ABSTRACT

MOORE, AMBER DAWN. Modeling erosion on construction sites (Under the direction of Richard A. McLaughlin and Keith Cassel.)

Our first objective was to develop suitable construction site parameters for the validated WEPP erosion prediction model. Predicted values were correlated with field observations for runoff and sediment yield. Runoff volumes and sediment yields similar to those measured on an active construction site were achieved by removing the A horizon from the soil input parameter and applying a landcover parameter with no ground cover and minimal roughness. Increasing critical shear stress to 384 Pa (as recommended by an erosion mat manufacturer) efficiently predicted runoff volume (E = 0.66) and sediment yield (E = 0.57) when compared to a construction site stabilized with straw, tar and erosion blankets.

Our second and third objectives were to use to evaluate state-approved sediment traps and riparian buffers with WEPP and GeoWEPP, and to create erosion and sediment control scenarios that would achieve the NC water quality standard of 50 Nephlometric Turbidity Units. Two sediment traps on an actual school construction site were modeled with WEPP, and a 15.2 m width forest buffer on a planned golf course site was modeled with GeoWEPP. WEPP predicted average trapping efficiencies of sediment traps A and B to meet the NC standard of 70 % trapping efficiency. WEPP predicted runoff from sediment trap B met the turbidity standard for 11 % of the modeled storm events. GeoWEPP predicted that the riparian buffers would not meet the turbidity standard for any of the modeled storm events. The existing sediment controls were adjusted to meet water quality standards by increasing sediment trap size, replacing free-draining traps rock outlets with standing pools behind culvert outlets, extending the riparian buffer, and adding vegetation to highly erosive areas

determined by GeoWEPP. Turbidity standards were met on watershed A by removing the outlet from the second sediment trap and increasing the trap area 6-fold. WEPP and GeoWEPP are useful for modeling construction sites and for designing erosion control scenarios, although the new parameters and the GeoWEPP model will need to be validated on other construction sites to improve confidence in the model output.

Modeling Erosion on Construction Sites

by

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BIOGRAPHY

Amber was raised in Soddy-Daisy, Tennessee by her parents, Shirley and Roger, with her siblings, Eric and Kala. Growing up she enjoyed activities such as playing soccer, performing the clarinet, and spending summers riding horses at Girl Scout camp. After high school she moved to Alabama, where she completed a B.S. degree in Environmental Science at Auburn University. Wanting to combine her interests in working with children and protecting the environment, Amber moved to Trinity, Texas to work at the Outdoor Education Center, a state-funded program for fifth grade children from Houston, Texas. While in Texas, Amber was inspired to return to college to strengthen her environmental science background. Two years later she moved to Raleigh, N.C. to pursue a M.S. in Soil Science at North Carolina State University under Rob Mikkelsen, where her research focused on nitrogen availability of swine lagoon. Shifting her focus from soil fertility to soil physics, she collaborated with Rich McLaughlin and Helena Mitasova for her Ph.D., focusing her research on erosion prediction models and best management practices on construction sites. Upon the completion of her Ph.D. degree, she plans to decompress from five consecutive years of graduate school, eventually pursuing a postdoctoral research position in the field of soil erosion. When Amber finds a moment of free time, she practices yoga in her living room, goes jogging around town, and pretends to pedal on the back of Chloe's tandem bicycle. She is also fond of trying new vegetarian recipes, watching independent films, encouraging Chloe's rottweiler to chase the cat, and tending to her tiny garden when the mood hits her.

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LIST OF ABBREVIATIONS

BMP - Best Management Practice

CRP - Conservation Reserve Program

DEM - Digital Elevation Model

GeoWEPP - Geospatial interface for WEPP

GIS - Geographic Information Systems

GRASS - Geographic Resources Analysis Support System

LIDAR - LIght Detection And Ranging

NPS - Non-Point Source

NTU - Nephelometric Turbidity Units

RUSLE - Revised Universal Soil Loss Equation

SIMWE - Simulated Water Erosion

SSURGO - Soil Survey Geographic Database

TSS - Total Suspended Solids

WEPP - Water Erosion Prediction Project

Chapter 1: Introduction to Sediment Pollution from Construction Sites and Erosion Prediction Modeling

Introduction

Recently, non-point source pollution (NPS) has been the focus of efforts to reduce human impacts on streams, lakes, and estuaries. These sources contribute sediment, nutrients, bacteria, heavy metals, and many other types of contaminants, resulting in a decline in the function and aesthetics of the receiving waters. The North Carolina Division of Water Quality (2003) estimated that 3500 miles of stream in our state were polluted with sediment. Cost of managing sediment pollution in streams in the U.S. is estimated at $16 billion per year (Osterkamp et al, 1998).

NEGATIVE IMPACTS OF SEDIMENT POLLUTION

Sediment pollution has negative impacts on a variety of areas, as seen in Table 1-1. We will be focusing on problems associated with aquatic life, economics (not listed), and aesthetics, as these areas are usually the driving force responsible for changes in sediment pollution policy.

Table 1-1. Examples of sediment impacts on designated or existing use categories[a]

Type	Resource Problem	Sediment Issue
Aquatic life		
Fish	Adult migration Spawning Fry emergence Juvenile rearing Escapement Winter rearing habitat Reduced or hidden food supply	Passage barriers Cobble/gravel burial or scour Turbidity/suspended sediment Aggradation /scour Changed channel form Loss of riparian vegetation Reduced interstitial dissolved oxygen due to filling of substrate with fines
Invertebrates	Reduced diversity, population density	Filling of substrate with fines Loss of riparian vegetation
Amphibians	Larval development	Filling of substrate with fines
Drinking Water	Reduced reservoir capacitiy Poor taste/appearance Intakes clogged Impaired treatment	Sediment deposition Turbidity Total suspended solids Aggradation or scour (disturbs intakes)
Recreation/Aesthetics	Cloudy water Channel modification impairs fishing, swimming, rafting	Turbidity Channel modification Pool filling
Agriculture	Fouled pumps Livestock watering Loss of reservoir capacity	Suspended sediment Turbidity too high to drink Sediment mass load
Industrial	Process water Cooling water	Suspended sediment fouls equipment TSS too high to treat water
Navigation	Navigation channel changes	Sediment deposition

[a]Source: U.S.E.P.A, 1999.

AQUATIC LIFE

Deposited sediments can degrade natural habitats for aquatic animals. For example, Harrison and Elsworth (1958) found that the nymph of the mayfly Pseudocloeon would only attach itself to clean, sediment-free vegetation. Similarly, Simulium larvae migrated to portions of vegetation where silt was not deposited (Wu, 1931). And freshwater mussels could not tolerate silt deposits in streambeds greater than 6.4 mm per year (Ellis, 1936). Because so many aquatic animals require clean living environments, aquatic habitats must remain low in silty deposits to ensure their survival.

Sediments that remain in suspension inhibit the growth of rooted aquatic plants by depositing on the plant leaves and blocking photosynthesis (Cordone and Kelley, 1960).

Corfitzen (1939) noted an absence of algae in turbid canals and attributed the phenomena to the lack of sunlight penetration in the water column. Cordone and Pennoyer (1960) found that an abundant population of algal pads of the genus Nostoc was virtually destroyed by sediment discharge. Such a loss of aquatic plants reduces habitat quality, oxygenation, and food supply for aquatic animals.

Suspended sediments are also harmful to aquatic animals. Shapovalov and Berrian (1940) found that only 10 % of king salmon eggs deposited in a silty gravel medium in a wire hatchery trough survived, compared to a 50 % survival rate for eggs deposited in a standard wire trough with no medium. A large number of partially developed eggs were found in the silty gravel, indicating that eggs were smothered by the silt and unable to develop to completion. Wallen (1951) found that warm-water fish did not show observable behavioral reactions until turbidity concentrations reached 20,000 ppm, with one species not showing a reaction until 100,000 ppm. Lethal turbidities ranged between 175,000 ppm and 225,000 ppm. After examination, the opercular cavities and gill filaments were clogged with silty clay particles, inhibiting respiration. In another study, ventilation rates increased 50-70% at turbidities exceeding 1012 and 898 NTUs at 15 and 25 degrees C, respectively, as a result of reduced respiratory efficiency (Horkel and Pearson, 1976). These studies illustrate that reproduction inhibition and respiration reduction produce damaging effects to aquatic ecosystems, and must be prevented to maintain healthy habitats.

ECONOMICS

The impacts of soil erosion become costly, especially when agricultural fields are stripped of their valuable topsoil. Cropland in the U.S. decreased by 4.5 million ha, or 2.6%, between 1982 and 1997 as a result of soil erosion (USDA, NRCS, 1997a). It has also been reported that a third of cropland is threatened by soil erosion (USDA, NRCS, 1997b). On a larger scale, the world's per capita food supply declined between 1985 and 1995 due to the erosion and depletion of nutrient-rich soils (Pimental et al., 1995). Limiting cropland limits food supply, which can cause an area's economy to suffer.

In addition to losing arable land, controlling erosion is also a costly endeavor. Farmers often cannot afford to exchange cropland for vegetated riparian buffers, or to plant cover crops when their fields are bare. It has been noted that the economics of conservation practices are a major reason for their acceptance, or the lack thereof (Weesies et al., 1994). For instance, in contrast to farming, developers generally incur lower costs by ignoring erosion altogether. Environmental regulation that can stop the project from proceeding and certifications are their only economic incentives to prevent sediment pollution in streams.

AESTHETICS

Eroded surfaces and muddy water are generally considered as unattractive sites. Herzog et al. (2000) discovered that homebuyers and landowners perceived the value of green, vegetated building sites exceeded that of similar brown, barren sites, even more than the cost of seeding temporary vegetation. Landowners who pay high prices for waterfront property expect, and often demand, to see crystal clear waters. Complaints of taxpayers are often the necessary motivation needed for the adoption of effective erosion practices.

TARGET AREAS FOR CONTROLLING EROSION

AGRICULTURE

In recent years, the strongest focus for reducing soil erosion has been on agricultural areas. In the U.S., we have successfully reduced sediment yields from agricultural areas. Erosion on cropland and Conservation Resource Protection (CRP) land reportedly decreased by 32% between 1982 and 1997 (USDA, NRCS, 1997b). Commonly used erosion prediction models, such as the Revised Universal Soil Loss Equation (RUSLE) and Water Erosion Prediction Project (WEPP), were designed to simulate topsoil erosion from areas with agricultural landcover. Although reducing sediment losses from agricultural areas should be recognized as a major achievement, other areas susceptible to erosion need to be acknowledged to continue the improvement of soil and water quality in our country.

CONSTRUCTION SITES

As land-development activities require vegetation removal and landscape reshaping, soils are left exposed to the elements and are subject to erosion. Toy and Hadley (1987) noted that land disturbance from mining, residential, commercial and highway construction can accelerate erosion by two or more orders of magnitude. By 1980, construction activities had disturbed an estimated 1.7% of U.S. land (Toy and Hadley, 1987). Although the impacts of construction may appear to be short-term, sediment erosion from construction site erosion can still be very harmful, long past after the disturbance is over. Wolman and Schick (1967) found that construction areas contributed more sediment per land area than agricultural fields. The U.S.E.P.A (1976) has also documented the magnitude of construction site impact on surface erosion to be greater for construction than agricultural fields (Table 1-2). From an environmental perspective, several studies have illustrated that sediment loads from land-disturbing activities can result in population reductions and imbalances for riffle and pool macroinvertebrates (Hog and Norris, 1991; Barton, 1977; Taylor and Roff, 1986).

Table 1-2. Some reported quantitative effects of man's activities on surface erosion[a]

Initial Status	Type of disturbances	Magnitude of impact[b]
Row crop	Construction	10
Pastureland	Construction	200
Forestland	Construction	2000
Grassland	Planting row crops	20 - 100
Forestland	Planting row crops	100 - 1000
Forestland	Woodcutting and skidding	1.6
Forestland	Mining	1000
Forestland	Fire	7 - 1500

[a] Source: U.S. E.P.A. (1976).
[b] Relative magnitude of surface erosion from disturbed surface, assuming "1" for the initial status.

REGULATIONS

In 1973, the Clean Water Act was passed. Title II, section 208, placed the responsibility of maintaining water quality from construction sites on state governments. In response, North Carolina passed and published the Sedimentation Pollution Control Act of 1973 in the NC General Statutes. Laws governing the control of sediment include the requirement for erosion control plans to be approved by the Sediment Control Commission (113A-54.d4), for buffer zones to be established along lakes and water courses (113A-57.1), the vegetation of exposed surfaces after 15 working or 30 calendar days (113A-57.2), the use of erosion controls on sites exceeding one acre of land-disturbing activity (113A-57.3), and the issuance of stop-work orders to land-disturbing activities in violation of this act (113A-65.1f). Laws of greater detail can be found in the NC Administrative Code, 2001, which states that control measures shall be planned, designed, and constructed to provide protection from the runoff of a 10-year storm for that area (15ANCAC04B.0124b), that sediment traps have 70 % settling efficiency for particles greater than or equal to 0.04 mm in diameter for a 2-year storm (15ANCAC04B.0124c), and the issuance of civil penalties based on the severity of the violation(s) (15ANCAC04C).

North Carolina has also set standards for turbidity levels, although they seem more difficult to meet. As stated in the Fresh Surface Water Quality Standards for Class C Waters,"...the turbidity in the receiving water shall not exceed 50 NTUs in streams not designated as trout water...compliance with this turbidity standard can be met when land management activities employ BMPs recommended by the Designated Source Agency". The Department of Natural Resources was challenged on this law in 2001 in the cases of Wallace Burt Jr. et al vs. DENR and Highlands Cove, and Whiteside Estates vs. DENR and Highlands Cove. In the end, the administrative judge ruled in favor for Wallace Burt Jr. and Whitesides Estates, stating that either BMPs need to be improved to meet the 50 NTU standard, or the standard needs to be changed. As can be calculated by Stokes Law, suspended silt and clays may take days, weeks, and even months before they can settle out of solution. This suggests that making turbidity much more difficult to control than the sediment typically trapped by sediment control devices.

USING MODELS TO OPTIMIZE BMP EFFICIENCY

Optimal placement of controls is dependent on climate, topography, soil, and landcover. The traditional method for designing erosion and sediment control plans was based on visual interpretations of contour maps, soil survey maps, and field surveys (Goldman et al., 1986). However, this method is labor and time intensive, is heavily dependent on the competency of the designer, and makes interactions between elevation, soil, and landcover difficult to predict. Another method uses computer erosion prediction modeling, allowing the user to identify erosive areas and to compare the effectiveness of different control measures with each other (Goldman et al., 1986).

There are several computer models being applied by researchers to test the effect of BMPs on sediment control. Yuan et al. (2001) applied AnnAGNPs Annualized Agricultural Non-Point Source to test impoundments and winter cover crops as BMPs for reducing sediment loads on a large watershed. Wright et al. (1992) used CREAMS-DRAINMOD (Chemicals, Runoff, and Erosion from Agricultural Management Systems - Drainage Simulation Model) to evaluate the effects of different types of water table management runoff, erosion, and nitrogen losses. Gerwig et al. (2001) examined the effect of riparian buffers using GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) and REMM (Riparian Ecosystem Management Model) on phosphorous and nitrogen transport from agricultural fields receiving swine effluent.

