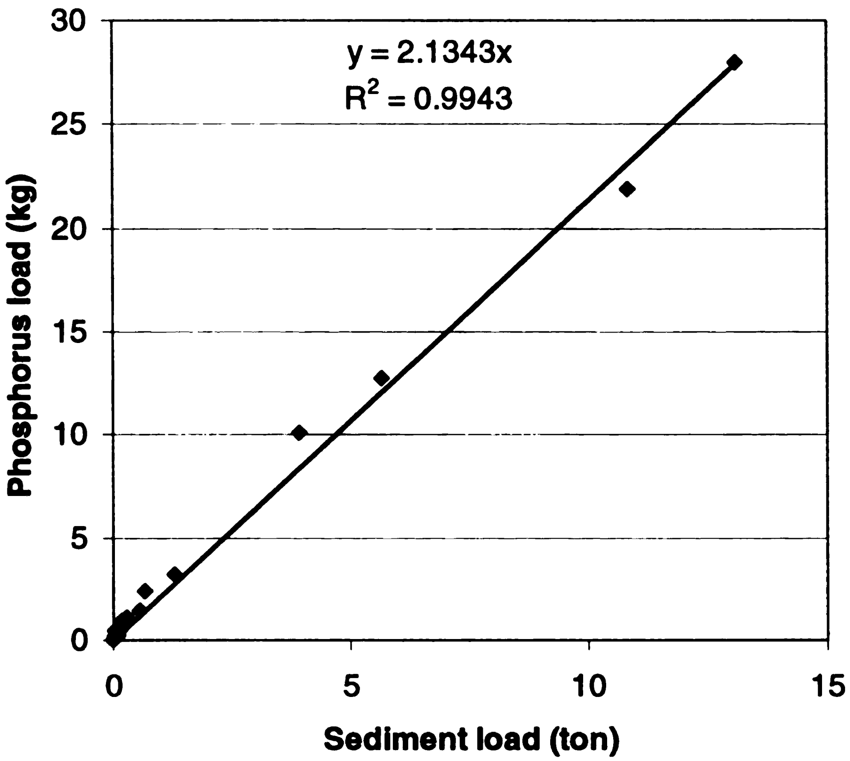

Figure 4.4.1 Monitored sediment load and total phosphorus load

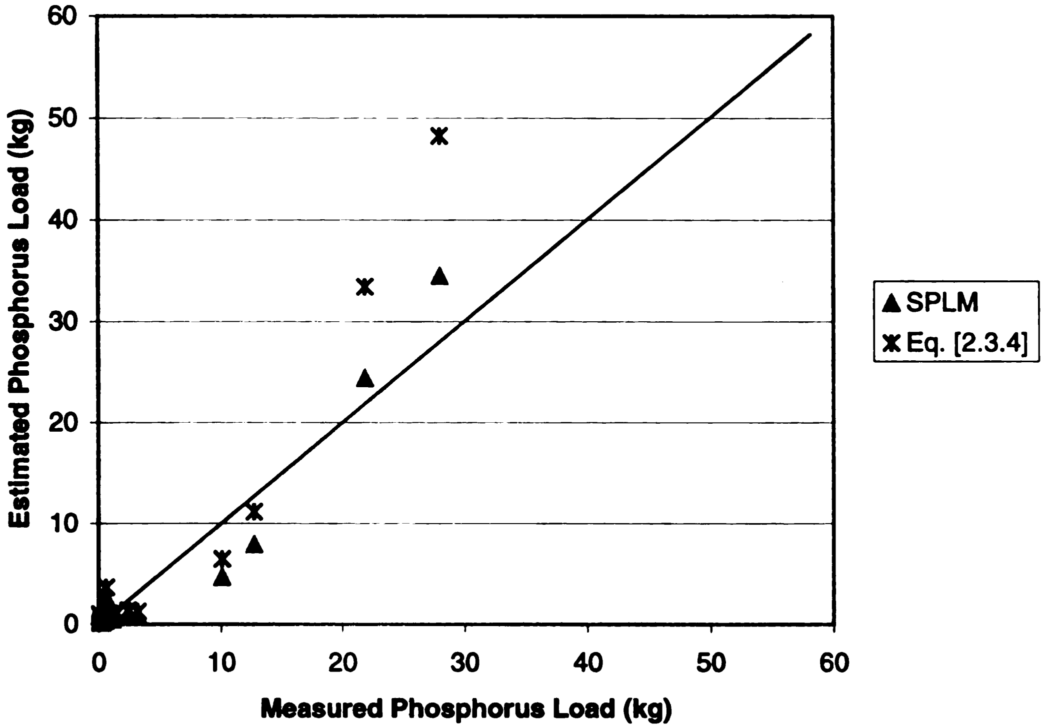

Figure 4.4.2 Monitoring and estimated phosphorus loading from the modified RUSLE with SEDMOD and SDR Model [2.3.4]

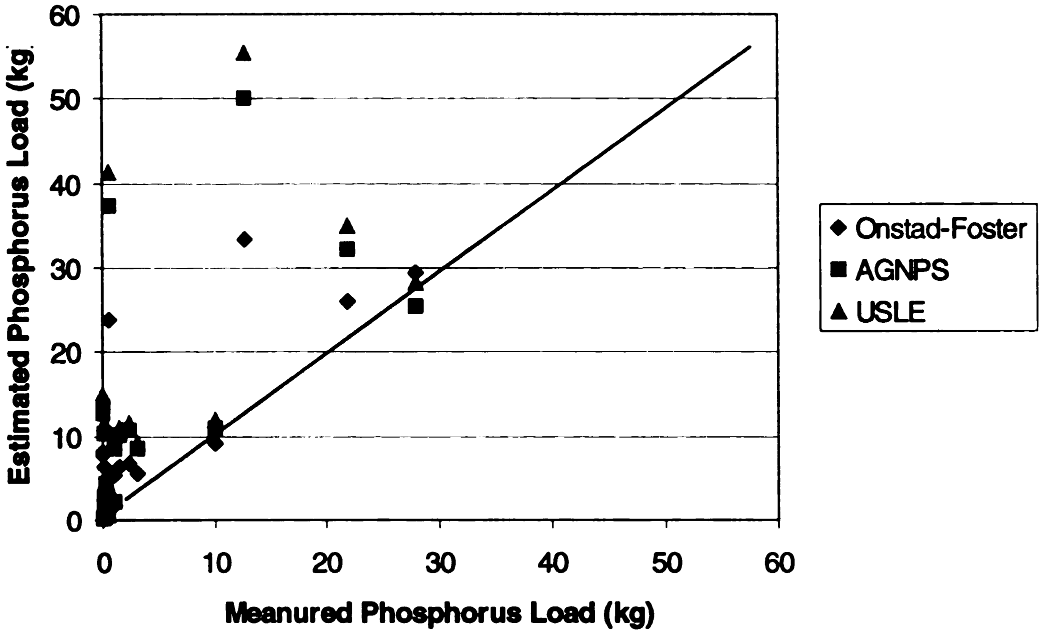

Figure 4.4.3 Measured phosphorus load and estimated from SEDMOD for delivery ratio, and three soil erosion models.

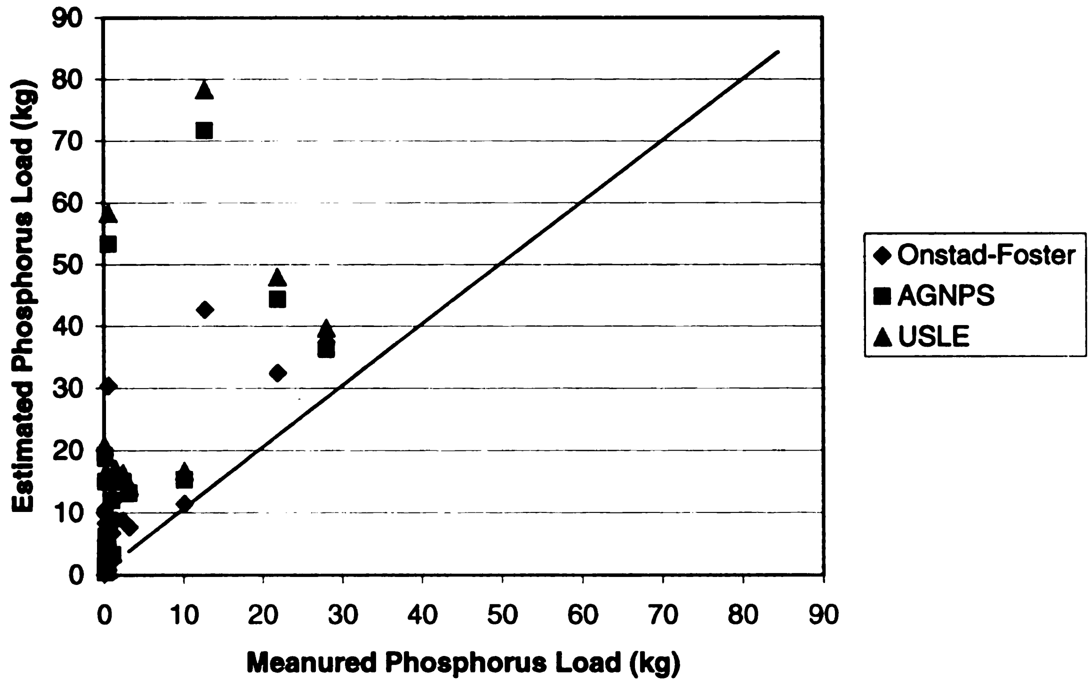

Figure 4.4.4 Measured phosphorus load and estimated from Eq. [2.3.4] for delivery ratio, and three soil erosion models.

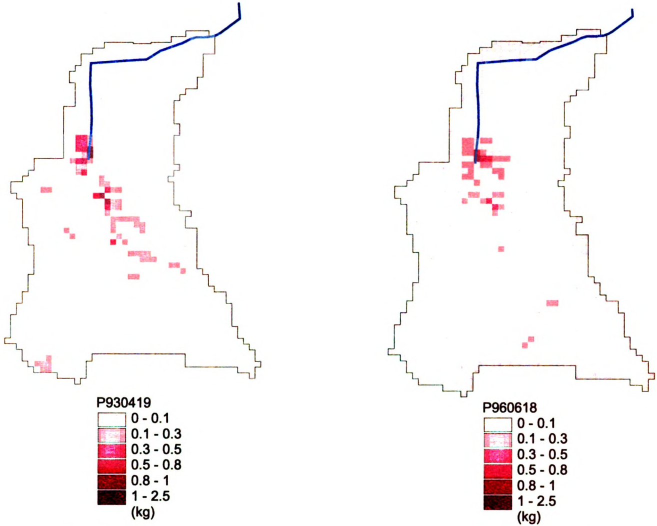

Figure 4.4.3 Estimated P load (two storms) for Marshall Drain Watershed

Table 4.4.1 Monitored phosphorus load and its estimation based on sediment phosphorus content, spatially distributed SDR model (SEDMOD) and four soil erosion models

Date	Monitored Phosphorus Load (kg)	SPLM (kg)	Onstad-Foster (kg)	AGNPS (kg)	USLE (kg)
3/27/91	3.18	0.822	5.492	8.454	9.201
4/4/91	0	0.019	0.188	0.295	0.320
4/9/91	1.42	0.713	6.311	10.089	10.981
4/15/91	0.49	0.284	1.835	2.726	2.967
4/19/91	1.09	0.467	1.750	2.147	2.346
4/23/91	0.199	0.198	1.831	2.877	3.144
4/24/92	10.1	4.674	9.064	10.889	11.946
7/14/92	0.22	0.589	6.450	10.426	11.493
4/19/93	28	34.448	29.492	25.528	28.262
5/4/93	0.06	0.687	7.837	12.725	14.099
6/7/93	0.58	2.593	23.853	37.397	41.418
6/14/93	0.05	0.709	8.162	13.301	14.733
6/19/93	12.75	7.914	33.346	50.113	55.447
4/12/94	0.22	0.333	1.106	1.443	1.575
4/30/94	0.15	0.028	0.265	0.416	0.452
7/20/94	0.24	0.222	2.583	4.284	4.681
4/26/95	0.22	0.090	0.724	1.071	1.176
7/4/95	0.05	0.709	8.185	13.476	14.806
5/10/96	2.4	0.986	6.830	10.631	11.557
5/21/96	1	0.617	5.334	8.552	9.316
6/18/96	21.9	24.380	26.073	32.134	34.926
4/5/97	0.46	0.344	0.700	0.589	0.642
5/5/97	0.15	0.064	0.610	0.973	1.052
5/19/97	0.27	0.162	1.240	1.966	2.102
6/23/97	0.19	0.117	1.146	1.876	2.006
R^2		0.94	0.62	0.38	0.38
Standard Error		2.12	6.09	10.34	11.45

Table 4.4.2 Monitored phosphorus load and its estimation based on sediment phosphorus content, spatially lumped SDR model (equation [2.3.4]) and four soil erosion models.

Date	Monitored Phosphorus Load (kg)	Modified RUSLE (kg)	Onstad-Foster (kg)	AGNPS (kg)	USLE (kg)
3/27/1991	3.18	1.268	7.690	13.111	14.206
4/4/1991	0	0.028	0.265	0.457	0.493
4/9/1991	1.42	1.101	8.842	15.653	16.961
4/15/1991	0.49	0.440	2.574	4.230	4.582
4/19/1991	1.09	0.706	2.403	3.274	3.551
4/23/1991	0.199	0.299	2.514	4.388	4.759
4/24/1992	10.1	6.475	11.389	15.282	16.547
7/14/1992	0.22	0.839	8.328	15.017	16.362
4/19/1993	28	48.231	37.453	36.283	39.574
5/4/1993	0.06	0.963	9.935	19.204	19.706
6/7/1993	0.58	3.643	30.384	53.313	58.183
6/14/1993	0.05	0.997	10.398	18.963	20.692
6/19/1993	12.75	11.162	42.665	71.715	78.211
4/12/1994	0.22	0.474	1.430	2.077	2.245
4/30/1994	0.15	0.041	0.361	0.627	0.679
7/20/1994	0.24	0.322	3.385	6.253	6.766
4/26/1995	0.22	0.120	0.884	1.460	1.586
7/4/1995	0.05	0.980	10.255	18.818	20.451
5/10/1996	2.4	1.385	8.695	15.025	16.223
5/21/1996	1	0.860	6.729	11.990	12.962
6/18/1996	21.9	33.417	32.414	44.355	47.872
4/5/1997	0.46	0.446	0.826	0.773	0.837
5/5/1997	0.15	0.102	0.888	1.575	1.688
5/19/1997	0.27	0.284	1.966	3.438	3.673
6/23/1997	0.19	0.201	1.795	3.244	3.464
R^2		0.94	0.62	0.37	0.37
Standard Error		2.95	7.76	14.75	16.07

4.5 Assessing Annual Sediment and Phosphorus Loading

The Revised Universal Soil Loss Equation (RUSLE) was used to predict average annual soil loss. The modified RUSLE (MRUSLE) was used to estimate soil loss for single events. Sediment and Phosphorus Loading Model (SPLM) is developed based on SEDMOD and MRUSLE, which is a single event model for estimating sediment and phosphorus loads. When the original RUSLE was used, in place of the modified RUSLE, SPLM can be used to estimate annual sediment and phosphorus loads. Unfortunately, there were no data available in the study watershed to verify sediment and phosphorus loading on an annual basis. SPLM for annual sediment and phosphorus loading assessment needs to be tested in the future in other watersheds where annual data are available or collected.

CHAPTER FIVE

CONCLUSIONS

Although great progress has been made in controlling point source pollution in the past three decades, nonpoint source pollution, particularly from agriculture, is considered the leading cause for water pollution in the United States. Sediment and phosphorus are two major pollutants that are responsible for water pollution. Soil erosion degrades soil productivity and causes water quality problems through sediments and nutrients. Excessive fertilization, particularly from phosphorus, causes surface water deterioration. Efforts have been made to minimize agricultural nonpoint source pollution such as implementing the best management practices. Controlling agricultural nonpoint source pollution requires the information and knowledge on identifying the source areas and quantifying the loading. Water monitoring program is helpful but costly. Science based modeling provides an alternative to provide a quantitative estimation on soil erosion, sediment and nutrient loadings, and helps identify the source areas.

The goal of this research is to investigate various agricultural nonpoint source pollution modeling options, and develop a GIS based and spatially distributed approach for estimating soil erosion, sediment and phosphorus loading in agricultural watershed context.

Spatially lumped and temporally lumped models that are often used in soil erosion and sediment delivery generally can not provide good site-specific and event-specific estimation for the varying conditions. Most agricultural NPS models generally require extensive data inputs which are often not readily available in many cases. This dissertation has investigated and evaluated various commonly used models with ground truth water monitoring data. A spatially explicit sediment delivery model (SEDMOD) has been integrated with the modified Revised Universal Soil Loss Equation (MRUSLE). This integrated model led to the development of Sediment and Phosphorus Loading Model – SPLM which is capable of calculating soil erosion, sediment delivery ratios, sediment yield and phosphorus loading. Because it is also integrated with Geographic Information System, it has automated spatial data processing and provided spatial representation of NPS pollution in the watershed context. From the output maps of the model, high risk areas can be identified to help prioritize and/or initialize the best management practice implementation.

In this study watershed, the spatially explicit sediment delivery model not only provides information for spatial analysis, but also improves the accuracy of modeling compared to the spatially lumped model. The new model shows less systemic errors than spatially lumped models which most often overestimated the sediment. The integrated model SPLM requires only a few data layers (i.e. soils, DEM, streams, surface roughness) which are readily available or can be easily created.

For the soil erosion sub-model used in SPLM, both rainfall and runoff effects on soil erosion have been taken into account in energy term. The accuracy of the modified Revised Universal Soil Loss Equation (MRUSLE) model is improved compared to the original equation which primarily considers the rainfall energy. When the energy term is modified, the Revised Universal Soil Loss Equation is capable of estimating soil erosion for single storm events although the model was initially designed for predicting long term average annual soil loss.

Phosphorus loading is calculated based on sediment yield and phosphorus-sediment ratio in SPLM. The water quality monitoring data showed that sediment attached phosphorus is the major form of phosphorus that is transported to stream system. Phosphorus loading is found to be directly related to sediment yield. In this watershed, total phosphorus is highly correlated with sediment yield ($R^2 = 0.99$). This suggests that management practices that are used to control sediment may control phosphorus loading as well.

Among the combined uses of several sediment delivery ratio models and soil erosion models, the integrated model with SEMOD and the modified RUSLE (i.e. SPLM) has been proven to provide the most accurate estimation on sediment yield and phosphorus loading in the study watershed. SPLM has a user-friendly menu driven interface and requires a minimum input data set.

In summary, the development of Sediment and Phosphorus Loading Model (SPLM) based the spatially explicit sediment delivery model and the modified RUSLE, provides an easy-to-use tool for agricultural nonpoint source pollution assessment. Compared to other models used in the study watershed, SPLM estimates soil erosion, sediment delivery ratio, and sediment and phosphorus loading on a watershed basis with an improved accuracy. It has demonstrated the benefits of using spatially explicit model combined with GIS technology. This allows users to identify the source areas and estimate NPS loadings which may lead to a cost-effective watershed management planning for minimizing agricultural nonpoint source pollution.

5.1 Recommendations for Future Study

Although SPLM was used to estimate soil erosion, sediment load, and phosphorus load for a single storm, it could be used to estimate annual average soil erosion, sediment load, and phosphorus by simply using Revised Universal Soil Loss Equation (RUSLE) to replace the modified RUSLE. Because RULSE can predict annual average soil erosion, when used with SEDMOD, it will provide an estimation of annual average sediment load and phosphorus load. This has yet to be tested in other watersheds where annual data are available.

Like spatially explicit sediment delivery model (SEDMOD), Sediment and Phosphorus Loading Model (SPLM) is a newly developed model and has not been widely tested on other watersheds. Further calibrations and verifications may be needed for its application in other watersheds with different conditions.

APPENDICES

Appendix A Estimates of Manning's n for overland flow and soil covers based on n=0.01 for smooth bare soil (Engman, 1985)

Treatment		Manning's n
Cornstalk residue applied to fallow surface	1 ton/acre	0.020
	2 tons/acre	0.040
	4 tons/acre	0.070
Cornstalk residue disk-harrow incorporated	1 ton/acre	0.012
	2 tons/acre	0.020
	4 tons/acre	0.023
Wheat straw mulch	0.25 ton/acre	0.015
	0.5 ton/acre	0.018
	1 ton/acre	0.032
	2 tons/acre	0.070
	4 tons/acre	0.074
Grass	Sparse	0.015
	Poor	0.023
	Fair	0.032
	Good	0.046
	Excellent	0.074
	Dense	0.150
	Very dense	0.400
Small grain (20% to full maturity)		
Across slope	Poor stand	0.018
	Moderate stand	0.023
	Good stand	0.032
	Dense	0.046
Upslope and downslope	Poor stand	0.012
	Moderate stand	0.015
	Good stand	0.023
	Dense	0.032

Appendx B The program code to calculate soil erosion and sediment yield based on results from SEDMOD and Modified RULSE

```
/******************************************************************
/* File name: erosion_sediment.aml                                *
/*                                                                *
/* Purpose:                                                       *
/* This program to calculate the soil erosion and                 *
/* sediment yield based on the sediment delivery ratio            *
/* computed from SEDMOD and the modified Revised Soil             *
/* Loss Equation.                                                 *
/*                                                                *
/* Usage: under Arc/Info prompt,                                  *
/* Arc: &run erosion_sediment.aml input.data output.file          *
/*                                                                *
/* Written by Da Ouyang                                           *
/* Date: August 2000                                              *
/*                                                                *
/******************************************************************


&args input_file output_file

&if [null %input_file%] or [null %output_file%] &then
    &return &warning Specify the file names. - Usage: PORG.aml
IN_file OUT_file

/******************************************************************
/* open the input file to read - outside of the loop - open one
/*
/******************************************************************

&s my_in := [open %input_file% openstat -r]

&if %openstat% ne 0 &then
    &return &error The input data file can not open to read

/******************************************************************
/* read the records from the input file, skip the first two lines
/* outside of the loop
/*
/******************************************************************

&s line1 := [read %my_in% readstat]
&s line2 := [read %my_in% readstat]

/* open the file to write records - outside of the loop
/* open once
&s my_out := [open %output_file% openstat -w]

&if %openstat% ne 0 &then
```

```
    &return &error The file can not open to write

/* open the file to read the monitoring data for comparsion
&s monitoring = marshall.data
&s my_data := [open %monitoring% openstat -r]
&if %openstat% ne 0 &then
    &return &error The monitoring data file can not open to read

&s count = 1

/* check if it reaches the end of file, which returns 102
&do &while %readstat% ne 102

  /* After read 25 storms, there is a sperator
  &if %count% eq 26 &then &do
    &s terms := [read %my_in% readstat]
    &s count = 0
  &end

  &if %count% ne 0 &then &do
    &do I := 1 &to 4
      &s record%I% := [read %my_in% readstat]
    &end

  /* To save the records, the file has to be closed before return
  &if %readstat% eq 102 &then &do
        &s writestat = [write %my_out% [quote %terms%]]
/*        &s writestat = [write %my_out% ------------------]
        &s closestat := [close -all]
/*       &system perl out.cgi
        &return &inform It has reached the END OF FILE - DONE
   &end

    /*  read the monitoring data
    &s measured_data := [read %my_data% readstat]

    /* To read again, the file has to be closed then open again
to read
    &if %readstat% eq 102 &then &do

        &s writestat = [write %my_out% [quote %terms%]]
/*        &s writestat = [write %my_out% -----------------]

        &s closestat := [close %my_data%]
        &s my_data := [open %monitoring% openstat -r]
        &s measured_data := [read %my_data% readstat]
    &end
```

```
/*************************************************************
/* Erosion calculation for marsahll watershed
/*
/* &if [exists soil_loss -GRID] &then kill soil_loss
/* &sv wshed  = [response 'Enter watershed name ']
/*
/*************************************************************

&sv wshed = Marshall

/* &sv year1  = [response 'Enter the year YY ']
/* &sv month1 = [response 'Enter the month MM ']
/* &sv date1  = [response 'Enter the date DD ' ]
/* &sv ei     = [response 'Enter the EI value ']

&sv year1  = %record1%
&sv month1 = %record2%
&sv date1  = %record3%
&sv ei     = %record4%

&type
&type ---> Erosion calculation for %wshed% watershed
%year1%%month1%%date1% <---
&type

&if %date1% < 16 &then
  &sv date2 = 1
&if %date1% > 15 &then
  &sv date2 = 2

/***************************************************************
/* define the data file path
/*
/***************************************************************

&sv ls = /home/mydata/ls/%wshed%_ls
&sv sdr = /home/mydata/sdr/%wshed%/sdr%year1%/del_ratio
&sv k = /home/mydata/k/k%month1%%date2%
&sv c = /home/mydata/c/c%year1%%month1%%date2%

&if %:program% <> GRID &then grid

&messages &on

/***************************************************************
/* soil_loss = E * K * C * LS * P   ( in tons / acre / storm)
/*
/* where E = energy term
/*
/***************************************************************
```

```
/**************************************************************
/*
/*  define a name for different storms
/*
/**************************************************************

&sv erosion = er%year1%%month1%%date1%
&sv sediment = sy%year1%%month1%%date1%
&sv erosion2 = e%year1%%month1%%date1%
&sv sediment2 = s%year1%%month1%%date1%
&sv sum_er = te%year1%%month1%%date1%
&sv sum_sy = ts%year1%%month1%%date1%

&if [exists %erosion% -GRID] &then kill %erosion%
%erosion% = %ei% * %k% * %c% * %ls% * 1

describe %erosion%

/**********************************************************
/* convert short ton to kg, convert square meters to acre
/*
/**********************************************************

&if [exists %erosion2% -GRID] &then kill %erosion2%
%erosion2% = 907 * %erosion% * %grd$dx% * %grd$dy% / 4047

DOCELL

  %sum_er% += %erosion2%

END

&s result1 = [show %sum_er%]

&type The total soil loss is %result1% Kg from this storm event

/**************************************************************
/* write a record in the output file
/*  single quote is needed if the record contains a space
/*
/**************************************************************

&s sperator = <---%year1%%month1%%date1%--->

&s writestat = [write %my_out% [quote %sperator%]]

&s writestat = [write %my_out% [quote %result1%]]
```

```
/****************************************************************
/* calculate sediment yield based on soil erosion
/*
/* sediment delivery ratio needs to be divided by 100
/*
/****************************************************************

&if [exists %sediment% -GRID] &then kill %sediment%
%sediment% = %erosion% * (float(%sdr%) / 100)

describe %sediment%

/* converted a ton to kilograms, converted square memters to acre
&if [exists %sediment2% -GRID] &then kill %sediment2%
%sediment2% = 907 * %sediment% * %grd$dx% * %grd$dy% / 4047

DOCELL

  %sum_sy% += %sediment2%

END

&s result2 = [show %sum_sy%]

&type The total sediment yield is %result2% Kg from this storm
event

/*  Write a record in the output file
&s delta = %result2% - %measured_data%
&if %measured_data% eq 0 &then
    &s delta2 = NA
&else
    &s delta2 = %delta% / %measured_data%

&s writestat = [write %my_out% [quote %result2%, %measured_data%,
%delta%, %delta2%]]

/* delete variables
&dv %sum_sy% %sum_er% %result1% %result2% %delta% %delta2%

kill %erosion% all
kill %erosion2% all
kill %sediment% all
kill %sediment2% all

&end      /* end of   &if %count% eq 0 &then &do

&s count = %count% + 1
```

```
/******************************************************
/* End the loop of reading input file
/*
/******************************************************

&end     /* end of &do &while

/* close the output file
&s closestat := [close -all]

&return
```