EROSION PREDICTION MODELING

To meet government regulations, land developers and contractors must estimate runoff volumes and sediment yields from their sites in order to estimate the type, size, quantity, and placement of erosion and sediment controls. Erosion prediction models can be useful tools for this purpose, as they reveal new information related to complex interactions in the soil environment, and allow for new land-use ideas to be evaluated before they are implemented (Doe and Harmon, 2001).

Erosion prediction models apply physics and mathematics to simulate real-world processes (Haan et al., 1982). Various types of computer models are used to simulate erosion processes on landscapes. The empirical model is the simplest and oldest computer model used, and is based on statistically significant relationships between model inputs and expected output derived from specific lab and field data. Empirical models are simple to use and understand, but are not valid for areas or conditions where data is not available. Thus they are highly limited in their application. For example, the Universal Soil Loss Equation (USLE) is not capable of estimating runoff volume, does not predict sediment yield from discrete storm events, and can not be used on complex slopes (Morgan and Quinton, 2001). Many people prefer process-based models, which attempt to simulate significant processes in a real-life system, and are based on laws and theories of physical processes. The process-based models are easily applied to a large variety of landscapes and situations, but they are very complex and parameter intensive, which makes the isolation of problems within the model difficult.

Process-based models may be spatially averaged, or spatially distributed. Spatially averaged models lump together components within a landscape into single homogenous units and follow one-dimensional patterns. These models are relatively easy to use and can be very effective for simulating erosion-related processes on simple landscapes. However, because landscapes are inherently complex and follow two-dimensional patterns, these models only perform an adequate job of simulating erosion processes. In contrast, spatially distributed models represent the spatial variability of landscape components, and can thus be used to simulate soil erosion on complex slope, soil, and landcover patterns.

The Water Erosion Prediction Project (WEPP) is a well-documented process-based erosion prediction model originally designed for the management of sediment on agricultural areas. WEPP was developed as a replacement for the USLE model to provide users with a model that 1) could be applied to a variety of situations, 2) could predict erosion losses from both single storm events and long-term averages, 3) estimate erosion and deposition on both hillslopes and watersheds, 4) estimate deposition in small impoundments, and 5) is user-friendly for field technicians (Flanagan et al., 2001). There has been a great effort to calibrate WEPP parameters for agricultural fields (Zhang et al., 1995a; Zhang et al., 1995b; McIsaac et al., 1992; Lienbow et al., 1990) and rangelands (Savabi et al., 1995; Simanton et al., 1991; Wilcox et al., 1990; Nearing et al., 1989), and a moderate effort to calibrate WEPP parameters for forests (Elliot and Hall, 1997). However, there has been very limited work on calibrating WEPP parameters for construction sites (Laflen et al., 2001; Lindley et al., 1998). In contrast to construction site conditions, models designed for agricultural areas work with relatively small concentrations of sediment, simple slopes, and relatively constant landscape conditions. In addition, erosion output for agriculture is usually expressed as soil loss, as farmers greatest concern is the conservation of topsoil. Soil loss is irrelevant on construction sites, with greater emphasis toward sediment pollution in neighboring streams.

WEPP does provide specific options for impoundments in the watershed version of WEPP, but these are not yet developed for GeoWEPP, the spatially explicit version of WEPP (see below). WEPP also does not provide options for commonly used BMPs, including controls that do not impound water (such as rock check dams placed in channels), non-vegetative BMPs placed outside of channels (such as silt fences and level spreaders), and added flocculants (such as gypsum and polyacrylamide). Options for disturbed areas have recently been added to the landcover and soil input parameters in the WEPP model, however, they were derived from disturbed areas in forested regions and may not represent construction site conditions in urban areas.

Another limitation of the WEPP model is that the user must manually create landscapes by estimating parameters such as landcover, soil type, and slope for an entire hillslope. Because these parameters can vary dramatically over relatively small areas, it is often necessary to account for these variations in order to accurately predict erosion and deposition rates. In response, Renschler (2003) developed GeoWEPP, a geospatial interface for WEPP that operates within ArcView GIS. GeoWEPP uses a Digital Elevation Model (DEM) supplied by the user to create channels and sub-watersheds, runs the WEPP model on individual raster cells containing soil, landcover, and elevation information, and outputs the data both as maps and as estimated runoff volume and sediment yield for each sub-watershed. This allows the user the capability to pinpoint specific areas of erosion and deposition within the watershed, along with the ability to predict how much runoff and sediment to expect from a watershed during a rainstorm.

OBJECTIVES

The primary goals of the research documented in this dissertation were to calibrate WEPP for construction site conditions, apply WEPP and GeoWEPP to determine the efficiency of planned BMPs on construction sites, and to create BMP scenarios to meet North Carolina water quality standards.

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Chapter 2: Adapting WEPP Model Parameters for Erosion Prediction on Construction Sites

ABSTRACT: *Soil erosion and sediment losses on construction sties can be much greater than agricultural fields yet there has been little modeling done for these conditions. Our objective was to adapt the agriculturally - based erosion prediction model GeoWEPP for pre-, during, and post-construction site conditions. Data from watersheds in the Piedmont region of North Carolina were used to compare model results with actual runoff volume and sediment yields. Input parameters were modified with the Water Erosion Prediction Project (WEPP) model and storm events were simulated with GeoWEPP. Model parameters were adjusted from the WEPP default parameters as supported by the literature and site observations. Predicted values were regressed against field data for Nash &Sutcliffe Efficiency (E). After adjustments were made to the forest landcover input parameter, WEPP predicted runoff adequately (E = 0.21) although not sediment yield (E = -1033.3) for the pre-construction phase. For the construction phase, the removal of the A horizon in the soil series soil input parameter resulted in high runoff efficiency (E = 0.78) and sediment yield efficiency (E = 0.66), suggesting that GeoWEPP may be effective for predicting runoff volumes from construction sites. GeoWEPP efficiently predicted runoff volume (E = 0.66) and sediment yield (E = 0.57) from a residential development site during post-construction when critical shear stress was adjusted to 384 Pa and the landcover parameter was set to "cutslope", as recommended for erosion blanket cover.*

Keywords. *Erosion, Construction, Watershed, Calibration, Validation, WEPP model, GeoWEPP, GIS, Sediment, Runoff.*

Introduction

In recent years, there has been a lot of focus on controlling erosion on agricultural areas. Erosion from U.S. croplands and CPR land was reduced by 32% between 1982 and 1997 (USDA-NRCS, 1997). This trend is a result of strong financial incentive to prevent the loss of nutrient-rich topsoil. Unfortunately, there are other sources of sediment pollution that are overlooked, such as exposed soil on construction sites. Toy and Hadley (1987) noted that land disturbance from mining, residential, commercial and highway construction can accelerate erosion by two or more orders of magnitude. By 1980, construction activities had disturbed an estimated 1.7% of U.S. land (Toy and Hadley, 1987). Wolman and Schick (1967) noted that construction areas contributed more sediment on an area basis than agricultural fields. In addition, the U.S.E.P.A. (1976) has also documented the magnitude of impact to be greater for forested areas disturbed by construction sites than by farmland. Regarding environmental impacts, several studies have illustrated the harmful impacts of sediment from land-disturbing activities on riffle and pool macroinvertebrates, resulting in population reductions and imbalances (Hog and Norris, 1991; Barton, 1977; Taylor and Roff, 1986).

Romkens et al. (1975) noted the challenge of adapting erosion prediction models for land-disturbing conditions because they have equations that are based on relationships determined from surface soils that are coarser textured and less dense than soil found on construction sites. In contrast to construction site conditions, models designed for agricultural areas work with relatively small concentrations of sediment, simple slopes, and relatively constant landscape conditions. In addition, erosion output for agriculture is usually expressed as soil loss, as farmers greatest concern is the conservation of topsoil. Soil loss is irrelevant on construction sites, with greater emphasis toward sediment pollution in neighboring streams. Commonly used erosion prediction models, such as the Revised Universal Soil Loss Equation (RUSLE) and Water Erosion Prediction Project (WEPP) were originally designed to simulate topsoil erosion from areas with agricultural landcover.

There has been a great effort to calibrate WEPP parameters for agricultural fields (Zhang et al., 1995a; Zhang et al., 1995b; McIsaac et al., 1992; Lienbow et al., 1990) and rangelands (Savabi et al., 1995; Simanton et al., 1991; Wilcox et al., 1990; Nearing et al., 1989), and a moderate effort to calibrate WEPP parameters for forests (Elliot and Hall, 1997). However, there has been very limited work on adapting WEPP parameters for construction sites (Laflen et al., 2001; Lindley et al., 1998). Options for disturbed areas have recently been added to the landcover and soil input files in the WEPP model, however they were derived from disturbed areas in forested regions and may not represent construction site conditions in urban areas.

Another limitation of the WEPP model is that the user must manually create landscapes by estimating landcover, soil type, and slope characteristics for an entire hillslope. Because these characteristics can vary dramatically over relatively small areas, it is often necessary to account for these variations in order to accurately predict erosion and deposition rates. In response, Renschler (2003) developed GeoWEPP, a geospatial interface for WEPP that operates within ArcView GIS. GeoWEPP uses a Digital Elevation Model (DEM) supplied by the user to create channels and sub-watersheds, runs the WEPP model on individual raster cells containing soil, landcover, and elevation information, and outputs the data both as maps and as estimated runoff volume and sediment yield for each sub-watershed. GeoWEPP allows the user the capability to pinpoint specific areas of erosion and deposition within the watershed, along with the ability to predict how much runoff and sediment to expect from a watershed during a rainstorm.

The goal of this research was to adapt the agriculturally based erosion prediction model GeoWEPP for typical conditions before, during, and after the occurrence of construction activities on three different watersheds, and to provide recommendations for landcover and soil input files to improve erosion prediction on construction sites.

METHODS AND MATERIALS

SITE DESCRIPTION

Three watersheds in Wake County, NC, were selected for modeling purposes, because each had been monitored for runoff and sediment yield (Figure 2-1, Figure 2-2). Detailed descriptions for each watershed are listed in Table 2-1. Elevation and soil maps are illustrated in Figure A2-1, Figure A2-2, and Figure A2-3. Watershed boundaries and stream networks were determined using TOPAZ software in GeoWEPP.

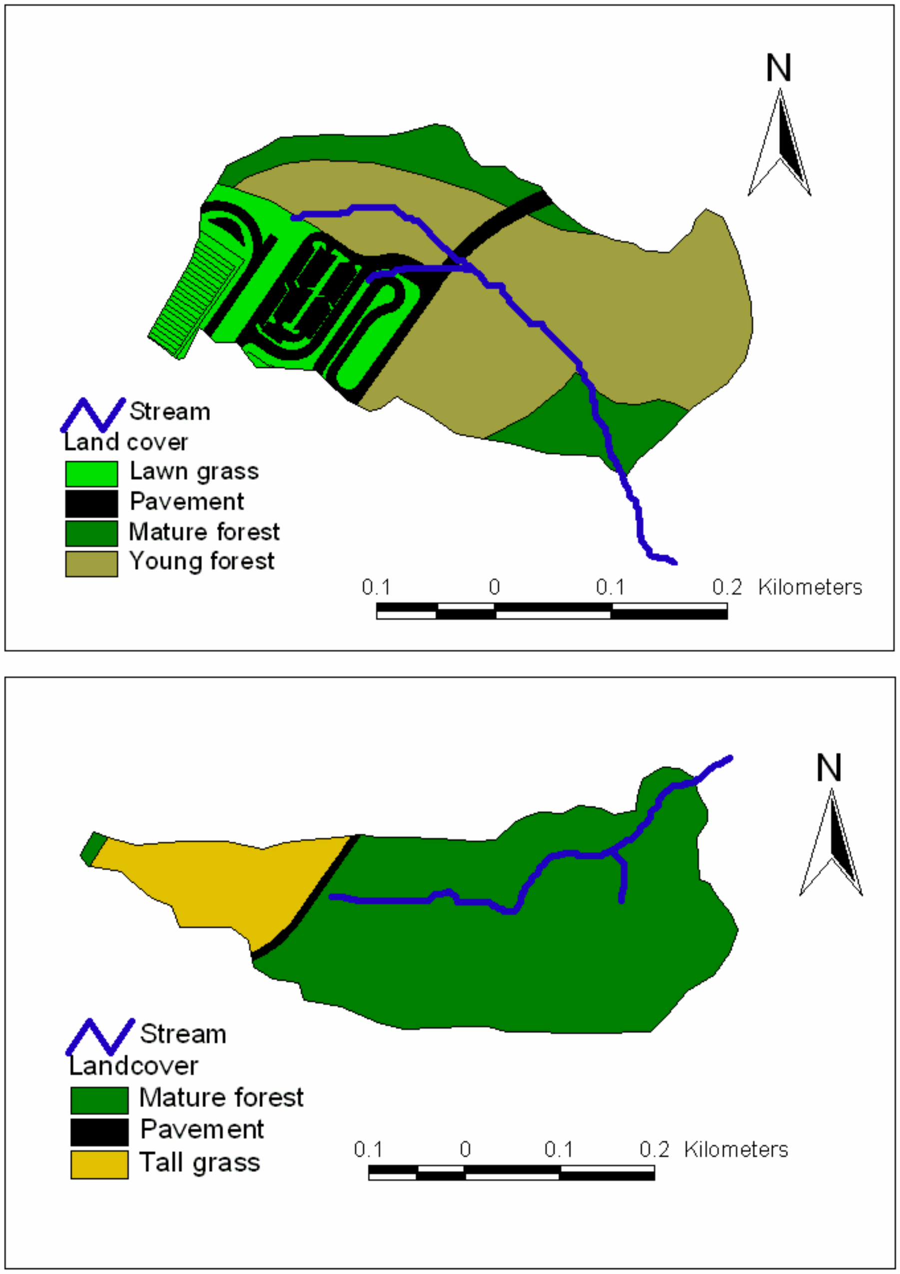


Figure 2-1. Landcoverage maps of Centennial watershed A (above) and C (below), located on the North Carolina State University Centennial Campus Middle School in Raleigh, North Carolina. Watersheds were delineated in GeoWEPP with TOPAZ software.