Appendix C Monitoring data from grab samples from Marshall Drain watershed

DATE	TIME	Flow	COD	O-P	T-P	Residue
		(cfs)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
5/2/1990	15:45	0.07	8		0.03	4
5/9/1990	11:25	0.02	8		0.029	5
5/14/1990	14:48	0.02	7		0.023	4
6/5/1990	15:33	0.2	7		0.032	4
6/19/1990	11:55	0.07	6		0.04	4
1/30/1991	13:23		5	0.004	0.053	9
5/29/1991	10:30	0.3	13	0.011	0.041	8
4/7/1992	8:15	0.4	10	0.002	0.014	4
4/27/1992	14:00	1	17		0.066	7
4/30/1992	13:10	0.6	16	0.01	0.025	4
5/11/1992	9:00	0.3	5	0.012	0.017	4
5/24/1992	8:15	0.2	10	0.013	0.03	4
7/13/1992	13:55	0.07	5	0.022	0.046	10
04/26/93	13:00	0.39	12		0.060	21
05/03/93	11:40	0.41	6	0.012	0.028	4
05/10/93	08:20	0.3	11	0.011	0.021	4
05/17/93	08:45	0.18	7	0.010	0.023	4
05/24/93	13:40	0.15	10	0.019	0.041	5
06/02/93	13:50	0.15	6	0.005	0.030	4
06/14/93	12:57	0.45	16	0.012	0.075	6
06/21/93	14:00	3.8	22		0.112	4
06/28/93	09:48	0.32	14	0.037	0.074	11
07/06/93	12:20	0.28	11	0.028	0.042	7
07/13/93	11:35	0.32	12	0.020	0.036	4
07/19/93	16:10	0.26	9	0.200	0.032	4
07/29/93	13:30	0.25	6	0.019	0.033	4
04/08/94	12:00		6	0.008	0.016	4
04/14/94	12:00	0.5	18	0.012	0.032	4
04/19/94	12:00	0.05	12	0.01	0.03	4
04/26/94	12:00	0.26	13	0.006	0.029	4
05/03/94	12:00	0.45	5	0.01	0.023	4
05/10/94	12:00	0.34	20	0.01	0.018	4
05/17/94	12:00	0.23	8	0.06	0.02	4

05/24/94	12:00	0.2	11	0.014	0.05	5
06/01/94	12:00	0.16	6	0.024	0.045	6
06/07/94	12:00	0.13	11	0.032	0.058	8
06/14/94	12:00	0.12	11	0.036	0.064	9
06/21/94	12:00	0.07	5	0.48	0.074	8
06/28/94	12:00	0.36	15	0.035	0.062	4
07/05/94	12:00	0.24	28	0.001	0.105	6
07/12/94	12:00	0.12	10	0.027	0.041	6
07/19/94	12:00	0.11	7	0.027	0.039	7
07/26/94	12:00	0.23	11	0.03	0.041	9
08/02/94	12:00		7	0.027	0.049	4
08/09/94	12:00		11	0.022	0.038	5
08/16/94	12:00		23	0.077	0.105	4
08/26/94	12:00		12	0.027	0.039	4
08/30/94	12:00		8	0.02	0.025	5
04/04/95	12:00		8	0.007	0.032	4
04/12/95	09:57		22	0.029	0.086	4
04/17/95	16:10		8	0.009	0.022	5
04/26/95	10:05	0.4	9	0.006	0.016	4
05/01/95	08:26	0.35	13	0.005	0.014	4
05/08/95	12:30	0.31	8	0.006	0.019	4
05/18/95	15:39	0.23	8	0.011	0.032	4
05/24/95	09:50	0.36	29	0.079	0.16	29
06/01/95	11:45	0.18	11	0.027	0.048	6
06/08/95	09:25	0.16	11	0.027	0.054	6
06/15/95	10:00	0.12	5	0.021	0.052	6
06/21/95	10:00	0.11	24	0.03	0.46	7
06/28/95	09:52	0.13	10	0.032	0.127	49
07/06/95	12:30	0.28	11	0.026	0.047	4
07/13/95	09:30	0.18	15	0.028	0.077	24
07/20/95	09:30	0.22	5	0.033	0.072	8
07/27/95	09:20	0.28	14	0.035	0.06	4
08/11/95	09:00			0.038	0.063	6
08/18/95	11:00			0.046	0.07	4
08/28/95	09:15		5	0.035	0.07	6
4/4/1996	8:50	0.45	18	0.011	0.021	4
4/9/1996	9:16	0.34	10	0.01	0.026	4
4/18/1996	12:00	0.38	8	0.053	0.041	4
4/23/1996	9:30	0.41	5	0.011	0.028	4
4/30/1996	8:41	0.38	24	0.032	0.08	13

5/7/1996	9:45	0.38	10	0.011	0.021	4
5/14/1996	11:30	0.49	26	0.023	0.065	4
5/22/1996	10:27	1.02	21	0.016	0.061	13
5/30/1996	9:30	0.45	13	0.013	0.056	4
6/4/1996	9:20	0.38	6	0.013	0.026	4
6/11/1996	10:30	0.41	10	0.011	0.035	4
6/20/1996	21:07	1.48	23	0.074	0.123	8
6/25/1996	11:00	0.72	12	0.028	0.046	4
7/2/1996	11:00	0.49	15	0.016	0.047	4
7/10/1996	10:00	0.41	12	0.017	0.034	4
7/16/1996	10:00	0.41	10	0.016	0.036	5
7/24/1996	11:20	0.30	10	0.019	0.042	7
7/31/1996	7:50	0.38	15	0.02	0.043	11
8/6/1996	13:00	0.41	6	0.023	0.038	15
8/13/1996	10:30	0.30	5	0.012	0.037	8
4/1/1997	10:50	0.85	9	0.011	0.017	4
4/7/1997	13:06	0.80	18	0.006	0.018	4
4/13/1997	12:00	0.60	16	0.004	0.015	4
4/22/1997	13:50	0.45	5	0.007	0.015	4
4/29/1997	12:00	0.35	5	0.004	0.02	4
5/13/1997	12:51	0.48	16	0.002	0.021	7
5/28/1997	9:20	0.25	21	0.006	0.092	6
6/4/1997	9:20	0.23	18	0.02	0.039	4
6/10/1997	9:11	0.10	24	0.008	0.1	5
6/17/1997	8:40	0.20	17	0.013	0.029	4
6/30/1997	9:21	0.30	15	0.016	0.049	12
7/8/1997	14:45	0.30	19	0.029	0.045	7
7/15/1997	15:00	0.30	12	0.021	0.038	4
7/22/1997	10:30	0.28	14	0.025	0.045	4
7/29/1997	10:30	0.20	7	0.029	0.043	10
8/5/1997	9:44	0.23	8	0.023	0.037	7
8/11/1997	11:07	0.18	10	0.024	0.046	4

Appendix D Calculated soil-loss ratio (SLR) from Revised Universal Soil Loss Equation

```
        RUSLE Version: SWCS1.05pre_d                 Input File: 1CC

                                                corn grain following corn grain
                                                      spring cult.
                                                       row cult. 1x
                                                      125 bu. yield
                                                      zone 102b

                              - Inputs for C-Factor -

                              city code: 22002   GRAND RAPIDS         MI
  adjust for soil moisture depletion: NO
 % surface covered by rock fragments: 0
 surface cover function; B-value code: (1) normal conditions


 1/2   crop: corn;125bu 90day 30"  senescence code: NO
---Date--------Field Operation-----Res. Add. (#/A)--------New Growth Set------
|4/20/2       cult;prim-swp 6-12 N                                           |
|5/5/2        planter;dbl.dsk.op N                                           |
|5/15/2       anhyd applic; disk N                                           |
|6/5/2        cult;row-mult sweepN                                           |
|10/15/2      harvest                    7000                                |
------------------------------------------------------------------------------


 2/2   crop: corn;125bu 90day 30"  senescence code: NO
---Date--------Field Operation-----Res. Add. (#/A)--------New Growth Set------
|4/20/3       cult;prim-swp 6-12 N                                           |
|5/5/3        planter;dbl.dsk.op N                                           |
|5/15/3       anhyd applic; disk N                                           |
|6/5/3        cult;row-mult sweepN                                           |
|10/15/3      harvest                    7000                                |
------------------------------------------------------------------------------

                                - Results By Crops -
                                                                    C
    crop                       start date    end date    %EI       factor
---------------------------------------------------------------------------
| corn;125bu 90day 30"          4/20/2       4/20/3     100.0      0.08    |
| corn;125bu 90day 30"          4/20/3       4/20/4     100.0      0.08    |
------------------------------------------ Rotation C Factor = 0.08 -----


                              - Results By Operations -

 crop # 1/2: corn;125bu 90day 30"    previous crop: corn;125bu 90day 30"

                          % res. cover    op.          date
     operation              after op.    date          next op.    SLR      %EI
------------------------------------------------------------------------------
| cult;prim-swp 6-12 N       53         4/20/2        5/5/2       0.054    3.3  |
| planter;dbl.dsk.op N       44         5/5/2         5/15/2      0.072    2.7  |
| anhyd applic; disk N       28         5/15/2        6/5/2       0.123    9.7  |
| cult;row-mult sweepN       19         6/5/2         10/15/2     0.088   69.4  |
| harvest                    93         10/15/2       4/20/3      0.02    15.0  |
------------ Rotation C Factor = 0.08 ------- Crop C Factor = 0.08 ---------
```

crop # 2/2: corn;125bu 90day 30"   previous crop: corn;125bu 90day 30"

operation	% res. cover after op.	op. date	date next op.	SLR	%EI
cult;prim-swp 6-12 N	53	4/20/3	5/5/3	0.054	3.3
planter;dbl.dsk.op N	44	5/5/3	5/15/3	0.072	2.7
anhyd applic; disk N	28	5/15/3	6/5/3	0.123	9.7
cult;row-mult sweepN	19	6/5/3	10/15/3	0.088	69.4
harvest	93	10/15/3	4/20/4	0.02	15.0

------------ Rotation C Factor = 0.08 ------- Crop C Factor = 0.08 ---------

- Results By 15-Day Period -   Page 1

	% res. cover	plu	* cc	* sc	* sr	* sm	= SLR	%EI
4/20/2	corn;125bu 90day 30" cult;prim-swp 6-12 N							
4/20 - 4/30/2	51	0.358	1	0.189	0.774	1	0.052	2.2
5/1 - 5/4/2	50	0.374	1	0.198	0.788	1	0.058	1.1
5/5/2	corn;125bu 90day 30" planter;dbl.dsk.op N							
5/5 - 5/14/2	43	0.371	0.983	0.241	0.815	1	0.072	2.7
5/15/2	corn;125bu 90day 30" anhyd applic; disk N							
5/15/2	28	0.341	0.967	0.404	0.819	1	0.109	0.3
5/16 - 5/31/2	26	0.359	0.938	0.428	0.832	1	0.12	7.0
6/1 - 6/4/2	24	0.375	0.908	0.458	0.847	1	0.132	2.4
6/5/2	corn;125bu 90day 30" cult;row-mult sweepN							
6/5 - 6/15/2	18	0.362	0.761	0.562	0.791	1	0.122	6.6
6/16 - 6/30/2	16	0.353	0.51	0.601	0.819	1	0.088	9.0
7/1 - 7/15/2	13	0.328	0.35	0.642	0.845	1	0.062	9.0
7/16 - 7/31/2	12	0.329	0.267	0.679	0.867	1	0.052	10.0
8/1 - 8/15/2	10	0.353	0.267	0.714	0.887	1	0.06	10.0
8/16 - 8/31/2	9	0.377	0.297	0.749	0.905	1	0.076	9.0
9/1 - 9/15/2	7	0.399	0.399	0.783	0.92	1	0.115	7.0
9/16 - 9/30/2	6	0.414	0.487	0.807	0.933	1	0.152	6.0
10/1 - 10/14/2	6	0.424	0.487	0.824	0.942	1	0.16	2.8
10/15/2	corn;125bu 90day 30" harvest							
10/15/2	93	0.431	1	0.041	0.945	1	0.017	0.2
10/16 - 10/31/2	93	0.44	1	0.042	0.948	1	0.017	2.0
11/1 - 11/15/2	91	0.456	1	0.043	0.954	1	0.019	2.0
11/16 - 11/30/2	91	0.465	1	0.044	0.959	1	0.02	1.0
12/1 - 12/15/2	90	0.468	1	0.045	0.963	1	0.02	1.0
12/16 - 12/31/2	90	0.468	1	0.045	0.967	1	0.02	0.0
1/1 - 1/15/3	90	0.465	1	0.045	0.969	1	0.02	0.0
1/16 - 1/31/3	90	0.463	1	0.045	0.971	1	0.02	1.0
2/1 - 2/15/3	90	0.46	1	0.045	0.972	1	0.02	1.0
2/16 - 2/28/3	90	0.458	1	0.045	0.974	1	0.02	1.0
3/1 - 3/15/3	90	0.457	1	0.045	0.975	1	0.02	1.0
3/16 - 3/31/3	89	0.462	1	0.046	0.978	1	0.021	2.0
4/1 - 4/15/3	88	0.471	1	0.048	0.98	1	0.022	2.0
4/16 - 4/19/3	87	0.477	1	0.049	0.981	1	0.023	0.8
4/20/3	corn;125bu 90day 30" cult;prim-swp 6-12 N							
4/20 - 4/30/3	51	0.358	1	0.189	0.774	1	0.052	2.2
5/1 - 5/4/3	50	0.374	1	0.198	0.788	1	0.058	1.1
5/5/3	corn;125bu 90day 30" planter;dbl.dsk.op N							
5/5 - 5/14/3	43	0.371	0.983	0.241	0.815	1	0.072	2.7
5/15/3	corn;125bu 90day 30" anhyd applic; disk N							
5/15/3	28	0.341	0.967	0.404	0.819	1	0.109	0.3
5/16 - 5/31/3	26	0.359	0.938	0.428	0.832	1	0.12	7.0
6/1 - 6/4/3	24	0.374	0.908	0.458	0.847	1	0.132	2.4
6/5/3	corn;125bu 90day 30" cult;row-mult sweepN							
6/5 - 6/15/3	18	0.361	0.761	0.562	0.791	1	0.122	6.6
6/16 - 6/30/3	16	0.353	0.51	0.601	0.819	1	0.088	9.0
7/1 - 7/15/3	13	0.328	0.35	0.642	0.845	1	0.062	9.0
7/16 - 7/31/3	12	0.329	0.267	0.679	0.867	1	0.052	10.0
8/1 - 8/15/3	10	0.353	0.267	0.714	0.887	1	0.06	10.0
8/16 - 8/31/3	9	0.377	0.297	0.749	0.905	1	0.076	9.0
9/1 - 9/15/3	7	0.399	0.399	0.783	0.92	1	0.115	7.0
9/16 - 9/30/3	6	0.414	0.487	0.807	0.933	1	0.152	6.0