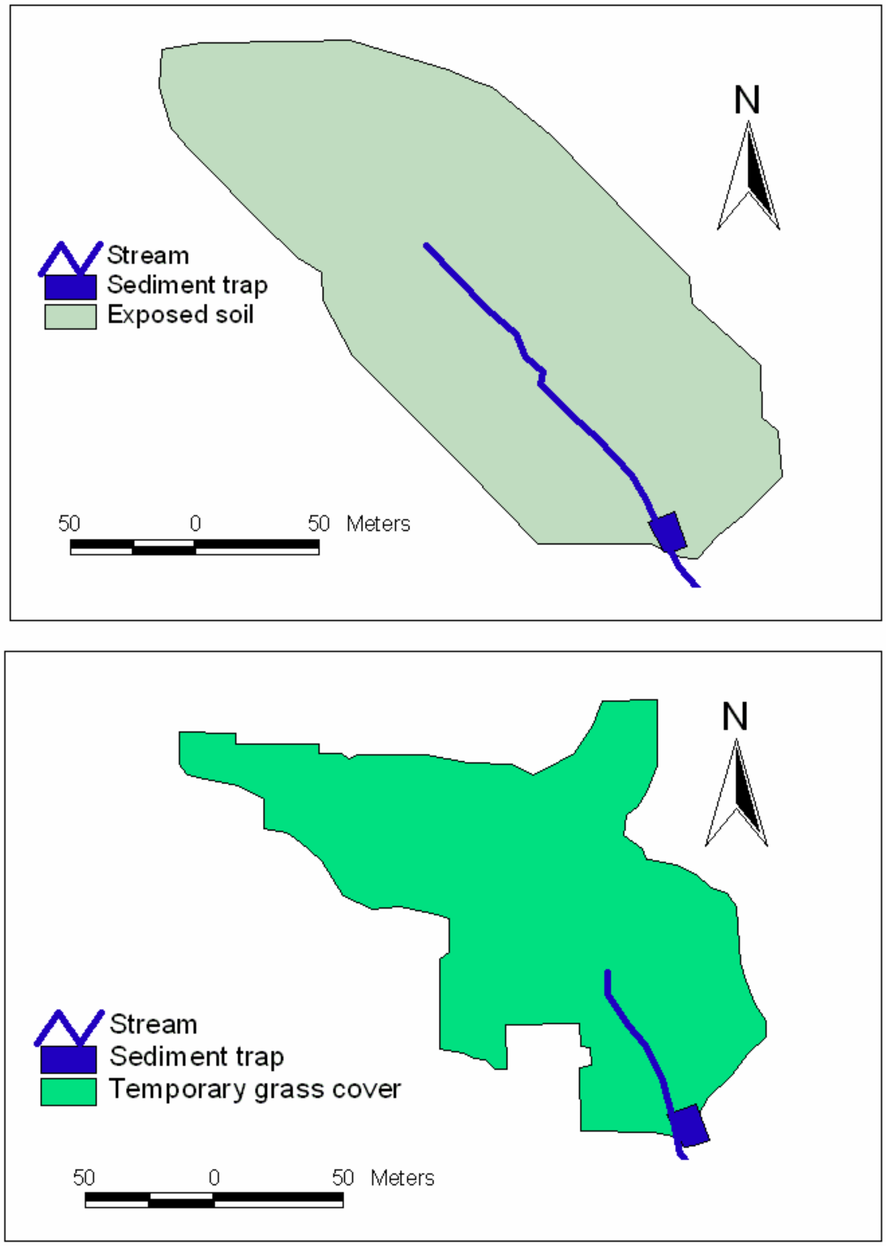


Figure 2-2. . Landcoverage maps of the Carpenter watershed during construction (above) and during site stabilization (below), located on the Carpenter Village Residential Community in Carpenter, North Carolina. Watersheds were delineated in GeoWEPP with TOPAZ software. Watershed boundaries before and after construction were altered as a result of clearing and grading changes made at the site.

Table 2-1. Site descriptions of three watersheds monitored in the piedmont region of North Carolina, modeled on landscapes representing before, during, and after construction phases.

	Construction	Post-construction[a]	Pre-construction	
	Carpenter	Carpenter	Centennial A	Centennial C
Elevation (m)	101 - 114	102 - 114	98 - 115	97 - 128
Area (ha)	4.2	2.5	9.3	11.8
Soil	15 % Worsham 24 % WhiteStore 61 % Creedmoor	22 % Worsham 26 % WhiteStore 52 % Creedmoor	13 % Pavement 29 % Appling 58 % Cecil	1 % Pavement 90 % Cecil 9 % Colfax
Landcover	100 % Bare soil	100 % Seed combined with stabilizaiton cover (hay straw with tar or erosion mats)	13 % Pavement 15 % Short grass 15 % Forest 57 % Young forest	1 % Pavement 41 % Tall grass 58 % Forest
# Storm events monitored	37	39	8	5
Sampling period	10 Dec 1997 - 13 Dec 1998	13 Dec. 1998 - 25 Apr. 2000	23 Jan 2002 - 17 Nov 2002	23 Jan 2002 - 17 Nov 2002

[a]Watershed characteristics were altered due to changes in topography that occurred during grading.

The two watersheds selected for the calibration of the stable, primarily forested phase (referred to as Centennial A & Centennial C) were located within North Carolina State University's future Centennial Campus golf course site in Raleigh, North Carolina (Figure 2-1). The Centennial C watershed was mostly forested and the Centennial A watershed was forested with some pavement and lawn grass at the location of the Centennial Middle School (Figure 2-1). Both were monitored prior to golf course construction, which was delayed several years due to financial considerations. The third watershed (referred to as Carpenter) was located on a 160-ha development site for Carpenter Village residential community in Carpenter, North Carolina (Figure 2-2). The Carpenter watershed was monitored during and after construction activity.

FIELD SAMPLING

Watershed monitoring

An H-flume and a V-notch weir were placed in the stream outlets of watersheds Centennial A & C, respectively, for flow measurements taken at one-minute intervals with an ISCO 730 Flow Bubbler Module (ISCO, Lincoln, NE, USA). The Isco 6712 Samplers were triggered to retrieve a 200 ml sample once water depth exceeded 1.5 cm above the bottom of the flume for Centennial A and 3.7 cm above the crest of the V-notch weir for Centennial C, and continuing to take samples for every 18.7 m^3 of runoff passing through the weir or flume. Four consecutive samples were composited into1000 ml bottles for laboratory analysis. Rainfall data was collected by an ISCO 674 Tipping Bucket Rain Gauge (ISCO, Lincoln, NE, USA) calibrated to tip at 0.025 cm of rainfall, and was placed in an open area between the two watersheds.

A rectangular weir was placed shortly downstream of the sediment trap at the Carpenter watershed. Flow measurements were taken 0.3 m upstream of the weir at 5-minute intervals. The automated sampler was triggered to extract samples once water depth exceeded 0.9 cm above the weir, and continuing to take samples for every 37.8 to 56.8 m^3 of runoff passing through the weir. Samples were combined into one sample per storm for laboratory analysis. Runoff volume and TSS fluctuations for Carpenter watershed over time are plotted in Figure 2-3 to illustrate the impact of construction on sediment concentrations in runoff. Precipitation depth was measured at 15-minute intervals with the tipping bucket rain gauge described earlier. Precipitation data for missed storm events due to equipment malfunction were obtained from the RDU airport weather station (SCONC, 2004).

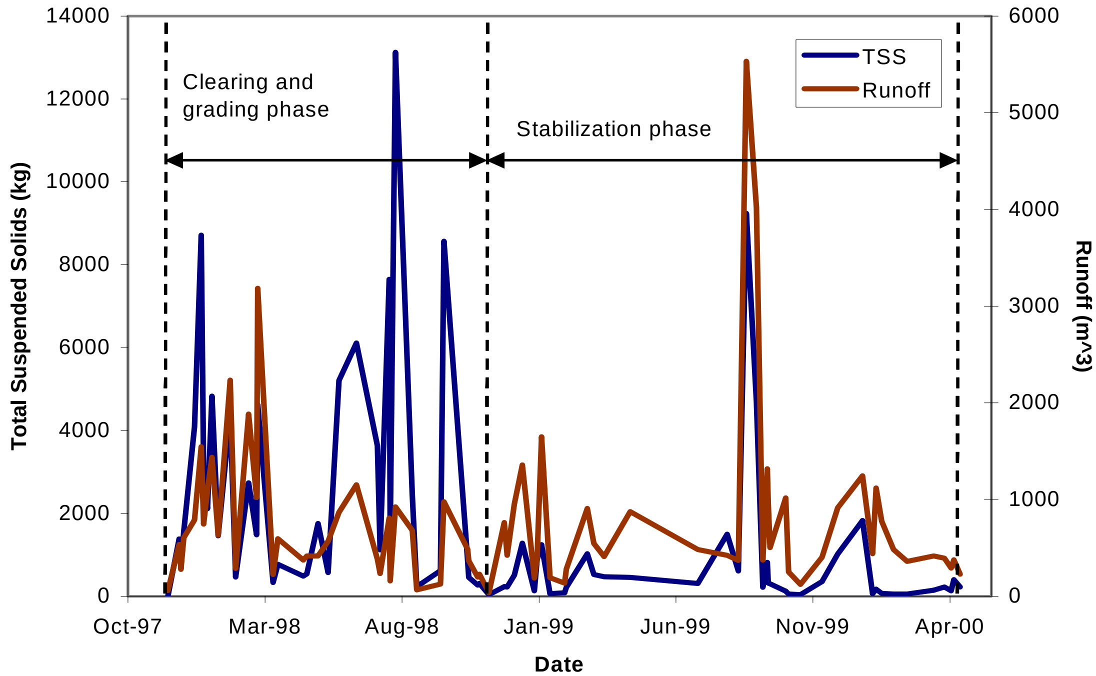


Figure 2-3. Sediment load (as suspended solids) and runoff volume exiting the sediment trap at the Carpenter watershed in Carpenter, North Carolina from December 10, 1997 to April 25, 2000.

Sediment yield estimation

Runoff samples from the Centennial watersheds were analyzed for turbidity using an Analite 152 Nephlometer Probe (McVan Instruments, Australia). The concentration of total suspended solids (TSS) from both the Carpenter watershed and the Centennial watersheds were determined by vacuum filtration as described by Clesceri et al. (1998). Fifty ml subsamples were filtered through 47 mm glass fiber ProWeigh filters distributed by Environmental Express (Mt. Pleasant, South Carolina). TSS concentrations for runoff samples retrieved at the Centennial watersheds from 5/8/02 to 11/17/02 were extrapolated to minimize lab analysis. A logarithmic regression was developed with the SAS procedure PROC NLIN using TSS and turbidity data retrieved from 1/23/02 to 4/1/02 (Figure 2-4)

(SAS, 1999). Sediment yield (kg) per storm at Centennial watersheds was calculated by summing the product of the one minute interval flow rate (m^3 sec^{-1}) and TSS (mg L^{-1}) multiplied by a conversion factor of 0.06 for each storm event.

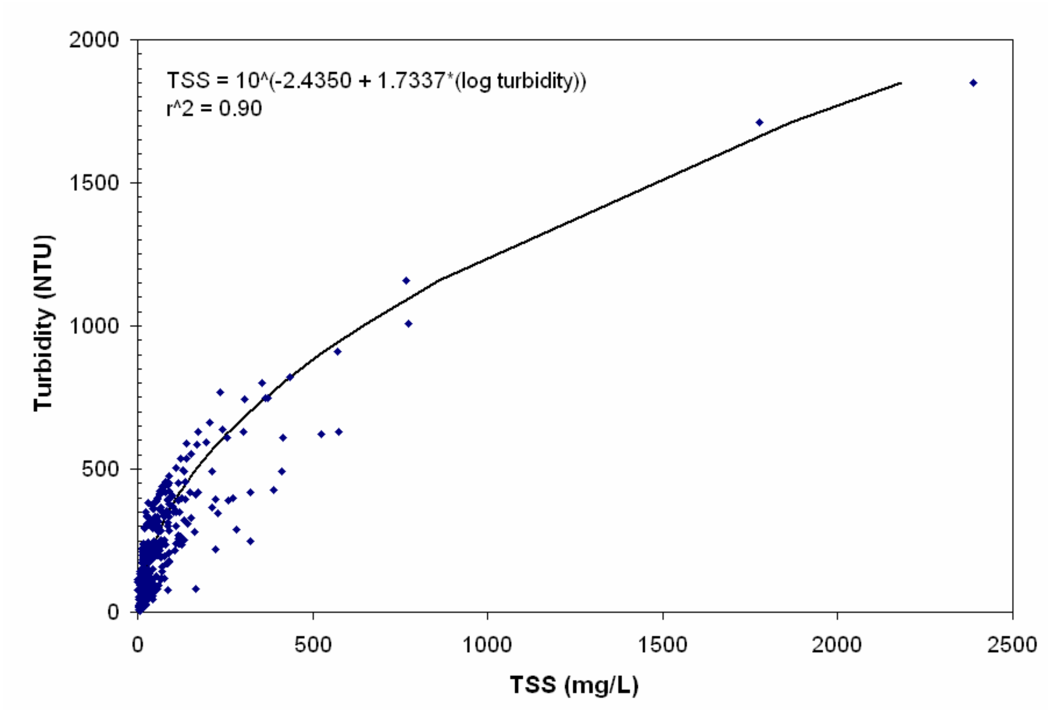


Figure 2-4. Relationship between TSS and turbidity in runoff samples collected from watershed outlets from the Centennial site.

The following methods for measuring sediment trap deposition were performed by Line and White (2001). The volume of sediment deposited in the sediment trap at the Carpenter watershed was determined by establishing cross-sections across the sediment trap every 1-3 m along the length with a standard surveying level. Distances between points along the cross section varied from 0.1 to 0.5 m depending on differences in the elevations of the surface. A grid of surveyed points was established for the sediment trap. The survey data was entered into the Surfer statistical package to create a surface using a kriging method. Each successive surface from later surveys was compared to the original surface to estimate the change in volume resulting from deposition of sediment during the period. To determine the mass of sediment collected in the sediment trap, bulk density was measured gravimetrically from three sediment cores extracted from different areas within the sediment trap. Bulk density for deposited sediment averaged 1.11 g cm^{-3}.

Sediment trapping efficiency was computed by dividing the mass of sediment deposited in the sediment trap by the sum of the mass deposited in the sediment trap and passing out of the sediment trap, and then multiplying by 100 to convert to a percentage. Total sediment yield per storm event was calculated as follows:

$$Total\ \ sed.\ yield\ per\ storm = TSSS + \left[TSSS - TSSS * \left(\frac{\%\ trap\ efficiency}{100}\right)\right]$$

where sediment yield and TSSS (total suspended solids per storm) expressed as kg of sediment per storm, and % trap efficiency expresses the percent of sediment remaining in the sediment trap between depth measurements. Trap efficiency was assumed either as constant between depth measurements, or as the average trap efficiency (59 %) for periods when measurements were not taken. To validate this assumption, sediment yield was calculated for the three bimonthly sediment depth measuring events between 6/26/98 and 10/14/98.

Observed rainfall, runoff, and sediment measurements are listed in Table A2-1 for Centennial A & C, and Table A2-2 for Carpenter.

MODEL DESCRIPTION

WEPP is a lumped parameter, one-dimensional, process-based erosion model that simulates the detachment, transport, and deposition of sediment on rectangular hillslopes during runoff events, and predicts sediment yield and runoff volume during storm events (Flanagan, 1995). Sediment yield and runoff volume were predicted using the GeoWEPP model with the input parameters adjusted in WEPP. Climate, landcover, and soil inputs were modified using WEPP Model version 2002.70. Model runs were simulated using GeoWEPP ArcX 2004.3, which is an ESRI-ArcView extension that directly links Geographic Information Systems (GIS) to WEPP. GeoWEPP allows the user to model raster cells as individual hillslopes, thus accounting for spatial variability among slope, soils, and landcover (Renschler, 2003).