	% res. cover	plu	*	cc	*	sc	*	sr	*	sm	=	SLR	%EI
10/15/3	corn;125bu 90day 30" harvest												
10/15/3	93	0.431		1		0.041		0.945		1		0.017	0.2
10/16 - 10/31/3	93	0.44		1		0.042		0.948		1		0.017	2.0
11/1 - 11/15/3	91	0.456		1		0.043		0.954		1		0.019	2.0
11/16 - 11/30/3	91	0.465		1		0.044		0.959		1		0.02	1.0
12/1 - 12/15/3	90	0.468		1		0.045		0.963		1		0.02	1.0
12/16 - 12/31/3	90	0.467		1		0.045		0.967		1		0.02	0.0
1/1 - 1/15/4	90	0.465		1		0.045		0.969		1		0.02	0.0
1/16 - 1/31/4	90	0.463		1		0.045		0.971		1		0.02	1.0
2/1 - 2/15/4	90	0.46		1		0.045		0.972		1		0.02	1.0
2/16 - 2/28/4	90	0.458		1		0.045		0.974		1		0.02	1.0
3/1 - 3/15/4	90	0.457		1		0.045		0.975		1		0.02	1.0
3/16 - 3/31/4	89	0.462		1		0.046		0.978		1		0.021	2.0
4/1 - 4/15/4	88	0.471		1		0.048		0.98		1		0.022	2.0
4/16 - 4/19/4	87	0.476		1		0.049		0.981		1		0.023	0.8

RUSLE Version: SWCS1.05pre_d   Input File: 1CNB

corn -> Notill SOYbean
fall chisel, twisted
field cult 1x, row cult 1x
125 bu, 35 bu
zone 102b

- Inputs for C-Factor -

city code: 22002 GRAND RAPIDS MI
adjust for soil moisture depletion: NO
% surface covered by rock fragments: 0
surface cover function; B-value code: (1) normal conditions

1/2 crop: corn;125bu 90day 30" senescence code: NO

Date	Field Operation	Res. Add. (#/A)	New Growth Set
10/15/1	chisel;twisted pts.F		
5/5/2	cult;secdry-sw6-12 F		
5/5/2	planter;dbl.dsk.op F		
5/15/2	anhyd applic; disk F		
6/5/2	cult;row-mult sweepF		
10/15/2	harvest	7000	

2/2 crop: soybean; 30" 35bu mw senescence code: YES

Date	Field Operation	Res. Add. (#/A)	New Growth Set
10/16/2	no operation		
5/15/3	drill;NT-f.res. fl F		
10/10/3	harvest	2625	

- Results By Crops -

crop	start date	end date	%EI	C factor
corn;125bu 90day 30"	10/15/1	10/16/2	100.2	0.259
soybean; 30" 35bu mw	10/16/2	10/15/3	99.8	0.064

Rotation C Factor = 0.162

- Results By Operations -

crop # 1/2: corn;125bu 90day 30" previous crop: soybean; 30" 35bu mw

operation	% res. cover after op.	op. date	date next op.	SLR	%EI
chisel;twisted pts.F	27	10/15/1	5/5/2	0.261	18.3
cult;secdry-sw6-12 F	9	5/5/2	5/5/2	0	0.0
planter;dbl.dsk.op F	7	5/5/2	5/15/2	0.513	2.7
anhyd applic; disk F	3	5/15/2	6/5/2	0.564	9.7
cult;row-mult sweepF	1	6/5/2	10/15/2	0.206	69.4
harvest	93	10/15/2	10/16/2	0.021	0.2

Rotation C Factor = 0.162 ------- Crop C Factor = 0.259

crop # 2/2: soybean; 30" 35bu mw previous crop: corn;125bu 90day 30"

operation	% res. cover after op.	op. date	date next op.	SLR	%EI
no operation	93	10/16/2	5/15/3	0.026	20.7
drill;NT-f.res. fl F	41	5/15/3	10/10/3	0.075	78.1
harvest	73	10/10/3	10/15/3	0.048	1.0

Rotation C Factor = 0.162 ------- Crop C Factor = 0.064

	% res. cover	plu	* cc	* sc	* sr	* sm	= SLR	%EI
10/15/1	corn;125bu 90day 30" chisel;twisted pts.F							
10/15/1	26	0.643	1	0.443	0.537	1	0.153	0.2
10/16 - 10/31/1	25	0.654	1	0.458	0.555	1	0.166	2.0
11/1 - 11/15/1	23	0.672	1	0.483	0.593	1	0.193	2.0
11/16 - 11/30/1	22	0.683	1	0.498	0.632	1	0.215	1.0
12/1 - 12/15/1	22	0.686	1	0.504	0.666	1	0.23	1.0
12/16 - 12/31/1	21	0.686	1	0.506	0.694	1	0.241	0.0
1/1 - 1/15/2	21	0.685	1	0.506	0.714	1	0.247	0.0
1/16 - 1/31/2	21	0.682	1	0.505	0.73	1	0.252	1.0
2/1 - 2/15/2	21	0.68	1	0.505	0.744	1	0.255	1.0
2/16 - 2/28/2	21	0.678	1	0.505	0.756	1	0.259	1.0
3/1 - 3/15/2	21	0.677	1	0.508	0.77	1	0.265	1.0
3/16 - 3/31/2	20	0.682	1	0.519	0.79	1	0.279	2.0
4/1 - 4/15/2	19	0.69	1	0.537	0.812	1	0.301	2.0
4/16 - 4/30/2	17	0.704	1	0.566	0.834	1	0.332	3.0
5/1 - 5/4/2	16	0.715	1	0.591	0.847	1	0.358	1.1
5/5/2	corn;125bu 90day 30" cult;secdry-sw6-12 F							
5/5/2	corn;125bu 90day 30" planter;dbl.dsk.op F							
5/5 - 5/14/2	7	0.739	0.983	0.801	0.882	1	0.513	2.7
5/15/2	corn;125bu 90day 30" anhyd applic; disk F							
5/15/2	3	0.73	0.967	0.919	0.888	1	0.576	0.3
5/16 - 5/31/2	2	0.729	0.938	0.927	0.896	1	0.568	7.0
6/1 - 6/4/2	2	0.717	0.908	0.936	0.905	1	0.552	2.4
6/5/2	corn;125bu 90day 30" cult;row-mult sweepF							
6/5 - 6/15/2	1	0.691	0.761	0.966	0.887	1	0.45	6.6
6/16 - 6/30/2	1	0.624	0.51	0.972	0.903	1	0.279	9.0
7/1 - 7/15/2	1	0.537	0.35	0.977	0.917	1	0.169	9.0
7/16 - 7/31/2	1	0.504	0.267	0.982	0.929	1	0.123	10.0
8/1 - 8/15/2	0	0.511	0.267	0.985	0.94	1	0.127	10.0
8/16 - 8/31/2	0	0.517	0.297	0.988	0.949	1	0.144	9.0
9/1 - 9/15/2	0	0.522	0.399	0.991	0.958	1	0.198	7.0
9/16 - 9/30/2	0	0.523	0.487	0.992	0.965	1	0.244	6.0
10/1 - 10/14/2	0	0.524	0.487	0.994	0.969	1	0.246	2.8
10/15/2	corn;125bu 90day 30" harvest							
10/15/2	93	0.526	1	0.04	0.971	1	0.021	0.2
10/16/2	soybean; 30" 35bu mw no operation							
10/16 - 10/31/2	92	0.534	1	0.041	0.972	1	0.021	2.0
11/1 - 11/15/2	91	0.548	1	0.043	0.975	1	0.023	2.0
11/16 - 11/30/2	90	0.555	1	0.044	0.978	1	0.024	1.0
12/1 - 12/15/2	90	0.557	1	0.044	0.98	1	0.024	1.0
12/16 - 12/31/2	89	0.556	1	0.045	0.982	1	0.024	0.0
1/1 - 1/15/3	89	0.553	1	0.045	0.983	1	0.024	0.0
1/16 - 1/31/3	89	0.55	1	0.045	0.984	1	0.024	1.0
2/1 - 2/15/3	89	0.547	1	0.045	0.985	1	0.024	1.0
2/16 - 2/28/3	89	0.544	1	0.045	0.985	1	0.024	1.0
3/1 - 3/15/3	89	0.542	1	0.045	0.986	1	0.024	1.0
3/16 - 3/31/3	88	0.546	1	0.046	0.987	1	0.025	2.0
4/1 - 4/15/3	87	0.552	1	0.048	0.989	1	0.026	2.0
4/16 - 4/30/3	85	0.565	1	0.051	0.99	1	0.029	3.0
5/1 - 5/14/3	82	0.581	1	0.056	0.991	1	0.032	3.7
5/15/3	soybean; 30" 35bu mw drill;NT-f.res. fl F							
5/15/3	40	0.393	1	0.252	0.94	1	0.093	0.3

	% res. cover	plu	*	cc	*	sc	*	sr	*	sm	=	SLR	%EI
6/1 - 6/15/3	34	0.455		0.862		0.316		0.953		1		0.118	9.0
6/16 - 6/30/3	29	0.491		0.692		0.364		0.96		1		0.119	9.0
7/1 - 7/15/3	26	0.513		0.466		0.413		0.966		1		0.095	9.0
7/16 - 7/31/3	22	0.504		0.205		0.46		0.971		1		0.046	10.0
8/1 - 8/15/3	21	0.515		0.144		0.483		0.975		1		0.035	10.0
8/16 - 8/31/3	31	0.541		0.215		0.341		0.979		1		0.039	9.0
9/1 - 9/15/3	48	0.564		0.486		0.191		0.982		1		0.051	7.0
9/16 - 9/30/3	49	0.579		0.67		0.184		0.985		1		0.07	6.0
10/1 - 10/9/3	44	0.586		0.703		0.215		0.986		1		0.087	1.8
10/10/3	soybean; 30" 35bu mw harvest												
10/10 - 10/14/3	72	0.595		1		0.081		0.987		1		0.048	1.0

RUSLE Version: SWCS1.05pre_d

Input File: 1NBNWH

SOYBEANS AFTER WHEAT
NO TILL SB AND WHEAT
35 bu soys, 50 bu wheat
zone 102b

- Inputs for C-Factor -

city code: 22002 GRAND RAPIDS MI
adjust for soil moisture depletion: NO
% surface covered by rock fragments: 0
surface cover function; B-value code: (1) normal conditions

1/2 crop: soybean; 30" 35bu mw senescence code: YES

Date	Field Operation	Res. Add. (#/A)	New Growth Set
7/16/0	no operation		
5/15/1	plantr;NT-fluted c N		
10/10/1	harvest	2625	

2/2 crop: wheat; winter 50bu senescence code: NO

Date	Field Operation	Res. Add. (#/A)	New Growth Set
10/15/1	drill;NT-f.res. fl F		
7/15/2	harvest	5100	

- Results By Crops -

crop	start date	end date	%EI	C factor
soybean; 30" 35bu mw	7/16/0	10/15/1	144.8	0.017
wheat; winter 50bu	10/15/1	7/16/2	55.2	0.026

Rotation C Factor = 0.019

- Results By Operations -

crop # 1/2: soybean; 30" 35bu mw previous crop: wheat; winter 50bu

operation	% res. cover after op.	op. date	date next op.	SLR	%EI
no operation	96	7/16/0	5/15/1	0.013	65.7
plantr;NT-fluted c N	68	5/15/1	10/10/1	0.02	78.1
harvest	82	10/10/1	10/15/1	0.02	1.0