MODEL INPUTS

Data layers for GeoWEPP Arc X 2004.3 were both constructed and modified using ArcView GIS 3.2a and GRASS 5.0. The digital elevation models (DEMs) were created using a spline algorithm in GRASS (Neteler and Mitasova, 2000) to interpolate 2 ft (0.6 m) interval contour maps to 7 m resolution grids for Centennial A and Centennial C, and to a 5 m resolution grid for the construction phase at the Carpenter watershed. The 5 m DEM for the stabilized phase was interpolated from LIDAR data with 1 point per 3 m density, using the same spline algorithm. Soils maps, at a scale of 1:24,000, were downloaded from the USDA-NRCS Soil Survey Geographic Database (SSURGO) (USDA-NRCS, 2000). The landcover map for Centennial A & C watersheds was derived from aerial photos of the site (Figure 2-1). Landcover grids for Carpenter watershed were assumed as bare soil during construction, and as vegetative cover for Carpenter during stabilization. Soil, landcover, and DEM grids were exported to the ASCII format required by GeoWEPP

CALIBRATION

Soils and landcover parameters were calibrated using sediment yield and runoff volume measurements for storm events from Carpenter and Centennial watersheds. For the calibration step, we used WEPP default parameters whenever possible to gain a better understanding of the current WEPP parameters for construction site conditions, with the intention of fitting the data to model output based on adjustments supported by previous research on WEPP parameters, suggestions from the WEPP manual (Alberts et al., 1995), and personal observations. Predicted values were regressed against field data for model efficiency (E), which is defined by Nash and Sutcliffe (1970) as the variance of prediction from a 1:1 line. E is calculated as follows:

$$E = 1 - \sum (Y_{obs} - Y_{pred})^2 \Big/ \sum (Y_{obs} - Y_{mean})^2$$

where

Y_{obs} = measured sediment yield (tonne) or runoff volume (m^3) for each storm event

Y_{pred} = model predicted sediment or runoff for each storm event

Y_{mean} = mean measured yield or runoff over all storm events

E ranges from -∞ to one, with a value of one representing a perfect fit between predicted and measured data. A model efficiency of zero indicates that the mean measured value is as good an overall predictor as the model, and a negative efficiency indicates that the measured mean is a better predictor than the model (Zhang et al., 1995). Quinton (1997) suggested that E values greater than 0.5 indicate satisfactory model performance. We used this suggestion as a guideline in our study to help us determine the optimal parameters for predicting erosion for each of the three phases.

Calibration of soil inputs

Adjustments made to soil parameters are listed in Table 2-2. The clay loam Cutslope (CLCS) soil parameter was selected from the WEPP soil database for calibration of construction and post-construction conditions, as all three soil series on the Carpenter watershed (Worsham, WhiteStore, and Creedmoor) have clay loam subsoils according to USDA-NRCS and the WEPP soil database. The Worsham, WhiteStore, and Creedmoor soil series parameters were also selected for calibration, which were mapped on the site by NRCS (Figure A2-3, Figure A2-5). Because the WhiteStore soil series was not included in the WEPP soil archive database, a new profile was created using NRCS soil series descriptions for soil texture related information and suggestions from the WEPP manual for soil erosion factors including critical shear stress and erodibility (Alberts et al., 1995). The soil series were also altered to account for the removal of topsoil during clearing by removing the soil surface A horizon in the soil files, and replacing it with the B horizon. Effective hydraulic conductivity (Kef), critical shear stress (tau), interrill erodibility (Ki), and rill erodibility (Kr), were adjusted manually based on the equation and suggestions from the WEPP manual (Alberts et al., 1995). Effective hydraulic conductivity is a parameter created for the Green-Ampt infiltration model, and is generally less than saturated conductivity because it accounts for entrapped air (Bouwer, 1966).

For the stable forested phase, the WEPP default soil series for the Centennial A & C watersheds were used (Table 2-2). The soil input parameter for the post-construction phase was selected based on results from calibration of the construction phase, with the assumption that soil properties had not significantly changed between grading and stabilization. To simulate a recently stabilized surface, readily available critical shear stress information from erosion mat manufacturers was used to replace critical shear stress values for each soil series. The area was stabilized with a combination of grass seed and either erosion mats or hay straw covered with tar. We applied critical shear stress values for erosion mat products that were not used on the site, but had been used in previous WEPP model testing (Laflen et al., 2001). MacMat-vegetated erosion mats produced by Maccaferri Bavions, Inc. (tau = 384 Pa) and short term mats S75, Ds75 produced by North American Green (tau = 74 Pa) were modeled on the temporary stabilized- site.

Table 2-2. Surface soil properties for WEPP input soil parameters for different phases of construction at Centennial and Carpenter watersheds.

Soil description	Soil Texture[a]	Hydologic soil class	Interrill erodibility, Ki kg sec m^{-4}	Kr, Rill erodibility sec m^{-1}	tau, crit. shear stress Pa	Hydr. cond., Kef mm h^{-1}	Sand %	Clay %	CEC meq/ 100 g	Rock %
Appling	SL	B	4.97 x 10^{6}	1.02 x 10^{-2}	2.5	4.4	65	15	3.0	3
Cecil	L	B	5.43 x 10^{6}	8.50 x 10^{-3}	3.3	4.8	50	12	7.3	3
CLCS	CL	Not applicable	1.50 x 10^{6}	1.00 x 10^{-3}	1.0	2.0	30	30	26.0	20
Colfax	L	C	5.31 x 10^{6}	7.00 x 10^{-3}	3.1	7.1	41	19	7.3	3
Creedmoor	SL	C	4.88 x 10^{6}	9.21 x 10^{-3}	2.8	12.6	68	12	4.5	3
Creedmoor subsoil	CL	C	4.31 x 10^{6}	4.80 x 10^{-3}	4.7	1.9	43	27	5.5	2
Pavement	SL	Not applicable	1.00 x 10^{3}	1.00 x 10^{-4}	100.0	0.1	10	70	25	90.0
WhiteStore	FSL	D	4.88 x 10^{6}	9.20 x 10^{-3}	2.8	0.3	60	10	10.0	3
WhiteStore subsoil	CL	D	4.31 x 10^{6}	4.80 x 10^{-3}	4.7	0.3	30	40	30.0	2
Worsham	FSL	D	6.02 x 10^{6}	9.56 x 10^{-3}	2.7	9.8	55	16	5.8	5
Worsham subsoil	C	D	2.15 x 10^{6}	8.90 x 10^{-3}	2.9	0.3	41	42	8.5	6

[a] SL - Sandy loam, L - Loam, CL - Clay loam, FSL - Fine sandy loam, C - Clay

Calibration of landcover inputs

Complete WEPP landcover input parameters are listed in Table A2-3. Select WEPP landcover parameters in Table 2-3 were chosen based on degree of sensitivity, using parameters as suggested by Nearing et al., 1990, as being highly sensitive parameters. Four WEPP forest landcover parameters (Road/forest, Disturbed/forest, Disturbed/2 yr forest, and Disturbed/ 20 yr forest) were applied to young and mature forested areas to determine the optimal forest parameter(s) for the Centennial site (Table 2-3). The WEPP Cutslope landcover parameter was applied to impermeable surfaces combined with the pavement soil parameter to simulate the absence of vegetation and extremely low permeability and erodibility. The WEPP continuous grass landcover parameter was applied to lawn grass, assuming this parameter would demonstrate similar characteristics as cut grass. WEPP Rangeland/Tall prairie grass landcover was applied to overgrown fields in Centennial watershed C. The WEPP Cutslope landcover input parameter was applied to represent the exposed soil surface during the construction phase, as the term "Cutslope" generally refers to graded areas on construction sites. An experimental "Baresoil" landcover parameter was also tested, and was originally created for construction site soils based on the WEPP fallow landcover parameter before the Cutslope parameter was released on WEPP version 2002.7. For the post-construction phase, the WEPP continuous grass parameter was applied, assuming full vegetative grass cover. The Cutslope landcover was used in conjunction with erosion mat soil parameters, assuming constant conditions of erosion mat coverage without vegetation.

Table 2-3. Selected WEPP landcover parameters used to model before, during, and after construction type conditions at the Carpenter and Centennial A & C watersheds.

Plant Growth and Harvest Parameters	Cut slope	Bare soil	Continuous grass	Tall Prairie Grass	Road/ Forest	Disturbed/ Forest	2 yr Forest	20 yr Forest
Maximum Darcy Weisbach friction factor for living plant	1	0	12	11	1	17	15	17
Days since last tillage	0	200	200	1000	0	1000	1000	1000
Days since last harvest	0	2000	92	900	0	100	100	100
Initial interrill cover (%)	0	0	50	80	0	100	20	100
Initial residue cropping system	Fallow	Fallow	Perennial	Perennial	Fallow	Perennial	Perennial	Perennial
Initial ridge height after last tillage (cm)	0.6	0	2	10	0.6	10	10	10
Initial rill cover (%)	0	0	50	80	0	100	20	100
Initial roughness after last tillage (cm)	0.6	0.1	2	10	0.6	10	10	10
Initial total dead root mass (kg m^{-2})	0	0	0.2	0.1	0	0.5	0.5	0.5

RESULTS AND DISCUSSION

CALIBRATION

WEPP model efficiency (E) for predicting sediment yield and runoff was determined for each of the three phases of construction. Model runs with E values greater than 0.5 were considered to have satisfactory model performance. Model runs with E values greater than zero but less than 0.5 were considered to have adequate model performance, and E values less than zero were considered to have poor performance. Optimal parameters for each phase of construction was determined by establishing first if runoff volume E was satisfactory, and secondly if sediment yield E was satisfactory. It was our assumption that if runoff volume efficiency was poor, than sediment yield would also be poor, regardless of value E was.

For the Carpenter watershed modeling, the bimonthly sediment yield E was used when comparing sediment yield E values between model runs, because it represented a measurement of sediment yield that was measured and not extrapolated, as was done for the by storm sediment yield E. The by storm sediment yield E was compared to the bimonthly sediment yield E to validate our extrapolation of the by storm sediment data.

Pre-construction phase – Centennial A & C watersheds

The WEPP Road/forest landcover parameter was not suitable for representing forest environments, as it apparently was intended for forest roads as opposed to forested areas. For this reason, sediment yield as grossly over-predicted (Table 2-4). Both the WEPP Disturbed/forest and the combined 2-year and 20-year forest landcover parameters applied to forested areas in the watersheds resulted in adequate runoff efficiencies for Centennial watersheds A. The combination of the 2-year and 20-year forest landcover parameters were only slightly more efficient than the Disturbed/forest parameter alone (runs 29.5 and 31.5, Table 2-4), despite the 80 % increase in rill and interrill covers in the 2 yr forest landcover in comparison to the 20 yr forest landcover. Therefore it seems that separating the forested areas based on maturity was probably not necessary, as the model showed little difference in efficiency.

Runoff volume was underpredicted for all landcovers (Table 2-4), excluding the WEPP Road/forest landcover for reasons previously discussed. This may have been a result of incorrect estimation of hydraulic conductivity, because the soil properties were based on

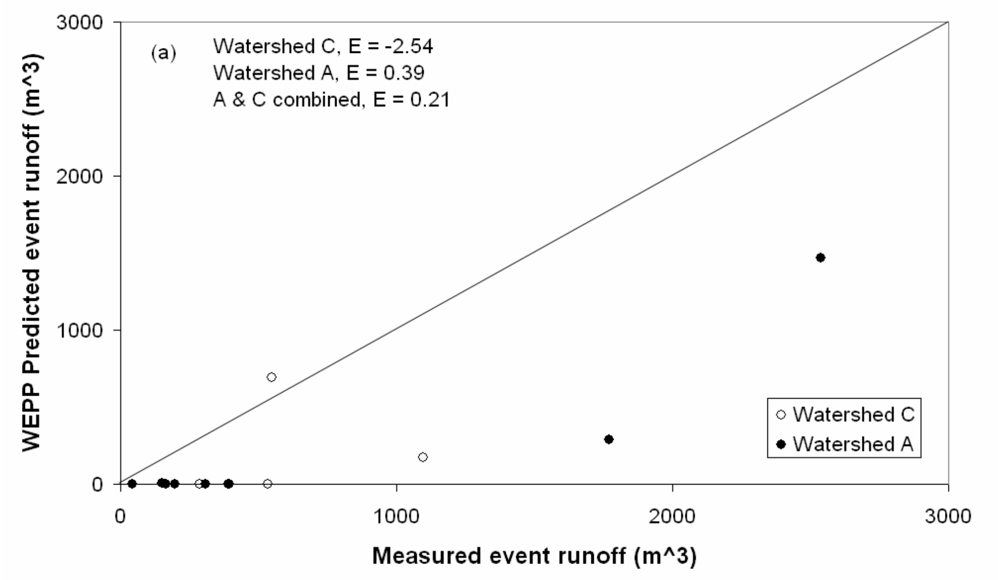
NRCS soil surveys soil map drawn at a scale of 1:24,000. For example, if the soil surface had been more clayey in texture, hydraulic conductivity would have been lower, infiltration would have been lower, and runoff volume would be greater. Another possible factor for the underprediction of runoff volume was that WEPP roughness factors for forests may need to be reduced to increase runoff velocity and lower infiltration rates.

Table 2-4. Model efficiency (E) between WEPP predicted output and measured values for the stable phase over 8 storm events on Centennial A, and 5 storm events on Centennial C.

I.D.	Watershed(s)	Landcover				E, Sediment yield	E, Runoff volume	Sed. yield diff. (tonne)[a]	Runoff diff. (m^3)[a]
		Tall grass	Pavement	Young forest	Mature forest				
26	C	Tall Prairie Grass	Cut Slope	Road /Forest	Road /Forest	-3303662.3	-1.57	-238.4	-5.3
27	C	Tall Prairie Grass	Cut Slope	Disturbed /Forest	Disturbed /Forest	-12.55	-2.54	-0.45	1985.7
29	A	Tall Prairie Grass	Cut Slope	Disturbed /Forest	Disturbed /Forest	-5911.5	0.39	-3.33	3794.4
29.5	A&C	Tall Prairie Grass	Cut Slope	Disturbed /Forest	Disturbed /Forest	-1033.3	0.21	-3.78	5780.1
30	C	Tall Prairie Grass	Cut Slope	2 yr Forest	20 yr Forest	-12.55	-2.54	-0.45	1985.7
31	A	Tall Prairie Grass	Cut Slope	2 yr Forest	20 yr Forest	-6929.3	0.41	-3.61	3739.5
31.5	A&C	Tall Prairie Grass	Cut Slope	2 yr Forest	20 yr Forest	-1209.5	0.23	-4.06	5725.3

[a]Sediment yield and runoff differences were between the total predicted and the total measured values for all storm events. Negative values represent an overprediction of runoff or sediment; positive values represent an underprediction.

Under stable pre-construction conditions, WEPP adequately predicts runoff (E = 0.21), but not sediment yield (E = -1033.3), based on results from Centennial watersheds A & C (Figure 2-5). It should be noted that model efficiency for sediment yield on watersheds A and C combined improved from -1033.3 to -11.16 when the largest storm event (109.7 mm) in Centennial watershed A was removed, reemphasizing the necessity of using a large number of storm events for determining ideal landcover parameters for stable forested areas. We only had complete runoff and turbidity/TSS data for 8 storms on Centennial watershed A and 5 storms on Centennial watershed C (Table 2-1).