Rotation C Factor = 0.019 ------- Crop C Factor = 0.017

crop # 2/2: wheat; winter 50bu previous crop: soybean; 30" 35bu mw

operation	% res. cover after op.	op. date	date next op.	SLR	%EI
drill;NT-f.res. fl F	47	10/15/1	7/15/2	0.027	54.6
harvest	96	7/15/2	7/16/2	0.008	0.6

Rotation C Factor = 0.019 ------- Crop C Factor = 0.026

- Results By 15-Day Period - Page 1

	% res. cover	plu *	cc *	sc *	sr *	sm =	SLR	%EI
7/16/0	soybean; 30" 35bu mw no operation							
7/16 - 7/31/0	95	0.252	1	0.036	0.992	1	0.009	10.0
8/1 - 8/15/0	94	0.269	1	0.037	0.993	1	0.01	10.0
8/16 - 8/31/0	93	0.288	1	0.039	0.993	1	0.011	9.0
9/1 - 9/15/0	91	0.306	1	0.042	0.994	1	0.013	7.0
9/16 - 9/30/0	89	0.319	1	0.044	0.995	1	0.014	6.0
10/1 - 10/15/0	88	0.328	1	0.047	0.995	1	0.015	3.0
10/16 - 10/31/0	86	0.335	1	0.049	0.995	1	0.016	2.0
11/1 - 11/15/0	86	0.338	1	0.05	0.996	1	0.017	2.0
11/16 - 11/30/0	85	0.339	1	0.051	0.996	1	0.017	1.0
12/1 - 12/15/0	85	0.338	1	0.051	0.996	1	0.017	1.0
12/16 - 12/31/0	85	0.336	1	0.052	0.996	1	0.017	0.0
1/1 - 1/15/1	85	0.333	1	0.052	0.996	1	0.017	0.0
1/16 - 1/31/1	85	0.331	1	0.052	0.996	1	0.017	1.0
2/1 - 2/15/1	85	0.328	1	0.052	0.996	1	0.017	1.0
2/16 - 2/28/1	85	0.326	1	0.052	0.996	1	0.017	1.0
3/1 - 3/15/1	84	0.324	1	0.052	0.997	1	0.017	1.0
3/16 - 3/31/1	84	0.324	1	0.053	0.997	1	0.017	2.0
4/1 - 4/15/1	83	0.326	1	0.054	0.997	1	0.018	2.0
4/16 - 4/30/1	82	0.33	1	0.056	0.997	1	0.019	3.0
5/1 - 5/14/1	81	0.336	1	0.059	0.997	1	0.02	3.7
5/15/1	soybean; 30" 35bu mw plantr;NT-fluted c N							
5/15/1	68	0.334	1	0.094	0.985	1	0.031	0.3
5/16 - 5/31/1	67	0.339	0.97	0.099	0.986	1	0.032	7.0
6/1 - 6/15/1	64	0.347	0.862	0.109	0.988	1	0.032	9.0
6/16 - 6/30/1	61	0.353	0.692	0.121	0.99	1	0.029	9.0
7/1 - 7/15/1	58	0.35	0.466	0.134	0.991	1	0.022	9.0
7/16 - 7/31/1	55	0.329	0.205	0.147	0.992	1	0.01	10.0
8/1 - 8/15/1	53	0.326	0.144	0.157	0.993	1	0.007	10.0
8/16 - 8/31/1	58	0.335	0.215	0.132	0.994	1	0.009	9.0
9/1 - 9/15/1	67	0.343	0.486	0.096	0.994	1	0.016	7.0
9/16 - 9/30/1	67	0.346	0.67	0.096	0.995	1	0.022	6.0
10/1 - 10/9/1	64	0.347	0.703	0.108	0.995	1	0.026	1.8
10/10/1	soybean; 30" 35bu mw harvest							
10/10 - 10/14/1	82	0.352	1	0.057	0.995	1	0.02	1.0
10/15/1	wheat; winter 50bu drill;NT-f.res. fl F							
10/15/1	47	0.339	1	0.199	0.943	1	0.063	0.2
10/16 - 10/31/1	46	0.344	0.97	0.208	0.946	1	0.066	2.0
11/1 - 11/15/1	44	0.345	0.862	0.224	0.952	1	0.063	2.0
11/16 - 11/30/1	42	0.323	0.716	0.235	0.957	1	0.052	1.0
12/1 - 12/15/1	42	0.309	0.657	0.239	0.962	1	0.047	1.0
12/16 - 12/31/1	41	0.308	0.657	0.242	0.965	1	0.047	0.0
1/1 - 1/15/2	41	0.306	0.657	0.242	0.968	1	0.047	0.0
1/16 - 1/31/2	41	0.304	0.657	0.242	0.97	1	0.047	1.0
2/1 - 2/15/2	41	0.301	0.657	0.242	0.971	1	0.047	1.0
2/16 - 2/28/2	41	0.3	0.657	0.243	0.973	1	0.047	1.0
3/1 - 3/15/2	41	0.299	0.657	0.246	0.975	1	0.047	1.0
3/16 - 3/31/2	40	0.302	0.657	0.254	0.977	1	0.049	2.0
4/1 - 4/15/2	38	0.307	0.632	0.267	0.979	1	0.051	2.0
4/16 - 4/30/2	36	0.309	0.48	0.288	0.982	1	0.042	3.0
5/1 - 5/15/2	33	0.287	0.249	0.318	0.984	1	0.022	4.0
5/16 - 5/31/2	30	0.247	0.151	0.358	0.985	1	0.013	7.0

	% res. cover	plu	*	cc	*	sc	*	sr	*	sm	=	SLR	%EI
6/16 - 6/30/2	23	0.229		0.144		0.456		0.989		1		0.015	9.0
7/1 - 7/14/2	20	0.238		0.144		0.5		0.99		1		0.017	8.4
7/15/2	wheat; winter	50bu		harvest									
7/15/2	96	0.243		1		0.035		0.991		1		0.008	0.6

RUSLE Version: SWCS1.05pre_d   Input File: 1BC

Soybean -> Corn

- Inputs for C-Factor -

city code: 22002   GRAND RAPIDS   MI

adjust for soil moisture depletion: NO

% surface covered by rock fragments: 0

surface cover function; B-value code: (1) normal conditions

1/2   crop: soybean; 30" 35bu mw   senescence code: NO

Date	Field Operation	Res. Add. (#/A)	New Growth Set
11/1/1	chisel;twisted pts.N		
5/15/2	cult;secdry-sw6-12 N		
5/15/2	planter;dbl.dsk.op N		
6/15/2	cult;row-mult sweepN		
10/10/2	harvest	2625	

2/2   crop: corn;125bu 90day 30"   senescence code: NO

Date	Field Operation	Res. Add. (#/A)	New Growth Set
10/15/2	chisel;twisted pts.F		
5/5/3	cult;secdry-sw6-12 F		
5/5/3	planter;dbl.dsk.op F		
5/15/3	anhyd applic; disk F		
6/5/3	cult;row-mult sweepF		
10/15/3	harvest	7000	

- Results By Crops -

crop	start date	end date	%EI	C factor
soybean; 30" 35bu mw	11/1/1	10/15/2	97.8	0.355
corn;125bu 90day 30"	10/15/2	11/1/4	202.2	0.184

Rotation C Factor = 0.24

- Results By Operations -

crop # 1/2: soybean; 30" 35bu mw   previous crop: corn;125bu 90day 30"

operation	% res. cover after op.	op. date	date next op.	SLR	%EI
chisel;twisted pts.N	17	11/1/1	5/15/2	0.447	18.7
cult;secdry-sw6-12 N	9	5/15/2	5/15/2	0	0.0
planter;dbl.dsk.op N	8	5/15/2	6/15/2	0.587	15.7
cult;row-mult sweepN	5	6/15/2	10/10/2	0.274	62.4
harvest	79	10/10/2	10/15/2	0.05	1.0

Rotation C Factor = 0.24 ------- Crop C Factor = 0.355

crop # 2/2: corn;125bu 90day 30"   previous crop: soybean; 30" 35bu mw

operation	% res. cover after op.	op. date	date next op.	SLR	%EI
chisel;twisted pts.F	27	10/15/2	5/5/3	0.284	18.3
cult;secdry-sw6-12 F	9	5/5/3	5/5/3	0	0.0
planter;dbl.dsk.op F	7	5/5/3	5/15/3	0.552	2.7
anhyd applic; disk F	2	5/15/3	6/5/3	0.603	9.7
cult;row-mult sweepF	1	6/5/3	10/15/3	0.215	69.4
harvest	93	10/15/3	11/1/4	0.096	102.2

Rotation C Factor = 0.24 ------- Crop C Factor = 0.184

	% res. cover	plu *	cc *	sc *	sr *	sm =	SLR	%EI
11/1/1	soybean; 30" 35bu mw chisel;twisted pts.N							
11/1 - 11/15/1	17	0.863	1	0.583	0.729	1	0.367	2.0
11/16 - 11/30/1	16	0.865	1	0.593	0.757	1	0.388	1.0
12/1 - 12/15/1	16	0.865	1	0.596	0.782	1	0.403	1.0
12/16 - 12/31/1	16	0.864	1	0.597	0.802	1	0.413	0.0
1/1 - 1/15/2	16	0.861	1	0.596	0.816	1	0.419	0.0
1/16 - 1/31/2	16	0.859	1	0.596	0.827	1	0.423	1.0
2/1 - 2/15/2	16	0.856	1	0.596	0.836	1	0.426	1.0
2/16 - 2/28/2	16	0.853	1	0.596	0.844	1	0.429	1.0
3/1 - 3/15/2	16	0.85	1	0.597	0.853	1	0.433	1.0
3/16 - 3/31/2	15	0.849	1	0.604	0.867	1	0.444	2.0
4/1 - 4/15/2	15	0.848	1	0.615	0.881	1	0.46	2.0
4/16 - 4/30/2	14	0.849	1	0.633	0.895	1	0.481	3.0
5/1 - 5/14/2	12	0.851	1	0.657	0.908	1	0.507	3.7
5/15/2	soybean; 30" 35bu mw cult;secdry-sw6-12 N							
5/15/2	soybean; 30" 35bu mw planter;dbl.dsk.op N							
5/15/2	8	0.875	1	0.762	0.921	1	0.614	0.3
5/16 - 5/31/2	7	0.875	0.97	0.777	0.927	1	0.611	7.0
6/1 - 6/14/2	6	0.871	0.862	0.803	0.937	1	0.565	8.4
6/15/2	soybean; 30" 35bu mw cult;row-mult sweepN							
6/15/2	5	0.864	0.791	0.851	0.918	1	0.534	0.6
6/16 - 6/30/2	4	0.859	0.692	0.862	0.925	1	0.474	9.0
7/1 - 7/15/2	4	0.835	0.466	0.88	0.936	1	0.321	9.0
7/16 - 7/31/2	3	0.776	0.205	0.896	0.946	1	0.135	10.0
8/1 - 8/15/2	3	0.756	0.144	0.909	0.954	1	0.094	10.0
8/16 - 8/31/2	2	0.758	0.215	0.923	0.961	1	0.144	9.0
9/1 - 9/15/2	2	0.759	0.486	0.934	0.967	1	0.333	7.0
9/16 - 9/30/2	2	0.759	0.67	0.943	0.973	1	0.466	6.0
10/1 - 10/9/2	2	0.757	0.703	0.947	0.976	1	0.492	1.8
10/10/2	soybean; 30" 35bu mw harvest							
10/10 - 10/14/2	78	0.762	1	0.068	0.977	1	0.05	1.0
10/15/2	corn;125bu 90day 30" chisel;twisted pts.F							
10/15/2	27	0.698	1	0.434	0.564	1	0.171	0.2
10/16 - 10/31/2	26	0.708	1	0.449	0.583	1	0.185	2.0
11/1 - 11/15/2	24	0.726	1	0.476	0.619	1	0.214	2.0
11/16 - 11/30/2	22	0.735	1	0.492	0.656	1	0.237	1.0
12/1 - 12/15/2	22	0.738	1	0.498	0.689	1	0.253	1.0
12/16 - 12/31/2	22	0.738	1	0.5	0.715	1	0.264	0.0
1/1 - 1/15/3	22	0.736	1	0.5	0.734	1	0.27	0.0
1/16 - 1/31/3	22	0.734	1	0.5	0.749	1	0.275	1.0
2/1 - 2/15/3	22	0.731	1	0.499	0.762	1	0.278	1.0
2/16 - 2/28/3	21	0.729	1	0.5	0.773	1	0.282	1.0
3/1 - 3/15/3	21	0.727	1	0.503	0.786	1	0.288	1.0
3/16 - 3/31/3	20	0.731	1	0.514	0.805	1	0.303	2.0
4/1 - 4/15/3	19	0.739	1	0.534	0.826	1	0.326	2.0
4/16 - 4/30/3	17	0.751	1	0.564	0.846	1	0.358	3.0
5/1 - 5/4/3	16	0.76	1	0.591	0.858	1	0.385	1.1
5/5/3	corn;125bu 90day 30" cult;secdry-sw6-12 F							
5/5/3	corn;125bu 90day 30" planter;dbl.dsk.op F							
5/5 - 5/14/3	7	0.784	0.983	0.803	0.893	1	0.552	2.7
5/15/3	corn;125bu 90day 30" anhyd applic; disk F							
5/15/3	2	0.774	0.967	0.92	0.898	1	0.618	0.3