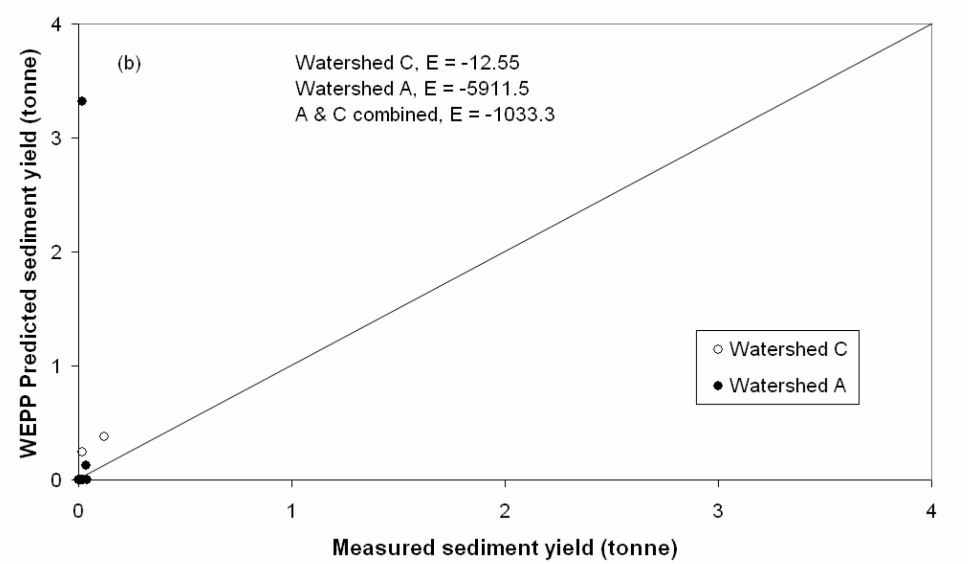


Figure 2-5. Observed and WEPP predicted (a) runoff volumes and (b) sediment yields for Centennial watersheds A (area = 9.3 ha) & C (area = 11.8 ha), applying the Disturbed/forest landcover parameter for the pre-construction phase.

For both watersheds, soil loss was less than 1 tonne ha^{-1} on shallow slopes in forested and lawn grass areas, and between 1 and 4 tonne ha^{-1} on steeper slopes and some areas of tall grass (Figure 2-6, Figure 2-7). These patterns most likely occurred due to higher runoff velocities on steeper slopes and lower values for friction factor and interrill cover for tall grass. The watersheds delineated by GeoWEPP and the stream networks created by the TOPAZ hydrology model in GeoWEPP closely reflected observed watershed boundaries and stream locations.

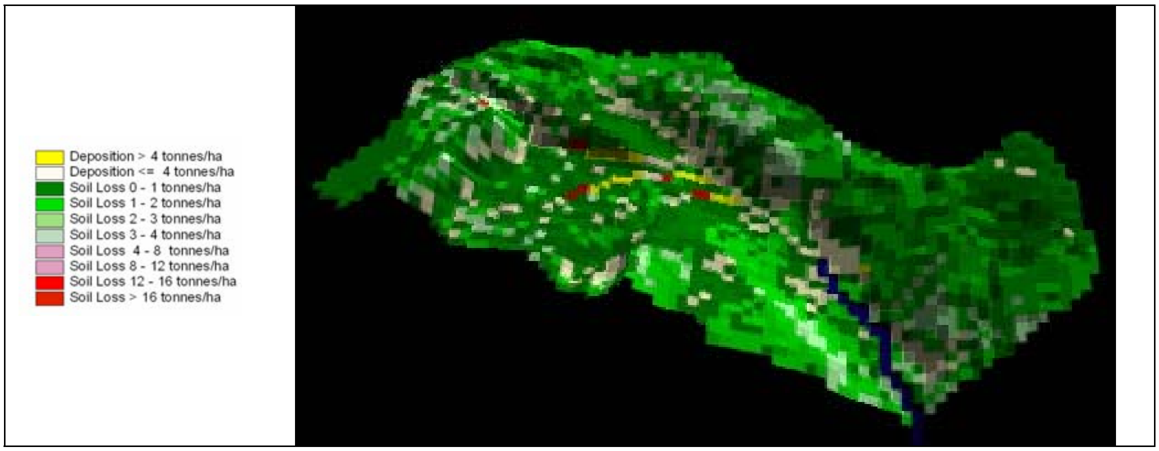


Figure 2-6. GeoWEPP generated annual soil loss map for Centennial watershed A for the pre-construction phase. (DEM elevations exaggerated 5X to clearly illustrate topographical characteristics).

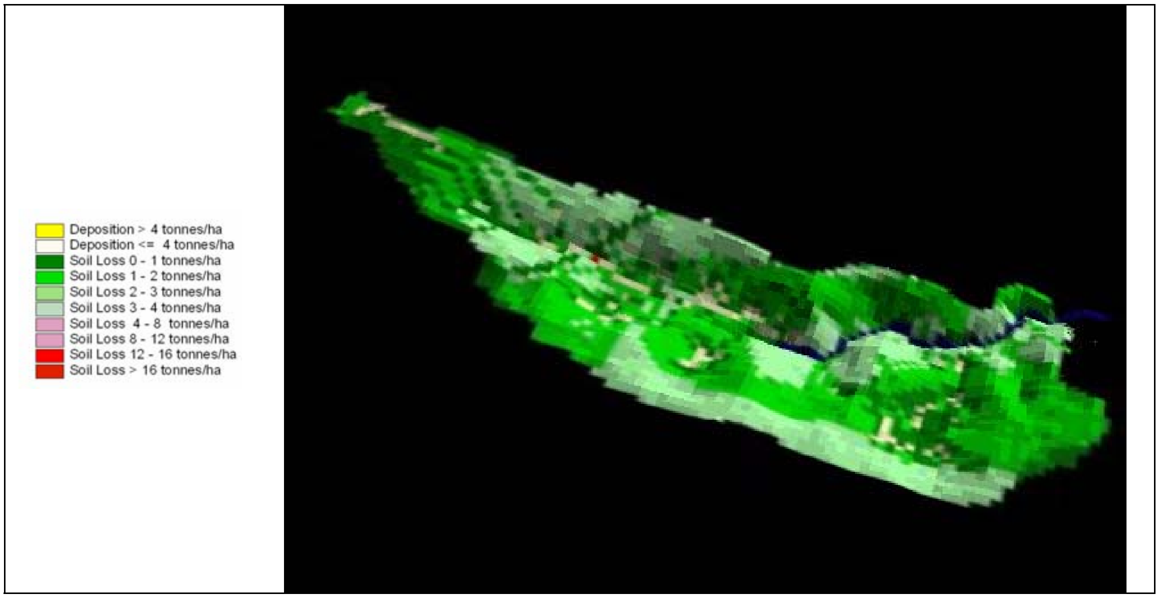


Figure 2-7. GeoWEPP generated annual soil loss map for Centennial watershed C for the pre-construction phase. (DEM elevations exaggerated 5X to clearly illustrate topographical characteristics).

During construction – Carpenter watershed

Regarding landcover inputs, the Baresoil landcover parameter was a more efficient representative of exposed subsoil soil conditions on construction sites than the WEPP Cutslope landcover parameter. The WEPP Cutslope landcover parameter provided high runoff efficiency when combined with the subsoil soil series soil parameters (E = 0.78), however the sediment efficiency was poor (E = -0.07) when analyzed on a bimonthly basis. The "Baresoil" landcover provided the same runoff efficiency as the Cutslope landcover parameter, and a satisfactory sediment yield efficiency (E = 0.66). The "Baresoil" landcover provided a smaller difference in soil loss between the total predicted and the total measured sediment load than the Cutslope landcover, with Cutslope landcover overpredicting by 31.4 tonne, and "Baresoil" overpredicting by 1.1 tonne (Table 2-5).

Table 2-5. Model efficiency (E) between WEPP predicted output and measured values for the construction phase.

I.D.	Land cover	Soil series			E, Runoff volume	E, Sed. yield	E, Sed. yield	Runoff difference (m^3)	Sediment yield difference (tonne)[a]	Sediment yield difference (tonne)[a]
	Exposed soil	Creedmoor	WhiteStore	Worsham	By storm	By storm	Bi-monthly	By storm	By storm	Bi-monthly
3b	Cut slope	CLCS[b]	CLCS	CLCS	0.01	-12.29	-0.04	16602.4	-305.4	-69.3
4b	"Bare Soil"	CLCS	CLCS	CLCS	0.26	-28.88	-1.62	16614.4	-304.0	-52.1
5b	Cut slope	Creedmoor	WhiteStore	Worsham	0.34	-3.91	0.44	15463.9	-111.5	-12.9
20b2	"Bare Soil"	Creedmoor	WhiteStore	Worsham	0.33	-3.54	0.53	15511.1	-62.0	11.4
6b	Cut slope	Creedmoor subsoil	WhiteStore subsoil	Worsham subsoil	0.78	-3.38	-0.07	1475.2	-152.5	-31.4
20	"Bare Soil"	Creedmoor subsoil	WhiteStore subsoil	Worsham subsoil	0.78	-2.90	0.66	1262.5	-81.9	-1.1

[a]Sediment yield and runoff differences were between the total predicted and the total measured values for all storm events. Negative values represent an overprediction of runoff or sediment; positive values represent an underprediction.
[b]Clay loam cutslope soil parameter.

The “Baresoil” landcover had an initial 200 days since the last tillage event, compared to zero days for the WEPP Cutslope parameter (Table 2-3). Because the WEPP model calculates sealing and crusting as a function of cumulative days since last soil disturbance (Alberts et al., 1995), the “Baresoil” landcover is more representative of compacted soils on sites as opposed to a freshly tilled soil, as exists for the Cutslope parameter. Although validation of applying the “Baresoil” landcover parameter on other sites would be necessary to confirm our findings, it seems logical that the sealed and crusted “Baresoil” landcover should be used on construction sites as opposed to the freshly tilled WEPP Cutslope parameter.

Regarding soil inputs for construction site conditions, WEPP clay loam Cutslope (CLCS) soil parameter proved to be inefficient by consistently under predicting runoff volume and over predicting soil loss (Table 2-5, Figure 2-8). The assumption that the effective hydraulic conductivity would remain constant for all three mapped soil series at 2.0 mm hr^{-1} was most likely inaccurate, since there were three different soils mapped for that site with hydraulic conductivities ranging from 0.3 to 12.6 mm hr^{-1} (Table 2-2). It should also be noted that rock content was much higher (20 %) than is typical for the Appling, Cecil, and Colfax soils (Table 2-2). Applying individual WEPP soil series with the A horizon remaining improved model efficiencies for both sediment and runoff compared to CLCS (run 5b, Table 2-5), but still predicted runoff volume to be less than actually measured (Figure 2-9). This was likely a result of increased hydraulic conductivity in the soil, which was estimated to be as high as 12.6 mm hr^{-1} using the recommended equations from the WEPP manual (Alberts et al., 1995). The increase in hydraulic conductivity was related to the greater macropore space associated with surface soil horizons, in comparison to clay loam cutslope soils from lower subsoil horizons (Table 2-3).

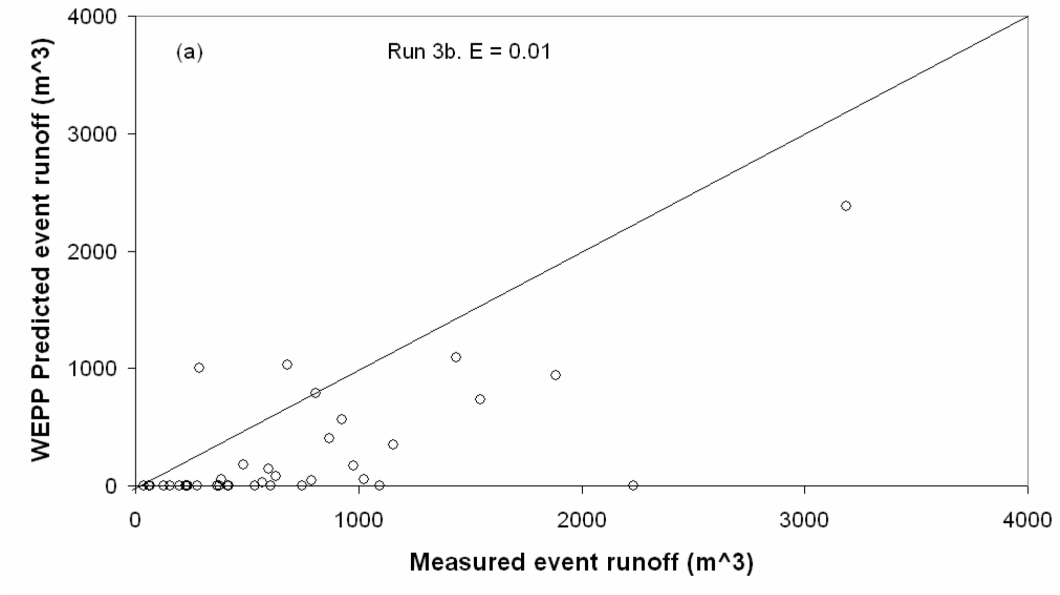


Figure 2-8. Observed and WEPP predicted runoff volumes for Carpenter during the construction phase, applying WEPP clay loam Cutslope soil parameter.

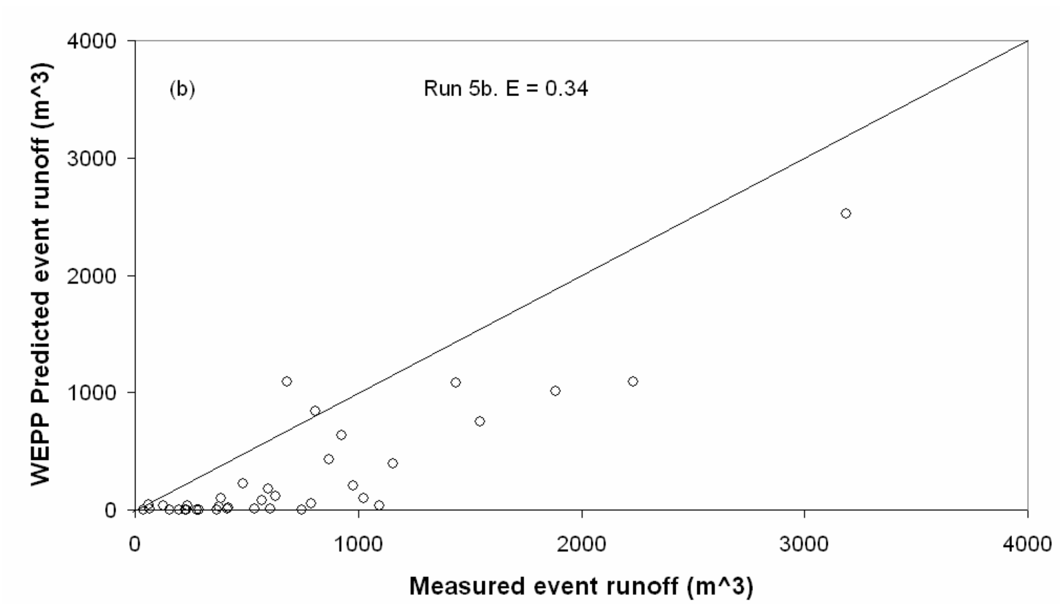


Figure 2-9. Observed and WEPP predicted runoff volumes for Carpenter during the construction phase, applying WEPP individual soil series soil parameter with the A horizon.

Applying individual WEPP soil series with the A horizon removed further improved model efficiency for runoff volume from 0.33 to 0.78 and for sediment yield from -0.07 to

0.66 when used with the “Baresoil” landcover parameter (Figure 2-10, Figure 2-11, Table 2-5). This improvement is related to a reduction in infiltration, ranging in effective hydraulic conductivity from 0.3 to 1.9 mm hr^{-1}. These results suggest that GeoWEPP could be an effective model for predicting runoff volumes and sediment yields from construction sites, although the correct input parameters are not always obvious.

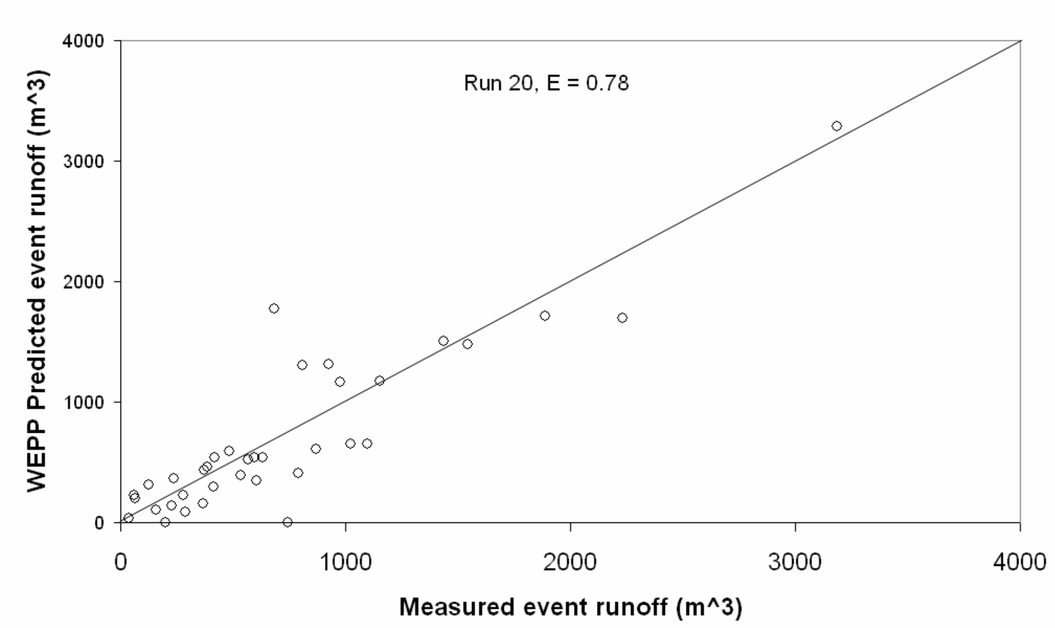


Figure 2-10. Observed and WEPP predicted runoff volumes for Carpenter watershed , applying WEPP individual soil series soil parameter without the A horizon along with the “Baresoil” landcover.

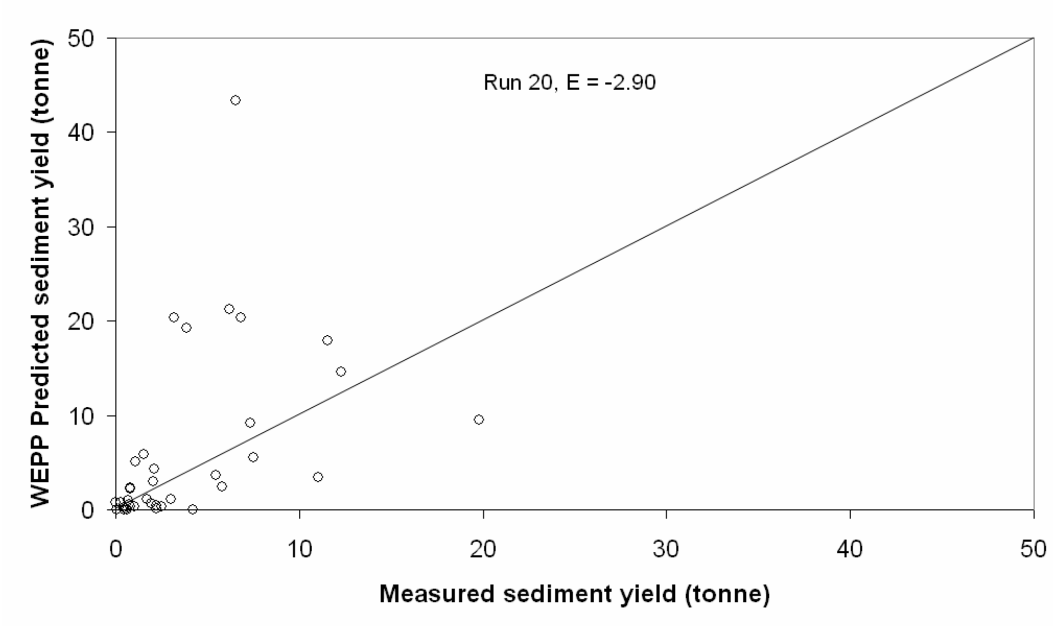


Figure 2-11. Observed and WEPP predicted sediment yields for Carpenter watershed , applying WEPP individual soil series soil parameter without the A horizon along with the "Baresoil" landcover.

All 5 by-storm efficiencies for sediment yield illustrated poor model performance, in contrast to the bimonthly sediment yield efficiencies, with 2 efficiency values showing satisfactory model performance (Table 2-5). This illustrates that is was not sufficient to assume constant trap efficiency between sediment depth measurements in the trap, and that the method used for measuring sediment by Line and White (2001) was an effective method for estimating sediment load in runoff.

GeoWEPP delineated the Carpenter watershed as expected in comparison to personal observations of the site. The critical source area (CSA) was decreased from 5 ha to 1 ha in order to extend the stream into the watershed, as had been visually observed at the site. The CSA parameter represents the threshold drainage area necessary for a channel to begin forming. The model produced patterns of less erosion on gradual slopes near the watershed boundary and more erosion on steeper slopes leading into the stream, as we would expect (Figure 2-12).

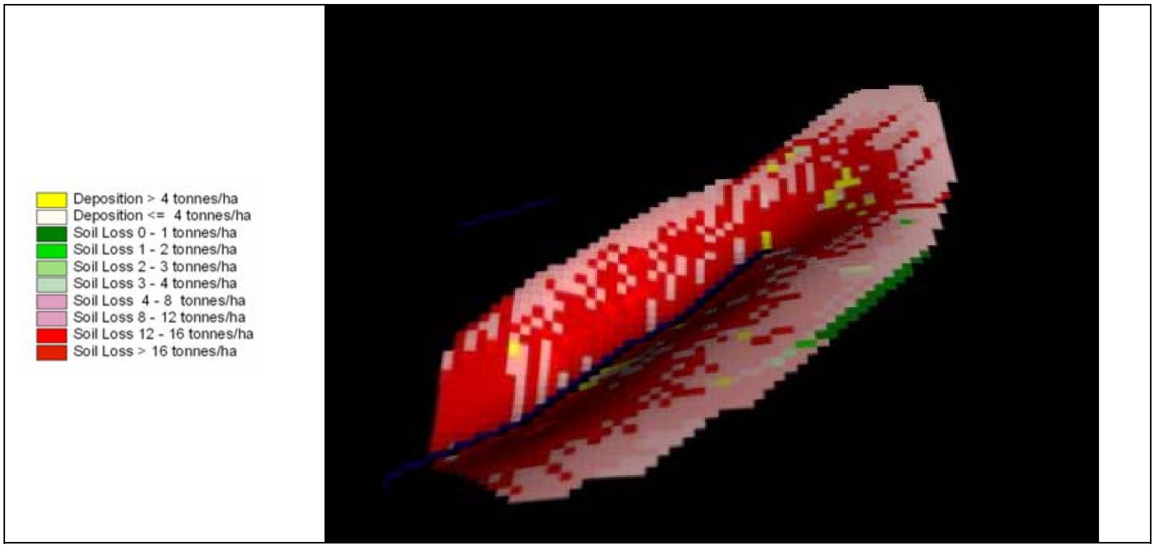


Figure 2-12. GeoWEPP generated annual soil loss map for Carpenter watershed, applying optimal parameters for the during construction phase. . (DEM elevations exaggerated 5X to clearly illustrate topographical characteristics).

Temporary Stabilization – Carpenter watershed

We initially selected WEPP grass cover to represent the seed along with the hay/tar and erosion mat covering on the soil, with assumption that the properties of the germinating grass combined with the coverings would be similar to lawn grass. The WEPP grass cover was an adequate landcover for the straw and mat coverings (runoff E = 0.27), but still below the efficiency target of 0.50 (Table 2-6). The underprediction of runoff was most likely an effect of the Darcy-Weisbach friction factor of 12, and to the 50 % rill and interrill covers , which greatly affect the flow velocity of the runoff (Gilley and Weltz, 1995).

Table 2-6. Model efficiency (E) between WEPP predicted output and measured values for the post-construction phase.

Test I.D. #	Landcover	Soil Series			E, Sed. yield	E, Runoff	E, Sed. yield	Runoff difference (m^3)	Sediment yield difference (tonne)	Sediment yield difference (tonne)
	Stabilized area	Creedmoor	WhiteStore	Worsham	By storm	By storm	Bi-monthly	By storm	By storm	Bi-monthly
21	Grass	Creedmoor subsoil	WhiteStore subsoil	Worsham subsoil	0.34	0.27	0.11	25171.8	38.0	36.9
22	Cut Slope	Creedmoor subsoil, (tau = 74 Pa)	WhiteStore subsoil, (tau = 74 Pa)	Worsham subsoil, (tau = 74 Pa)	0.12	0.63	0.31	14511.0	-27.4	-27.0
23	Cut Slope	Creedmoor subsoil, (tau = 384 Pa)	WhiteStore subsoil, (tau = 384 Pa)	Worsham subsoil, (tau = 384 Pa)	0.57	0.66	0.78	14243.7	16.9	27.6
24	Cut Slope	CLCS, (tau = 384 Pa)	CLCS, (tau = 384 Pa)	CLCS, (tau = 384 Pa)	0.90	0.37	0.94	23340.9	13.7	12.9

[a]Sediment yield and runoff differences were between the total predicted and the total measured values for all storm events. Negative values represent an overprediction of runoff or sediment; positive values represent an underprediction.

Because the grass cover underpredicted runoff volume, we decided to experiment with the method suggested by Laflen et al. (2001) to account for the properties of the erosion mats instead of the grass properties. We applied the Cutslope landcover parameter in conjunction with critical shear stress values recommended for erosion mat materials by their manufacturers, assuming that their erosion mats would have similar critical shear stress as the tar covered hay straw and erosion mats used at our site. Increasing the critical shear stress by several orders of magnitude basically eliminates the possibility of rill erosion, as erosion mats are designed to do (Laflen et al., 2001). It should be noted that vegetation properties are usually accounted for with parameters in the landcover component of WEPP, but because erosion mat manufacturers publish information on critical shear stress instead of on roughness coefficients and other landcover parameters used by WEPP, we had to make adjustments accounting for landcover in the soil component instead of in the landcover component.

The critical shear stress for the short term blankets S75, Ds75 produced by North American Green (tau = 74 Pa) was applied to each subsoil soil series in WEPP, and resulted in satisfactory runoff efficiency (E = 0.66) and adequate sediment yield efficiency (E = 0.31). Sediment yields for larger runoff events greatly exceeded measured yields (Figure 2-13), suggesting that a higher critical shear stress is needed to delay soil detachment. Applying the critical shear stress of MacMat-vegetated erosion mats produced by Maccaferri Bavions, Inc. to the same soil series improved model efficiency for sediment yield to exceed our efficiency target (E = 0.57), most likely because the higher tau value (384 Pa) delayed the release of sediment to something similar to what was occurring on the site (Figure 2-14).

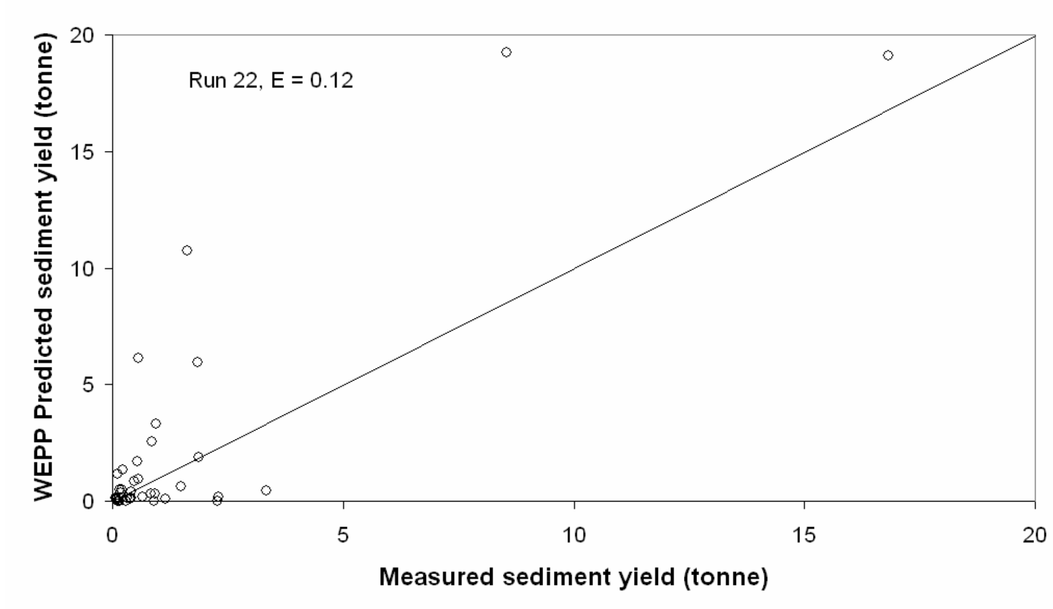
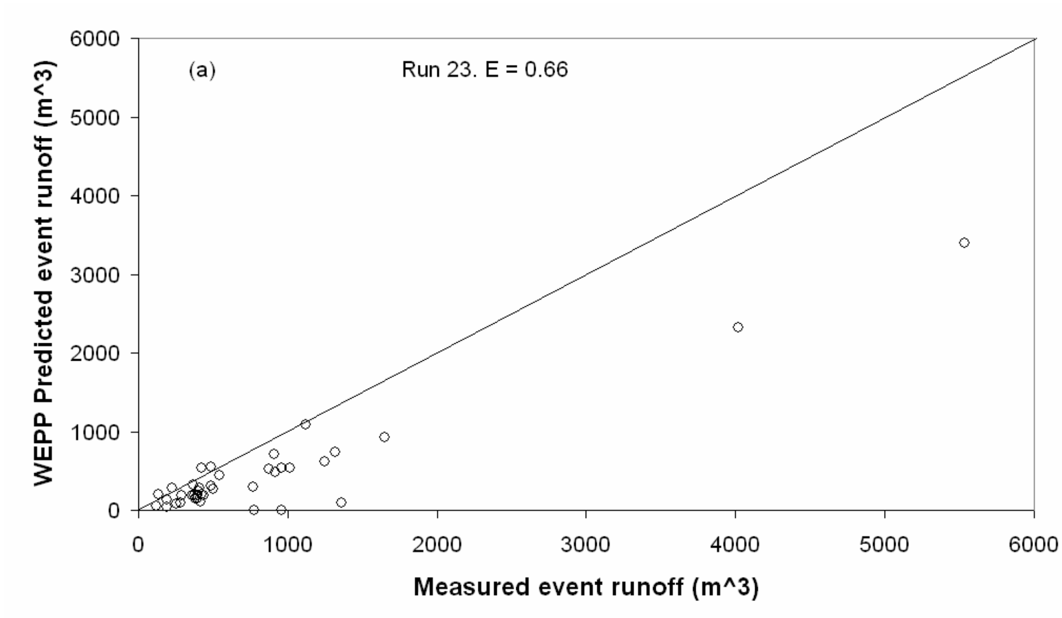


Figure 2-13. Observed and WEPP predicted sediment yield for Carpenter watershed for the post-construction phase, applying the short term blankets S75, Ds75 critical shear stress value (tau = 74 Pa) .