	% res. cover	plu *	cc *	sc *	sr *	sm =	SLR	%EI
6/1 - 6/4/3	2	0.754	0.908	0.938	0.914	1	0.587	2.4
6/5/3	corn;125bu 90day 30" cult;row-mult sweepF							
6/5 - 6/15/3	1	0.724	0.761	0.967	0.898	1	0.479	6.6
6/16 - 6/30/3	1	0.651	0.51	0.973	0.912	1	0.294	9.0
7/1 - 7/15/3	1	0.557	0.35	0.979	0.925	1	0.177	9.0
7/16 - 7/31/3	0	0.521	0.267	0.983	0.936	1	0.128	10.0
8/1 - 8/15/3	0	0.526	0.267	0.987	0.946	1	0.131	10.0
8/16 - 8/31/3	0	0.53	0.297	0.99	0.954	1	0.148	9.0
9/1 - 9/15/3	0	0.532	0.399	0.992	0.962	1	0.203	7.0
9/16 - 9/30/3	0	0.533	0.487	0.994	0.968	1	0.25	6.0
10/1 - 10/14/3	0	0.532	0.487	0.995	0.972	1	0.251	2.8
10/15/3	corn;125bu 90day 30" harvest							
10/15/3	93	0.534	1	0.04	0.973	1	0.021	0.2
10/16 - 10/31/3	92	0.542	1	0.041	0.975	1	0.022	2.0
11/1 - 11/15/3	91	0.556	1	0.043	0.977	1	0.023	2.0
11/16 - 11/30/3	90	0.563	1	0.044	0.98	1	0.024	1.0
12/1 - 12/15/3	90	0.564	1	0.044	0.982	1	0.025	1.0
12/16 - 12/31/3	89	0.563	1	0.045	0.983	1	0.025	0.0
1/1 - 1/15/4	89	0.56	1	0.045	0.984	1	0.025	0.0
1/16 - 1/31/4	89	0.557	1	0.045	0.985	1	0.025	1.0
2/1 - 2/15/4	89	0.554	1	0.045	0.986	1	0.024	1.0
2/16 - 2/28/4	89	0.551	1	0.045	0.987	1	0.024	1.0
3/1 - 3/15/4	89	0.55	1	0.045	0.987	1	0.024	1.0
3/16 - 3/31/4	88	0.553	1	0.046	0.988	1	0.025	2.0
4/1 - 4/15/4	87	0.559	1	0.048	0.989	1	0.027	2.0
4/16 - 4/30/4	85	0.571	1	0.051	0.99	1	0.029	3.0
5/1 - 5/15/4	82	0.587	1	0.056	0.991	1	0.033	4.0
5/16 - 5/31/4	78	0.608	1	0.065	0.992	1	0.039	7.0
6/1 - 6/15/4	73	0.631	1	0.078	0.993	1	0.049	9.0
6/16 - 6/30/4	67	0.652	1	0.096	0.994	1	0.062	9.0
7/1 - 7/15/4	61	0.67	1	0.118	0.994	1	0.078	9.0
7/16 - 7/31/4	56	0.684	1	0.143	0.995	1	0.097	10.0
8/1 - 8/15/4	50	0.696	1	0.173	0.995	1	0.12	10.0
8/16 - 8/31/4	45	0.708	1	0.21	0.996	1	0.148	9.0
9/1 - 9/15/4	39	0.718	1	0.255	0.996	1	0.183	7.0
9/16 - 9/30/4	35	0.724	1	0.295	0.996	1	0.213	6.0
10/1 - 10/15/4	32	0.727	1	0.329	0.996	1	0.238	3.0
10/16 - 10/31/4	30	0.727	1	0.356	0.997	1	0.258	2.0

Appendix E Modeling outputs for the calculated soil erosion and sediment load from SEDMOD and four soil erosion models

Data format:
<---yymmdd--->
soil erosion (kg)
sediment yield (kg), monitored sediment yeild (kg), Δ, Δ%

Modeling outputs from the modified USLE used in AGNPS

<---910327--->
11439.05567648
3961.045283163, 1280, 2681.045283163, 2.094566627471
<---910404--->
397.7837936115
137.6865029824, 1, 136.6865029824, 136.6865029824
<---910409--->
13657.24359272
4727.236602181, 562, 4165.236602181, 7.411453028792
<---910415--->
3690.549639578
1277.424776283, 144, 1133.424776283, 7.871005390854
<---910419--->
2856.456249893
1005.610212734, 292, 713.610212734, 2.443870591555
<---910423--->
3828.866885747
1347.945605986, 43.4, 1304.545605986, 30.05865451581
<---920424--->
13333.07687242
5102.232105448, 3940, 1162.232105448, 0.2949827678802
<---920714--->
13103.34612345
4885.011000413, 50, 4835.011000413, 96.70022000826
<---930419--->
31657.03399741
11961.15303369, 13073, -1111.84696631, -0.0850491062732
<---930504--->
15756.00579978
5962.04516176, 16, 5946.04516176, 371.62782261
<---930607--->
46516.29578424
17521.8477963, 138, 17383.8477963, 125.9699115674
<---930614--->
16545.32598142
6232.325240302, 12, 6220.325240302, 518.3604366918

<---930619--->
62571.43449568
23480.01069774, 5654, 17826.01069774, 3.152814060442
<---940412--->
1810.949202128
675.6269852903, 35, 640.6269852903, 18.30362815115
<---940430--->
548.2294178137
194.8990468269, 27, 167.8990468269, 6.218483215811
<---940720--->
5456.434383847
2007.442610518, 114, 1893.442610518, 16.6091457063
<---950426--->
1273.156196689
501.5537998959, 53.5, 448.0537998959, 8.374837381232
<---950704--->
16418.76396908
6314.389190491, 4.9, 6309.489190491, 1287.650855202
<---960510--->
13110.29895763
4980.984184057, 647, 4333.984184057, 6.698584519408
<---960521--->
10461.81561377
4006.994025422, 179, 3827.994025422, 21.3854414828
<---960618--->
38700.51541314
15056.45406947, 10846, 4210.45406947, 0.3882033993611
<---970405--->
675.1987597818
275.9753927593, 50.5, 225.4753927593, 4.46485926256
<---970505--->
1373.720587761
457.5880910959, 34.4, 423.1880910959, 12.30197939232
<---970519--->
2999.589094702
920.7470092525, 51.3, 869.4470092525, 16.94828478075
<---970623--->
2830.47597479
878.5299220054, 32.3, 846.2299220054, 26.19906879274

Modeling outputs from USLE which use EI substitutes R factor in the equation to calculate the soil erosion for the single events

<---910327--->
12394.45481192
4311.051069357, 1280, 3031.051069357, 2.368008647935
<---910404--->
431.0204419598
149.8585100469, 1, 148.8585100469, 148.8585100469
<---910409--->
14798.36839036
5145.142188963, 562, 4583.142188963, 8.155057275735
<---910415--->
3998.911853768
1390.353941733, 144, 1246.353941733, 8.655235706479
<---910419--->
3097.509980671
1098.773039628, 292, 806.773039628, 2.762921368589
<---910423--->
4151.98145326
1472.82341607, 43.4, 1429.42341607, 32.93602341175
<---920424--->
14438.34597615
5597.346348065, 3940, 1657.346348065, 0.4206462812348
<---920714--->
14275.96995005
5384.937040796, 50, 5334.937040796, 106.6987408159
<---930419--->
34528.45716662
13242.87461312, 13073, 169.87461312, 0.0129943098845
<---930504--->
17193.61909081
6605.785895208, 16, 6589.785895208, 411.8616184505
<---930607--->
50756.48625545
19406.27336638, 138, 19268.27336638, 139.6251693216
<---930614--->
18053.51431794
6902.594333566, 12, 6890.594333566, 574.2161944638
<---930619--->
68239.70719787
25978.53284957, 5654, 20324.53284957, 3.594717518495
<---940412--->
1958.655496504
738.1618954916, 35, 703.1618954916, 20.09033987119
<---940430--->

592.1368510351
212.2461024822, 27, 185.2461024822, 6.8609667586
<---940720--->
5902.507023853
2193.174006692, 114, 2079.174006692, 18.23836847975
<---950426--->
1382.83492977
551.2059321604, 53.5, 497.7059321604, 9.302914619821
<---950704--->
17844.42345586
6936.717129256, 4.9, 6931.817129256, 1414.656556991
<---960510--->
14154.32294194
5415.044079757, 647, 4768.044079757, 7.369465347383
<---960521--->
11309.2822362
4365.156190516, 179, 4186.156190516, 23.38634743305
<---960618--->
41769.57425904
16364.5521291, 10846, 5518.5521291, 0.5088098957311
<---970405--->
730.2719118173
301.3180090148, 50.5, 250.8180090148, 4.966693247818
<---970505--->
1472.827916507
492.8410132475, 34.4, 458.4410132475, 13.32677364092
<---970519--->
3204.167073403
984.8523571166, 51.3, 933.5523571166, 18.19790169818
<---970623--->
3023.296773304
940.161430407, 32.3, 907.861430407, 28.10716502808

Modeling outputs from the modified USLE by Onstad and Foster (1974)

<---910327--->
6709.69988835
2573.069686516, 1280, 1293.069686516, 1.010210692591
<---910404--->
230.6158326291
88.40266888092, 1, 87.40266888092, 87.40266888092
<---910409--->
7715.218012783
2957.497989202, 562, 2395.497989202, 4.262451938082
<---910415--->
2244.733540664
860.4805431196, 144, 716.4805431196, 4.975559327219
<---910419--->
2097.21123236
820.2196503933, 292, 528.2196503933, 1.808971405457
<---910423--->
2192.570728816
857.5147573833, 43.4, 814.1147573833, 18.758404548
<---920424--->
9936.214459173
4246.962303721, 3940, 306.962303721, 0.0779092141424
<---920714--->
7266.360630277
3021.931841241, 50, 2971.931841241, 59.43863682482
<---930419--->
32677.33351274
13817.97546976, 13073, 744.97546976, 0.0569858081359
<---930504--->
8668.70586123
3672.012710608, 16, 3656.012710608, 228.500794413
<---930607--->
26511.41708352
11175.7389252, 138, 11037.7389252, 79.9836154
<---930614--->
9071.568015766
3824.068547789, 12, 3812.068547789, 317.6723789824
<---930619--->
37224.74264214
15624.34716169, 5654, 9970.34716169, 1.763414779216
<---940412--->
1246.702628833
518.0231354514, 35, 483.0231354514, 13.8006610129
<---940430--->
314.7841627771

124.4008143085, 27, 97.4008143085, 3.607437566981
<---940720--->
2953.180097887
1209.815717702, 114, 1095.815717702, 9.612418576333
<---950426--->
771.2201390432
338.9335932869, 53.5, 285.4335932869, 5.335207351157
<---950704--->
8947.212832221
3834.704874395, 4.9, 3829.804874395, 781.5928315092
<---960510--->
7586.557489669
3200.002818362, 647, 2553.002818362, 3.945908529153
<---960521--->
5872.273248573
2498.985365716, 179, 2319.985365716, 12.96081209897
<---960618--->
28281.29836904
12216.19993011, 10846, 1370.19993011, 0.1263322819574
<---970405--->
720.9320858499
327.9650456622, 50.5, 277.4650456622, 5.494357339846
<---970505--->
775.3251074916
286.0430468115, 34.4, 251.6430468115, 7.315204849172
<---970519--->
1715.277021559
581.2767604599, 51.3, 529.9767604599, 10.33093100312
<---970623--->
1565.875513989
536.8730398674, 32.3, 504.5730398674, 15.62145634264

Modeling outputs from the modified RULSE

<---910327--->
1105.981497918
384.6835361282, 1280, -895.3164638718, -0.6994659873998
<---910404--->
24.55685068063
8.538001213879, 1, 7.538001213879, 7.538001213879
<---910409--->
959.730942924
333.6822004465, 562, -228.3177995535, -0.4062594298105
<---910415--->
383.4376978423
133.3147951838, 144, -10.6852048162, -0.0742028112236
<---910419--->
616.1973782154
218.5823666417, 292, -73.4176333583, -0.2514302512271
<---910423--->
260.8551558487
92.53258633428, 43.4, 49.13258633428, 1.132087242725
<---920424--->
5650.18729969
2190.420935845, 3940, -1749.579064155, -0.4440556000393
<---920714--->
731.1081103026
275.7760880646, 50, 225.7760880646, 4.515521761292
<---930419--->
42081.62896873
16139.78087313, 13073, 3066.78087313, 0.2345889140312
<---930504--->
838.7372333714
322.2427199467, 16, 306.2427199467, 19.14016999667
<---930607--->
3178.30559278
1215.195768535, 138, 1077.195768535, 7.805766438659
<---930614--->
868.7224534947
332.1479989383, 12, 320.1479989383, 26.67899991153
<---930619--->
9739.554836428
3707.802302276, 5654, -1946.197697724, -0.344216076711
<---940412--->
412.95429705
155.630802694, 35, 120.630802694, 3.446594362686
<---940430--->
36.10882937206

12.94288359402, 27, -14.05711640598, -0.5206339409622
<---940720--->
280.8633249569
104.3594086209, 114, -9.6405913791, -0.0845665910447
<---950426--->
104.5279387141
41.66543574203, 53.5, -11.83456425797, -0.2212068085602
<---950704--->
853.9362219818
331.9532296641, 4.9, 327.0532296641, 66.74555707431
<---960510--->
1208.675579283
462.4051314673, 647, -184.5948685327, -0.2853089158156
<---960521--->
749.5007385397
289.2922575565, 179, 110.2922575565, 0.6161578634441
<---960618--->
29156.03666817
11422.799712, 10846, 576.799712, 0.0531808696294
<---970405--->
389.3946767272
160.6684118481, 50.5, 110.1684118481, 2.181552709863
<---970505--->
88.80017782228
29.71451663846, 34.4, -4.68548336154, -0.1362059116727
<---970519--->
247.046273248
75.93365087837, 51.3, 24.63365087837, 0.480188126284
<---970623--->
175.3758050177
54.5370103492, 32.3, 22.2370103492, 0.6884523327926

BIBLIOGRAPHY

BIBLIOGRAPHY

Ahuja, L. R., A. N. Sharpley, and O. R. Lehman. 1982. Effect of Soil Slope and Rainfall Characteristics on Phosphorus in Runoff. Journal of Environmental Quality. 11(1):9-12.