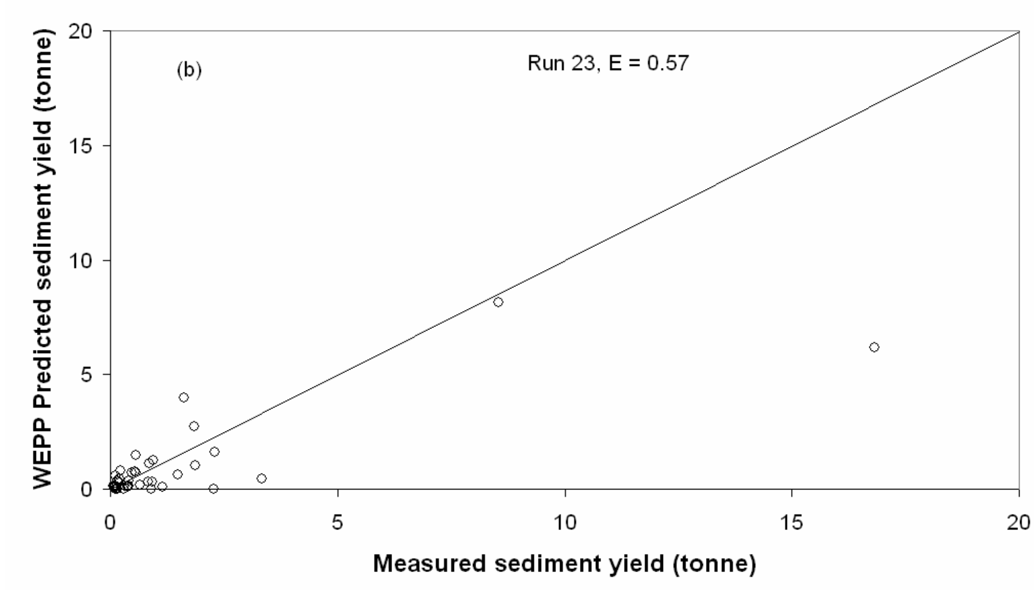


Figure 2-14. Observed and WEPP predicted runoff (a) and sediment yield (b) for Carpenter watershed for the post-construction phase, applying the MacMat-vegetated erosion blanket critical shear stress value (tau = 384 Pa) .

It was noted that bi-monthly and by storm efficiencies were within the same efficiency class (poor, adequate, or satifactory) for all 4 model simulations with stabilized conditions (Table 2-6), which was in contrast to simulations with construction site conditions (Table 2-5). It is not clear why there was a contrast between stabilized and construction conditions.

Watershed delineation by GeoWEPP did not match the watershed boundary from field observations, with the unexpected removal of a square-shaped piece of land in the lower right corner of the watershed (Figure 2-15), causing a decrease in size and an alteration of actual shape of the watershed. The watershed boundaries after clearing and grading were difficult to delineate because of the installation of storm drains, more shallow and complex changes in topography, and an increase in impermeable surfaces. GeoWEPP predicted an even distribution of soil loss between 4 and 12 tonnes ha^{-1} over most of the watershed, with the exception of erosion exceeding 16 tonnes ha^{-1} in and above the channel (Figure 2-15). It was observed at the site that a gully was forming in the lower half of the channel. Also, because we did not include the impermeable surfaces of the roads, driveways, and rooftops in the GIS landcover map, it would be more likely that there would be localized areas of low and moderate erosion throughout the development.

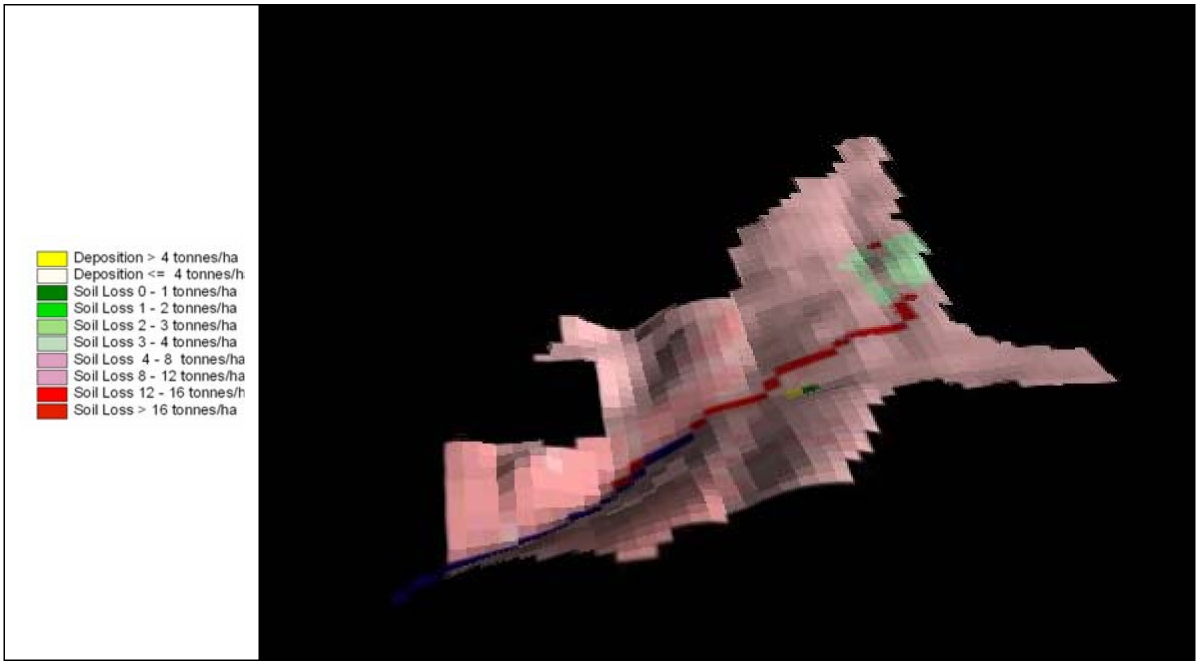


Figure 2-15. GeoWEPP generated annual soil loss map for Carpenter watershed, applying optimal parameters for the post construction phase. (DEM elevations exaggerated 5X to clearly illustrate topographical characteristics).

PARAMETER RECOMMENDATIONS

A summary of the recommended WEPP parameters based on our findings for the three construction phases are listed in Table 2-7. For soil series not installed in WEPP, we would recommend using soil series data from USDA-NRCS, 2002. In addition, Kef, Ki, Kr, and tau values should be calculated and/or estimated using the WEPP user manual (Alberts et al., 1995), as it was our experience that WEPP assumes these values to be zero if the "have model calculate" option in the soil input parameter is selected.

Table 2-7. Recommended WEPP soil and landcover parameters for pre-, during, and post-construction phases.

Construction phase	Suggested WEPP Soil Inputs	Suggested WEPP Landcover inputs
Pre construction (forested and developed arees)	1. WEPP Individual Soil Series 2. Create pavement parameter for impermeable surfaces, applying parameters suggested by Laflen et al. (2001) in Table 2-2	1. WEPP 2yr and 20yr forests for young and mature forests, respectively 2. WEPP Continuous grass for lawn grass 3. WEPP Tall grass for meadows 4. WEPP Cutslope for impermeable surfaces
During construction (graded areas)	1. WEPP Individual Soil Series, A horizon removed and parameters adjusted using WEPP user manual	1. “Baresoil” for all graded areas
Post construction (recently stabilized areas)	1. Same as during construction phase, except tau = 384 for each soil series.	1. WEPP Cutslope for all recently stabilized areas

CONCLUSION

The maximum model efficiency achieved by calibrating GeoWEPP for sediment yield and runoff volume varied among the three phases of construction. For the pre-construction phase, the WEPP model adequately predicted runoff volume (E = 0.21) but not sediment yield (E = -1033.3). Model efficiency for predicting sediment yield improved to -11.16 when the largest storm event was removed. During construction, we found that the removal of the A horizon in the soil series soil input parameter and altering specific land cover parameters resulted in satisfactory runoff (E = 0.78) and sediment yield (E = 0.66). GeoWEPP efficiently predicted runoff volume (E = 0.66) and sediment yield (E = 0.57) from a residential development site during post-construction with the application of an erosion blanket critical shear stress (tau = 384 Pa) in the soil component. Applying the Cutslope landcover with high critical stress values and the soil series minus A horizon soil parameter, was an effective method for predicting runoff volume and sediment yield for construction sites in the stabilization phase.

For future work, we would recommend improving WEPP forest parameters to prevent the underprediction of runoff volume, monitoring sediment yield and runoff volume from other construction sites to validate our findings, and verifying our post-construction results with known critical shear stress values of a variety of soils and erosion control products.

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APPENDIX

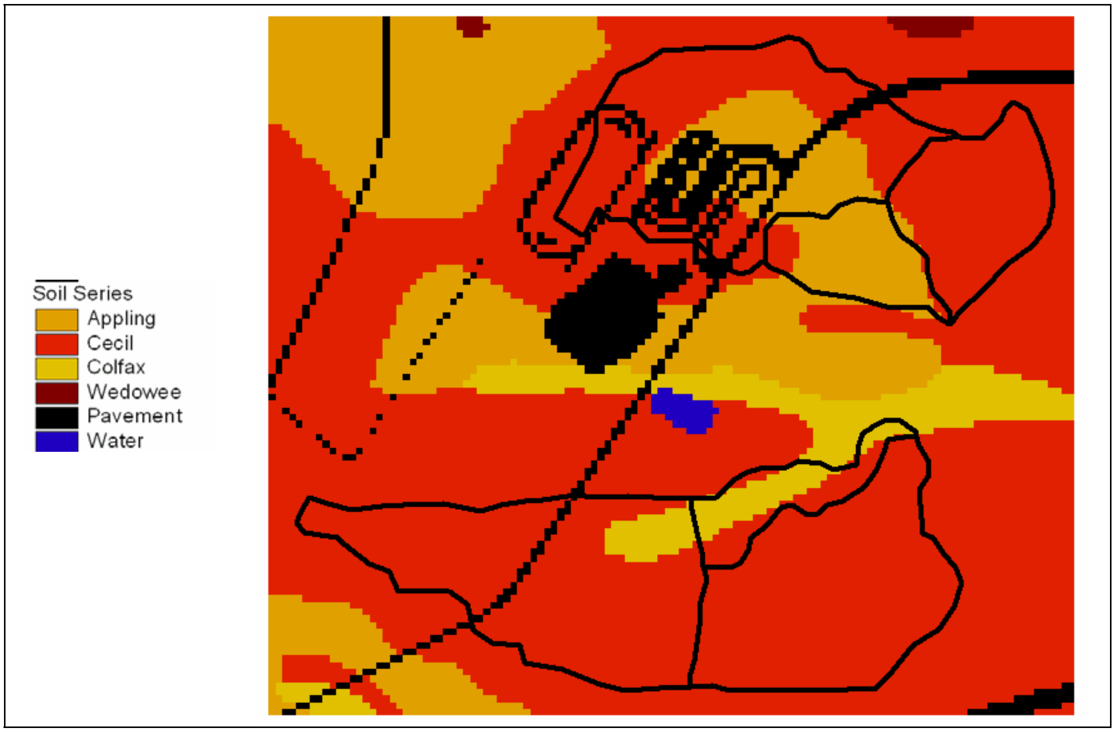


Figure A2-1. Soil grid map at 7 m resolution for watersheds Centennial A (above) and Centennial C (below). Watersheds are divided into three hillslopes by GeoWEPP.

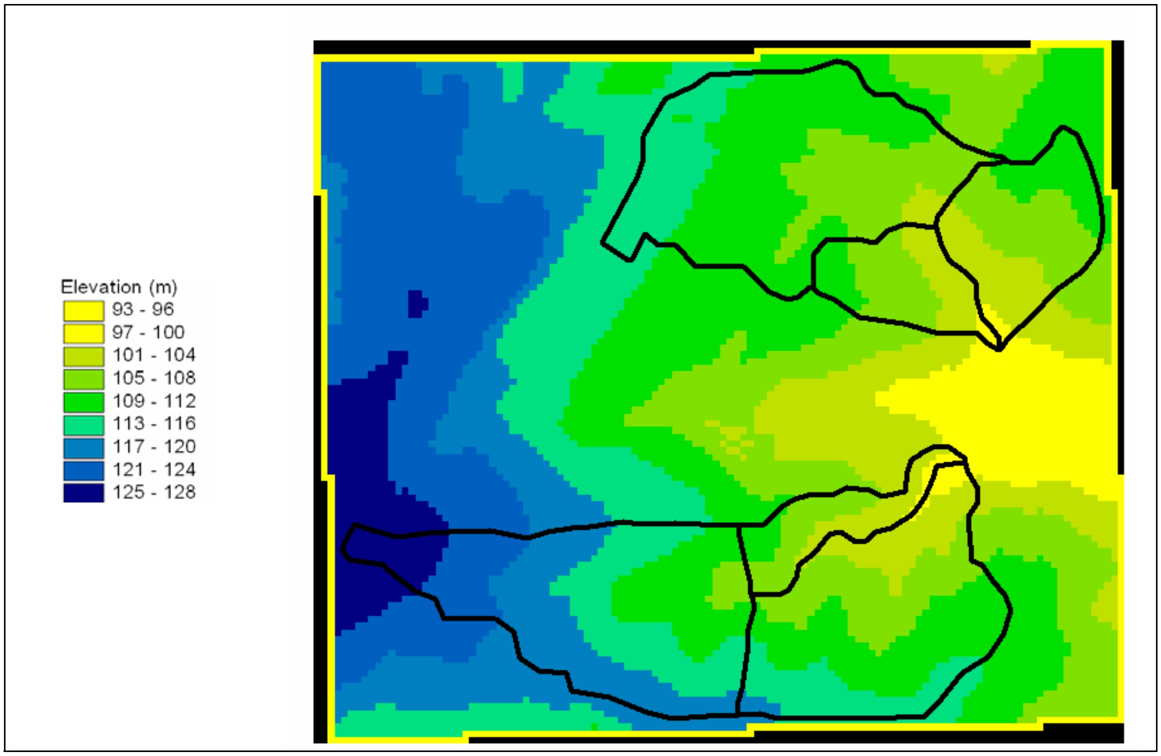


Figure A2-2. Digital elevation model at 7 m resolution for watersheds Centennial A (above) and Centennial C (below). Watersheds are divided into three hillslopes by GeoWEPP.