American Society of Civil Engineers (ASCE). 1975. Sedimentation Engineering, Chapter 4: Sediment Sources and Sediment Yields. p. 437-493. American Society of Civil Engineers. New York, NY.

Arnold, J. G., J. R. Williams, R. Srinivasan, and K. W. King. 1996. SWAT – Soil and Water Assessment Tool. SWAT User's Manual. Texas A & M University. Temple, TX.

Arnold, J. G., J. R. Williams, A. D. Nicks, and N. B. Sammons. 1990. SWRRB – A Basin Scale Simulation Model for Soil and Water Resources Management. Texas A & M University Press, College Station.

Arnold, J.G., M.D.Birket, J.R.Williams, W.F.Smith, and H.N.McGill. 1987. Modeling the effects of urbanization on basin water yield and reservoir sedimentation. Water Resources Bulletin. 23(6):1101-1107.

Beven, K. J., and M. J. Kirkby. 1979. A Physically Based, Variable Contributing Area Model of Basin Hydrology. Hydrological Sciences Bulletin. 24(1):43-69.

Bingner, R. L, and F. D. Theurer. 2001. Topographic Factors for RUSLE in the Continuous-Simulation Watershed Model for Predicting Agricultural, Non-Point Source Pollution (AnnAGNPS). In: Soil Erosion Research for the 21st Century – Proceedings of the International Symposium. Pp. 619-622. January 3-5, 2001. Honolulu, HI.

Bone, S. W., R. Christman, L. M. Feusner, R. L. Goettemoller, and B. H. Noltre. 1979. Ohio Erosion Control and Sediment Pollution Abatement Guide for Agricultural Land. The Ohio State University Extension Bulletin 594.

Borah, D. K. 1989. Runoff Simulation Model for Small Watersheds. Transactions of the ASAE. 32(2):881-886.

Borah, D. K., and M. S. Ashraf. 1990. Modeling Storm Runoff and Sediment With Seasonal Variations. Transactions in Agriculture. 33(1):105-110.

Brannan, K., and J. M. Hamlett. 1998. Using Geostatistics to Select Grid-Cell Layouts for the AGNPS Model. Transactions of the ASAE. 41(4):1011-1018.

Brenner, F. J. and J. J. Mondok. 1995. Nonpoint Source Pollution Potential in an Agricultural Watershed in Northwestern Pennsylvania. Water Resources Bulletin. 31(6):1101-1105.

Brown, L. C., and G. R. Foster. 1987. Storm erosivity using idealized intensity distributions. Transactions of ASAE. 30:379-386.

Clark, K. 1990. A Biological Investigation of Sycamore Creek and Tributaries Ingham County, Michigan. Michigan Department of Natural Resources, Lansing, Michigan.

Delwiche D. L. L., and D. A. Haith. 1983. Loading Functions for Predicting Nutrient Losses from Complex Watersheds. Water Resources Bulletin. 19(6):951-959.

Dingman, S. L. 1993. Chapter 9: Stream Response to Water-Input Events. Physical Hydrology. Macmillan Publishing Company.

Duda, A. M., and R. A. Johnson. 1985. Cost-effective Targeting of Agricultural Nonpoint Source Pollution Control. Journal of Soil and Water Conservation. 40: 108-111.

Edwards, C. L, R. D. Shannon, and A. R. Jerrett. 1999. Sedimentation Basin Retention Efficiencies for Sediment, Nitrogen, and Phosphorus from Simulated Agricultural Runoff. Transactions of the ASAE. 42(2):403-409.

Edwards, D. R., and T. C. Daniel. 1994. A Comparison of Runoff Quality Effects of Organic and Inorganic Fertilizers Applied to Fescuegrass Plots. Water Resource Bulletin. 30(1):35-41.

Engman, E. T. 1986. Roughness Coefficients for Routing Surface Runoff. Journal of Irrigation and Drainage Engineering. 112(1):39-53.

Flanagan, D. C., and G. R. Foster. 1989. Storm Pattern Effect on Nitrogen and Phosphorus Losses in Surface Runoff. Transactions of the ASAE. 32(2):535-544.

Fogel, M.M., L.H. Hekman, Jr., and L.Duckstein. 1976. A stochastic sediment yield model using the modified universal soil loss equation. In: Erosion and solid matter transport in inland waters. pp 226-233. IAHS-AISH publication No. 122.

Foster, G. R. 2000. RUSLE for single events. Personal Communications.

Foster, G. R., G. A. Weesies, K. G. Renard, D. C. Yoder, D. K. McCool, and J. P. Porter. 1997. Support Practice Factor (P). In: Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE). U.S. Department of Agriculture Handbook No. 703.

Foster, G. R. 1986. Understanding Ephemeral Gully Erosion. In: Soil Conservation: Assessing the National Resources Inventory. Volume 2. National Academy Press. Washington, D. C.

Foster, G. R. 1982. Modeling the erosion process, ch. 8. In: C. T. Haan, H. D. Johnson, and D. L. Brakensiek (eds.). Hydrologic Modeling of Small Watersheds. ASAE Monogr. No. 5, American Society of Agricultural Engineering. St. Joseph, MI.

Foster, G. R., L. D. Meyer, and C. A. Onstad. 1977. A Runoff Erosivity Factor and Variable Slope Length Exponents for Soil Loss Estimates. Transactions of the ASAE. 20:683-687.

Foster, G. R., L. D. Meyer, and C. A. Onstad. 1977. An Erosion Equation Derived from Basic Erosion Principles. Transactions of the ASAE. 20:678-682.

Foster, G. R., and W. H. Wischmeier. 1974. Evaluating Irregular Slopes for Soil Loss Prediction. Transactions of the ASAE. 17:305-309.

Foth, H. D., and B. G. Ellis. 1997. Soil Fertility. Second Edition. Lewis Publishers. New York.

Fraser, R. H. 1999. SEDMOD: A GIS-Based Delivery Model for Diffuse Source Pollutants. Ph.D. Dissertation. Yale University.

Fraser, R. H., P. K. Barten, and D. A. K. Pinney. 1998. Predicting Stream Pathogen Loading from Livestock Using a Geographical Information System-Based Delivery Model. Journal of Environmental Quality. 27:935-945.

Frere, M. H, J. D. Ross, and L. J. Lane. 1980. The nutrient submodel. In: Knisel, W. (ed.). CREAMS, A Field Scale Model for Chemicals, Runoff, and Erosion From Agricultural Management Systems. U.S. Department of Agriculture, Conservation Research Report 26, Vol. 1, ch. 4, pp 65-86.

Gianessi, L. P., H.M.Peskin, P. Crosson, and C. Puffer, 1986. Nonpoint source pollution: Are cropland controls the answer? Resources for the Future, Inc. Washington, D.C.

Gilley, J. E., D. C. Kincaid, W. J. Elliot, and J. M. Laflen. 1992. Sediment Delivery on Rill and Interrill Areas. Journal of Hydrology. 140(1992):313-341.

Green, I. R. A., and D. Stephenson. 1986. Criteria for Comparison of Single Event Models. Hydrological Sciences Journal. 31(3):395-411.

Grigar, J., and S. Davis. 1995. Water Erosion Prediction and Control. Technical Guide Section I-C. State Office of Michigan, NRCS, USDA.

Haith, D. A., and L. J. Tubbs. 1981. Watershed Loading Functions for Nonpoint Sources. Journal of the Environmental Engineering Division, ASCE, EE 1(107):121-137.

He, C., C. Shi, C. Yang, and B. P. Agosti. 2001. A Window-Based GIS-AGNPS Interface. Journal of The American Water Research Association. 37(2):1-12.

Hoover, K. A., M. G. Foley, P. G. Heasler, and E. W. Boyer. 1991. Sub-Grid-Scale Characterization of Channel Lengths for Use in Catchment Modeling. Water Resources Research. 27(11):2865-2873.

Inamdar, S. P., and T. A. Dillaha. 2000. Relationships Between Drainage Area, Slope Length, and Slope Gradient for Riparian Slops in Virginia. Transactions of the ASAE. 43(4):861-866.

Izuno, F. T., A. B. Bottcher, F. J. Coale, C. A. Sanchez, and D. B. Jones. Agricultural BMPs for Phosphorus Reduction in South Florida. Transactions of the ASAE. 38(3):735-744.

Jenq T. R., M. L. Granstrom, S. F. Hsueh, and C. G. Uchrin. 1984. A Phosphorus Management LP Model Case Study. Water Resources Bulletin. 20(4):511-519.

Kang, Y. T. 1998. A Watershed Based Optimization Approach for Agricultural Non-Point Source Pollution Management. Ph.D. Dissertation. Michigan State University.

Khanbilvardi, R. M., and A. S. Rogowski. 1984. Quantitative Evaluation of Sediment Delivery Ratios. Water Resources Bulletin. December 1984. pp 865-874.

Kinnell, P. I. A. 2001. Runoff, the Universal Soil Loss Equation and Event Erosion. In: Soil Erosion Research for the 21st Century – Proceedings of the International Symposium. Pp. 99-102. January 3-5, 2001. Honolulu, HI.

Lee, G. F. 1971. Role of Phosphorus in Eutrophication and Diffuse Source Control. Water Research Pergamon Press 1973, Vol. 7. pp. 111-128.

Lemunyon, J. L., and R. G. Gilbert. 1993. The Concept and Need for a Phosphorus Assessment Tool. Journal of Production Agriculture. 6(4):483-486.

Licciardello, F., N. Rizzo, F. Somma, and S. M. Zimbone. 2001. Runoff and Soil Erosion Modeling in a Small Sicilian Watershed. In: Soil Erosion Research for the 21st Century – Proceedings of the International Symposium. Pp. 298-301. January 3-5, 2001. Honolulu, HI.

Liew, M. W. V. 1997. Prediction of Sediment Yield on a Large Watershed in North Central China. Transactions of the ASAE. 41(3):599-604.

Lovejoy, S. B., J. G. Lee, T. O. Randhir, and B. A. Engel. 1997. Research Needs for Water Quality Management in the 21st Century. Journal of Soil and Water Conservation. January-February 1997: 18-21.

Manrique, L. A. 1988. Land Erodibility Assessment Methodology. University of Hawaii. Editorial & Publishing Shop, Honolulu, HI.

Maidment, D. R. (ed.) 1992. Chapter 12: Erosion and Sediment Transport. Handbook of Hydrology. McGraw-Hill, Inc.

McCool, D. K., G. R. Foster and G. A. Weesies. 1997. Slope Length and Steepness Factor (LS). In: Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE). U.S. Department of Agriculture Handbook No. 703.

McElroy, A. D., S.Y. Chiu, J. W. Nebgan, and others. 1976. Loading functions for assessment of water pollution from nonpoint sources. Environmental Protection Technical Service, EPA 600/2-76-151. Washington, D.C.

Mironenko, E. V., and Y. A. Pachepsky. 1998. Estimating Transport of Chemicals from Soil to Ponding Water. Journal of Hydrology. 208(1998):53-61.

Mitas, L., and H. Mitasova. 1998. Distributed Soil Erosion Simulation for Effective Erosion Prevention. Water Resources Research. 34(3): 505-516.

Mitasova, H, J. Hofierka, M. Zlocha, and L. R. Iverson. 1996. Modelling Topographic Potential for Erosion and Deposition Using GIS. International Journal of Geographic Information Systems. 10(5): 629-641.

Moore, I. D., and J. P. Wilson. 1992. Length-slope Factors for the Revised Universal Soil Equation: Simplified Method of Estimation. Journal of Soil and Water Conservation. 47(5):423-428.

Moore, I.D., and R.B. Grayson. 1991. Terrain-Based Catchment Partitioning and Runoff Prediction Using Vector Elevation Data. Water Resources Research. 27(6):1177-1191.

Moore, I. D., R. B. Grayson, R. B., and A. R. Landson. 1991. Digital Terrain Modelling: a Review of Hydrological, Geomorphological, and Biological Applications, Hydrological Processes. 5: 3-30.

Moore, I.D., and G.J. Burch. 1986a. Sediment Transport Capacity of Sheet and Rill Flow: Application of Unit Stream Power Theory. Water Resources Research. 22(8):1350-1360.

Moore, I.D., and G.J. Burch. 1986b. Modelling Erosion and Deposition: Topographic Effects. Transactions of the ASAE. 29:1624-1630.

Moore, I.D., and G.J. Burch. 1985. Physical Basis of the Length-slope Factor in the Universal Soil Loss Equation. Soil Science Society of America Journal. 50: 1294-1298.

Munoz-Carpena, R., J. E. Parsons, and J. W. Gillian. 1999. Modeling Hydrology and Sediment Transport in Vegetative Filter Strips. Journal of Hydrology. 214(1999):111-129.

Nearing, M. A., G. Govers, and L. D. Norton. 1999. Variability in Soil Erosion Data from Replicated Plots. Soil Sci. Soc. Am. J. 63:1829-1835.

Needham, S. E. 1994. Assessing A Geographic Information System and ANN-AGNPS Water Quality MODEL: A Case Study. Ph.D. Dissertation. Michigan State University.

Nelson, D. W., and T. J. Logan. 1983. Chemical Processes and Transport of Phosphorus. In: Schaller, F. W., and G. W. Bailey (eds). Agricultural Management and Water Quality. Pp 65-91.

Newson, M. 1994. Hydrology and the River Environment. Clarendon Press. Oxford.

Ng, H. Y. F., T. Mayer, and J. Marsalek. 1993. Phosphorus Transport in Runoff from a Small Agricultural Watershed. Wat. Sci. Tech. 28(3-5):451-460.

Novak, L. T., D. C. Adriano, G. A. Columan, and D. B. Shah. 1975. Phosphorus Movement in Soils: Theoretical Aspects. Journal of Environmental Quality. 4(1):93-98.

Novotny, V., and G. Chesters. 1989. Delivery of Sediment and Pollutants from Nonpoint Sources: A Water Quality Perspective. Journal of Soil and Water Conservation. 44(6):568-576.

Onstad, C. A., and G. R. Foster. 1974. Erosion Modeling on a Watershed. Transactions of the ASAE. 18:288-292.

Ouyang, D., J. Bartholic. 2001. Web-based Application for Soil Erosion Prediction. In: Soil Erosion Research for the 21st Century – Proceedings of the International Symposium. Pp 260-263. January 3-5, 2001. Honolulu, HI.

Ouyang, D., and J. Bartholic. 1997. Predicting sediment delivery ratio in Saginaw Bay Watershed. In: The 22nd National Association of Environmental Professionals Conference Proceedings. pp 659-671. May 19-23, 1997. Orlando, FL.

Ouyang, D., Y.-T. Kang, and J. Bartholic. 1996. Agricultural phosphorus assessment in the Great Lakes Basin: A case study. In: An Agricultural Profile of the Great Lakes Basin: Characteristics and Trends in Production, Land-use and Environmental Impacts. Great Lakes Commission. East Lansing, MI.

Perrone, J., and C. A. Madramootoo. 1999. Sediment Yield Prediction using AGNPS. Journal of Soil and Water Conservation. 54(1):415-419.

Petrie, J., and P. Diplas. 2000. Statistical Approach to Sediment Sampling Accuracy. Water Resources Research. 36(2):597-605.

Pierzynski, G. M., and T. J. Logan. 1993. Crop, Soil, and Management Effects on Phosphorus Soil Test Levels. Journal of Production Agriculture. 6(4):513-520.

Rapp, J. F., V. L. Lopes, K. G. Renard. 2001. Comparing Soil Erosion Estimates from RUSLE and USLE on Natural Runoff Plots. In: Soil Erosion Research for the 21st Century – Proceedings of the International Symposium. Pp. 24-27. January 3-5, 2001. Honolulu, HI.

Rast W., and G. F. Lee. 1983. Nutrient Loading Estimates for Lakes. Journal of Environmental Engineering. 109(2):502-517.

Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McCool, and D. C. Yoder, coordinators. 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE). U.S. Department of Agriculture Handbook No. 703.

Renard, K. G., and G. R. Foster. 1983. Soil Conservation: Principles of Erosion by Water. Dryland Agriculture. Agronomy Monograph No. 23. American Society of Agronomy. Madison, WI.

Richards, R. P., D. B. Baker, J. W. Kramer, and D. E. Ewing. 1996. Annual Loads of Herbicides in Lake Erie Tributaries in Ohio and Michigan. Journal of Great Lakes Research Vol. 22: 414-428.

Richards, R. P., and J. Holloway. 1987. Monte Carlo Strategies for Estimating Tributary Loads. Water Resources Research. 23(10): 1939-1948.

Risse, L. M., M. A. Nearing, A. D. Nicks, and J. M. Laflen. 1993. Error Assessment in the Universal Soil Loss Equation. Soil Sci. Soc. Am. J. 57:825-833.

Roehl, J. W., 1962. Sediment Source Areas, Delivery Ratios and Influencing Morphological Factors. International Association of Scientific Hyrology Commission of Land Erosion. Publication 59: 202-203.

Rudra, R. P., W. T. Dickinson, H. R. Whiteley. 2001. Lessons Learned from the Use of Erosion and Non-Point Source Pollution Model. In: Soil Erosion Research for the 21st Century – Proceedings of the International Symposium. Pp. 629-631. January 3-5, 2001. Honolulu, HI.

Saleh, A., and D. W. Fryrear. 1999. Soil Roughness for the Revised Wind Erosion Equation (QWEQ). Journal of Soil and Water Conservation. 2nd Quarter 1999. p. 473-476.

Selker, J. S., D. A. Haith, and J. E. Reynolds. 1990. Calibration and Testing of a Daily Rainfall Erosivity Model. Transactions of the ASAE. 33(5):1612-1618.

Seta, A. K., R. L. Blevins, W. W. Frye, and B. J. Barfield. 1993. Reducing Soil Erosion and Agricultural Chemical Losses with Conservation Tillage. Journal of Environmental Quality. 22:661-665.

Shah, D. B., G. A. Coulman, L. T. Novak, and B. G. Ellis. 1975. A Mathematical Model for Phosphorus Movement in Soils. Journal of Environmental Quality. 4(1):87-92.

Sharpley, A. N., and S. J. Smith. 1990. Phosphorus Transport in Agricultural Runoff: The Role of Soil Erosion. In: Boardman, J., I. D. L. Foster, and J. A. Dearing (eds.). Soil Erosion on Agricultural Land. Pp 351-366. John Wiley & Sons Ltd.

Sharpley, A. N., and M. Meyer. 1994. Minimizing Agricultural Nonpoint-Source Impacts: A Symposium Overview. Journal of Environmental Quality. 23:1-3.

Sharpley, A. N., S. C. Chapra, R. Wedepohl, J. T. Sims, T. C. Daniel, and K. R. Reddy. 1994. Managing Agricultural Phosphorus for Protection of Surface Waters: Issues and Options. Journal of Environmental Quality. 23:437-451.

Sharpley, A. N., S. J. Smith, and R. G. Menzel. 1982. Prediction of Phosphorus Losses in Runoff from Southern Plains Watersheds. Journal of Environmental Quality. 11(2):247-250.

Sharpley, A. N., and J. K. Syers. 1979. Phosphorus Inputs Into A Stream Draining An Agricultural Watershed II: Amounts Contributing and Relative Significance of Runoff Types. Water, Air, and Soil Pollution 11:417-428.

Stevens, R. G., T. M. Sobecki, and T. L. Spofford. 1993. Using the Phosphorus Assessment Tool in the Field. Journal of Production Agriculture. 6(4):487-492.

Suppnick, J. 1999. Water Chemistry Trend Monitoring in Sycamore Creek and Haines Drain, Ingham County, Michigan. Staff Report. Michigan Department of Environmental Quality, Surface Water Quality Division.

Tim, U. S., and S. Mostaghimi. 1989. Modeling Phosphorus Movement and Distribution in Vadose Zone. Transactions of the ASAE. 32(2):655-661.

Truman, C. C., G. J. Gascho, J. G. Davis, R. D. Wauchope. 1993. Seasonal Phosphorus Losses in Runoff From Coastal Plain Soil. Journal of Production Agriculture. 6(4):507-513.

U.S. Department of Agriculture, National Soil Erosion Research Laboratory. 1995. NSERL report No. 10. Water Erosion Prediction Project (WEPP) Technical Documentation. West Lafayette, IN.

U.S. Department of Agriculture, Natural Resources and Conservation Service. 1992. 1992 National Resource Inventory. Michigan's Land: Its Use and Condition.

U.S. Department of Agriculture, Soil Conservation Service. 1992. Soil Survey of Ingham County, Michigan.

U.S. Department of Agriculture, Soil Conservation Service. 1990. Sycamore Creek Watershed Water Quality Plan. Ingham County, Michigan.

U.S. Department of Agriculture, Soil Conservation Service. 1986. Technical Release 55 – Urban Hydrology for Small Watersheds, U.S. Dept. of Agriculture, Soil Conservation Service, Engineering Division, Washington, D.C.

U.S. Department of Agriculture, Soil Conservation Service. 1972. National Engineering Handbook, Hydrology Section 4, Chapters 4-10.

U.S. Environmental Protection Agency. 2000. Water Quality Conditions in the United States – A profile from the 1998 National Water Quality Inventory Report to Congress. EPA841-F-00-006. Office of Water, Washington, D.C.

U.S. Environmental Protection Agency. 1999. Total Maximum Daily Load. Office of Water, Washington, D.C. http://www.epa.gov/reg3wapd/tmdl/303d.htm.

U.S. Environmental Protection Agency. 1996 National Water Quality Inventory Report to Congress. Office of Water, Washington, D.C.

U.S. Environmental Protection Agency. 1994 National Water Quality Inventory Report to Congress. Office of Water, Washington, D.C.

U.S. Environmental Protection Agency. 1997. Compendium of Tools for Watershed Assessment and TMDL Development. EPA841-B-97-006. Washington, D.C.

U.S. Environmental Protection Agency. 1996. Section 319 National Monitoring Program Projects. 1996 Summary Report. EPA-841-S-96-002. Washington, D.C.

U.S. Environmental Protection Agency. 1994. Section 319 Success Stories. EPA-841-S-94-004. Washington, D. C.

U.S. Environmental Protection Agency. 1994. A Watershed Assessment Primer. EPA-910/B-94-005. Region 10, Seattle, WA.

U.S. Environmental Protection Agency. 1992. TMDL Case Study: Sycamore Creek, Michigan. EPA 841-F-92-012. Washington, D. C.

U.S. Environmental Protection Agency. 1992. Managing Nonpoint Source Pollution. EPA-506/9-90. Washington, D. C.

U.S. Environmental Protection Agency. 1988. Sediment, Nutrient and Pesticide Transport in Selected Lower Great Lakes Tributaries. EPA-905/4-88-001. GLNPO Report No. 1. Chicago, IL.

Wade, J. C., and E. O. Heady. 1976. A National Model of Sediment and Water Quality: Various Impacts of American Agriculture. Center for Agricultural and Rural Development, Iowa State University, Ames, IA.

Wagner, R. A., T. S. Tisdale, and J. Zhang. 1996. A Framework for Phosphorus Transport Modeling in the Lake Okeechobee Watershed. Water Resources Bulletin. 32(1):57-73.

Walling, D. E. 1983. The Sediment Delivery Problem. Journal of Hydrology. 65(1983):209-237.

Walling, D. E. 1994. Measuring Sediment Yield from River Basins. In: R. Lal (ed.) Soil Erosion Research Methods. Soil and Water Conservation Society.

Walpole, R. E., and R. H. Myers. 1985. Probability and Statistics for Engineers and Scientists. Third Edition. Macmillan Publishing Company. New York.

Williams, J. R., J. G. Arold, C. A. Jones, V. W. Benson, and R. H. Griggs. 1994. Water Quality Models for Developing Soil Management Practices. In: R. Lal, B. A. Stewart (eds.). 1994. Soil Processes and Water Quality. Lewis Publishers.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27:129-144.

Williams, J. R. 1983. Hydrology and Sediment Transport in Small Watersheds. In: Schaller, F. W., and G. W. Bailey (eds.). Agricultural Management and Water Quality. Pp 141-151.

Williams, J. R., and R. W. Hann. 1978. Optimal Operation of Large Agricultural Watersheds with Water Quality Constraints. Texas Water Resources Institute, Texas A & M University, Technical Report No. 96.

Williams, J. R., and H. D. Berndt. 1977. Sediment Yield Prediction Based on Watershed Hydrology. Transactions of the ASAE. Pp 1100-1104.

Williams, J. R. 1975. Sediment Routing For Agricultural Watersheds. Water Resources Bulletin. 11(5):965-974.

Wishmeier, W. H., and Smith, D. D. 1978. Predicting Rainfall Erosion Losses – A Guide To Conservation Planning. U.S. Department of Agriculture, Agriculture Handbook No. 537.

Wishmeier, W. H. 1976. Use and Misuse of the Universal Soil Loss Equation. Journal of Soil and Water Conservation. 31(1):5-9.

Wishmeier, W. H., C. B. Johnson, and B. V. Cross. 1971. A Soil Erodibility Nomograph for Farmland and Construction Sites. Journal of Soil and Water Conservation. 26:189-193.

Wishmeier, W. H., D. D. Smith, and R. E. Uhland. 1958. Evaluation of Factors in the Soil-Loss Equation. Agricultural Engineering. 39:458-462, 474.

Yitayew, M., S. J. Pokrzywka, K. G. Renard. 1999. Using GIS For Facilitating Erosion Estimation. Applied Engineering in Agriculture. 15(4):295-301.

Young, R. A., C. A. Onstad, D. D. Bosch, and W. P. Anderson. 1978. AGNPS, Agricultural Non-Point-Source Pollution Model. A Watershed Analysis Tool. U. S. Department of Agriculture, Conservation Research Report 35.

Yoder, D. C., J. P. Porter, J. M. Laflen, J. R. Simanton, K. G. Renard, D. K. McCool, and G. R. Foster. 1997. Cover-Management Factor (C). In: Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE). U.S. Department of Agriculture Handbook No. 703.

Yu, B. 1999. A Comparison of the R-Factor in the Universal Soil Loss Equation and Revised Universal Soil Loss Equation. Transactions of the ASAE. 42(6):1615-1620.

Yuan, Y., and J. K. Mitchell. 1999. A Model to Evaluate Pollutant Loads from Tile Drains. Transactions of the ASAE. 42(5):1313-1319.

Zeverbergen, L. W., and C. R. Thorne, 1987. Quantitative Analysis of Land Surface Topography, Earth Surface Processes and Landforms. 12:47 - 56.

Zhang, J., C. T. Haan, T. K. Tremwel, and G. A. Kiker. 1995. Evaluation of Phosphorus Loading Models for South Florida. Transactions of the ASAE. 38(3):767-773.