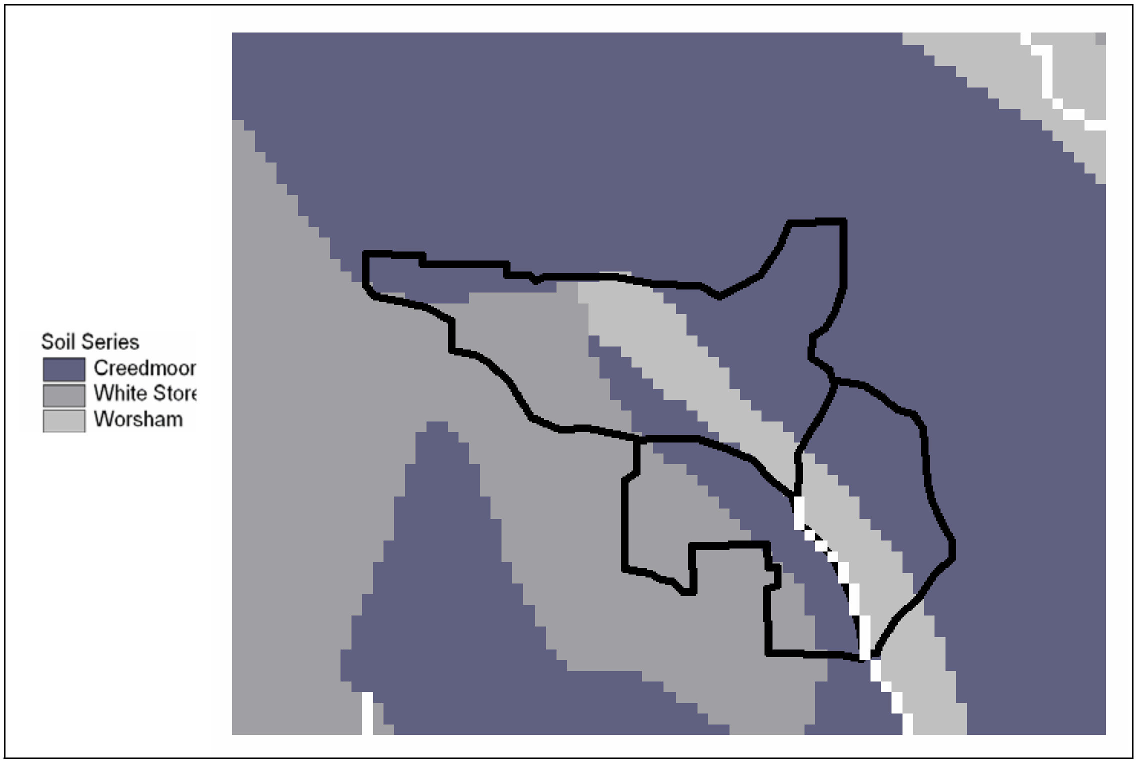


Figure A2-3. Soil grid map at 5 m resolution for the Carpenter watershed during construction. The watershed is divided into three hillslopes by GeoWEPP.

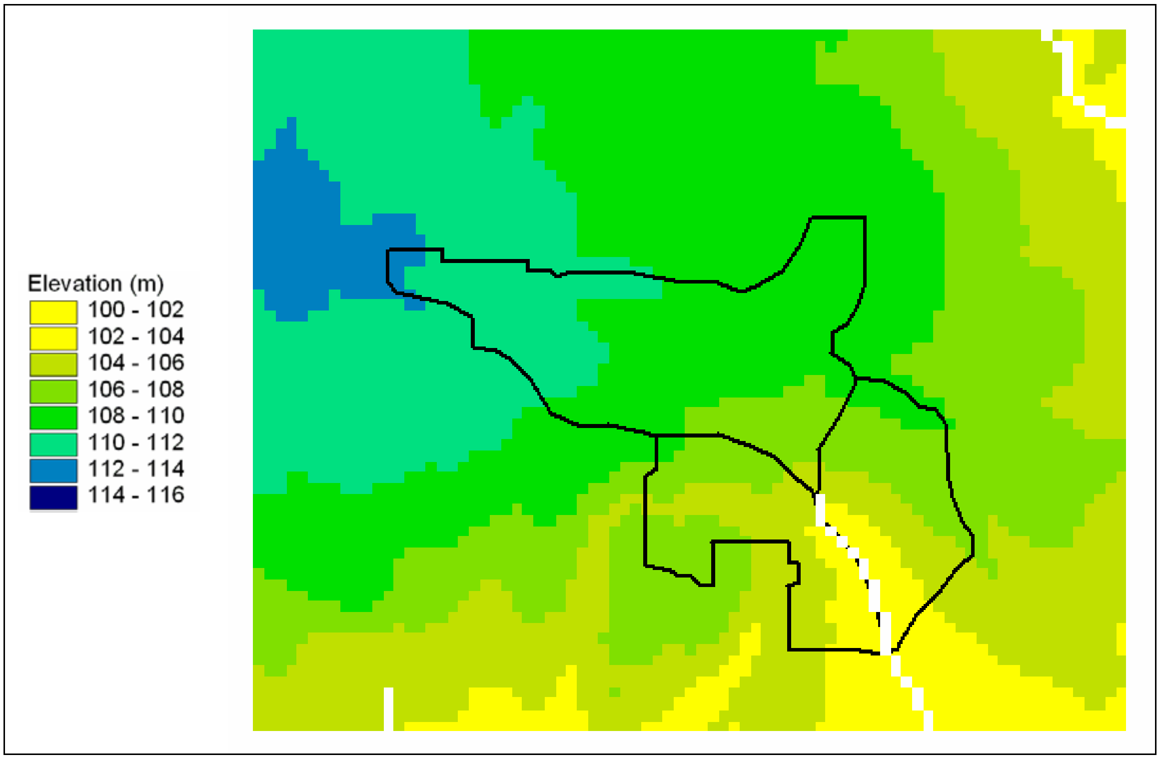


Figure A2-4. Soil grid map at 5 m resolution for the Carpenter watershed during construction. The watershed is divided into three hillslopes by GeoWEPP.

Table A2-1. Rainfall, runoff, and sediment measurements from selected storm events at Centennial watersheds A & C.

Date	Watershed	Rainfall amount (mm)	Peak rainfall intensity (mm/hr)	Runoff (m^3)	TSS (kg)
1/23/02	A	32.8	13.2	17.3	140
3/21/02	A	10.7	4.1	3.4	10
3/26/02	A	18.3	57.9	21.9	99
8/30/02	A	27.9	21.3	397.2	47
10/11/02	A	109.7	57.1	2536.8	318
10/29/02	A	4.3	7.1	164.7	40
11/6/02	A	23.9	35.6	6.1	33
11/17/02	A	24.1	5.1	307.0	34
1/23/02	C	32.8	2.5	547.0	224
3/31/02	C	47.5	61.9	1097.4	119
10/30/02	C	10.4	7.62	285.0	26
11/6/02	C	23.9	8.9	390.0	128
11/12/02	C	21.1	28.4	535.0	220

Table A2-2. Rainfall, runoff, and sediment measurements from selected storm events at Carpenter watershed.

Date	Construction phase	Rain (mm)	Runoff (m^3)	TSS (kg)	Estimated sediment trap efficiency (%)	TSS + trap sediment (kg)
12/10/97	During	13.2	60.6	8.4	59[a]	20.4
12/22/97	During	20.6	535.6	1385.1	59[a]	3353.8
12/24/97	During	13.0	277.5	717.6	59[a]	1737.6
12/27/97	During	22.6	604.4	1563.1	59[a]	3784.9
1/8/98	During	18.8	789.6	4089.9	59[a]	9902.8
1/15/98	During	53.6	1546.4	8710.3	59[a]	21090.3
1/18/98	During	24.9	745.9	2968.4	59[a]	7187.5
1/22/98	During	29.7	1097.3	2114.0	59[a]	5118.7
1/27/98	During	47.2	1439.1	4834.7	59[a]	11706.3
2/3/98	During	23.4	630.3	1462.1	59[a]	3540.1
2/16/98	During	58.7	2234.3	4390.0	59[a]	10629.4
2/22/98	During	11.7	286.7	461.5	59[a]	1117.5
3/8/98	During	60.5	1886.5	2739.8	59[a]	6633.9
3/17/98	During	26.9	1022.6	1485.2	59[a]	3596.2
3/18/98	During	98.8	3185.7	4626.7	59[a]	11202.7
4/4/98	During	11.1	225.9	328.0	59[a]	794.3
4/9/98	During	22.4	595.8	771.5	59[a]	1868.1
5/7/98	During	21.6	374.2	484.6	59[a]	1173.4
5/11/98	During	29.0	417.5	540.6	59[a]	1309.1
5/23/98	During	17.0	415.2	1755.9	59[a]	4251.7
6/3/98	During	20.1	567.8	570.6	59[a]	1381.6
6/15/98	During	26.7	870.6	5205.9	59[a]	12605.1
7/4/98	During	38.9	1155.1	6108.8	77	26559.8
7/27/98	During	20.3	385.3	3632.8	49	7123.2
7/30/98	During	15.7	236.1	1119.2	49	2194.5
8/9/98	During	39.9	809.3	7647.6	49	14995.2
8/10/98	During	11.2	157.1	1485.0	49	2911.8
8/16/98	During	41.2	927.0	13124.6	49	25734.5
9/3/98	During	61.7	682.2	2455.7	71	8467.9
9/8/98	During	12.2	65.1	234.4	71	808.2
10/4/98	During	15.2	124.6	617.8	71	2130.5
10/8/98	During	40.9	977.7	8564.1	71	29531.4
11/3/98	During	24.4	485.7	862.0	23	1119.4
11/4/98	During	10.9	367.6	453.9	23	589.5
11/14/98	During	9.4	198.1	268.4	23	348.6
11/16/98	During	12.9	229.2	310.5	23	403.2
11/26/98	During	5.6	36.0	37.9	23	49.3
12/13/98	Stabilization	21.6	765.5	235.2	23	305.4
12/16/98	Stabilization	17.3	423.8	226.1	23	293.7
12/24/98	Stabilization	33.0	957.2	510.8	23	663.4
1/2/99	Stabilization	45.0	1358.5	1281.0	23	1663.6
1/15/99	Stabilization	10.7	189.2	127.5	69	411.3
1/18/99	Stabilization	16.0	391.5	882.7	69	2847.4
1/23/99	Stabilization	52.3	1650.0	1240.7	69	4002.2
2/1/99	Stabilization	14.2	191.9	63.7	69	205.5
2/17/99	Stabilization	14.2	135.3	83.9	18	102.3
2/19/99	Stabilization	10.9	282.1	213.0	18	259.7
3/14/99	Stabilization	40.9	910.0	1022.7	18	1247.2
3/21/99	Stabilization	27.9	545.5	523.6	18	638.6
4/1/99	Stabilization	21.6	410.4	473.1	18	577.0
4/30/99	Stabilization	42.2	876.3	455.6	18	555.7
7/13/99	Stabilization	36.1	483.2	306.6	47	578.5
8/14/99	Stabilization	34.8	423.2	1498.1	47	2826.7
8/26/99	Stabilization	21.6	369.2	609.0	47	1149.1
9/4/99	Stabilization	168.2	5534.6	9237.0	18	11264.6
9/15/99	Stabilization	123.4	4020.3	4694.2	18	5724.6
9/22/99	Stabilization	15.7	372.1	213.6	18	260.5
9/27/99	Stabilization	43.7	1318.6	819.1	18	998.9

Date	Construction phase	Rain (mm)	Runoff (m^3)	TSS (kg)	Estimated sediment trap efficiency (%)	TSS + trap sediment (kg)
9/28/99	Stabilization	33.0	957.2	315.8	18	385.2
9/30/99	Stabilization	19.6	501.2	299.4	18	365.2
10/17/99	Stabilization	34.8	1017.4	122.1	18	148.9
10/20/99	Stabilization	12.7	252.5	52.0	18	63.4
11/2/99	Stabilization	8.1	122.0	39.8	18	48.5
11/26/99	Stabilization	18.3	404.1	357.7	18	436.3
12/13/99	Stabilization	29.7	917.6	1021.5	18	1245.7
1/9/00	Stabilization	38.3	1246.9	1832.8	18	2235.1
1/20/00	Stabilization	15.2	439.1	65.4	18	79.8
1/24/00	Stabilization	54.1	1121.5	167.1	18	203.8
1/30/00	Stabilization	27.7	776.5	71.4	18	87.1
2/12/00	Stabilization	19.0	484.0	55.8	18	68.0
2/27/00	Stabilization	15.7	359.1	53.5	18	65.2
3/27/00	Stabilization	12.4	416.4	149.7	59[a]	362.4
4/8/00	Stabilization	15.7	394.1	224.6	59[a]	543.9
4/15/00	Stabilization	14.5	292.5	134.5	59[a]	325.8
4/18/00	Stabilization	15.2	378.5	401.2	59[a]	971.5
4/25/00	Stabilization	13.7	228.4	226.1	59[a]	547.5

[a] Sediment trap efficiency based on overall efficiency average.

Table A2-3. Selected WEPP landcover parameters used to model before, during, and after construction type conditions at the Carpenter and Centennial A & C watersheds.

Plant Growth and Harvest Parameters	Cut slope	Bare soil	Continuous grass	Tall Prairie Grass	Road/ Forest	Disturbed/ Forest	2 yr Forest	20 yr Forest
Biomass energy ratio (kg MJ^{-1})	2	25	35	13	0	150	150	150
Growing degree days to emergence (ºC day)	30	60	30	5	30	5	5	5
Growing degree days for growing season (ºC day)	0	1500	0	0	0	0	0	0
In-row plant spacing (cm)	499.9	22	0.6	10	500	200	40	200
Plant stem diameter at maturity (cm)	0.1	0.003	0.22	1	0.1	25	25	25
Height of post-harvest standing residue; cutting height (cm)	1	0	15.2	10	1	2000	2000	2000
Harvest index (dry crop yield/total above ground dry biomass) (%)	42	90	90	42	42	42	42	42
Temperature and Radiation Parameters								
Base daily air temperature (ºC)	2	10	10	2	2	2	2	2
Optimal temperature for plant growth (ºC)	12	25	25	20	12	20	20	20
Maximum temperature that stops the growth of a perennial crop (ºC)	32	0	32	40	32	40	40	40
Critical freezing temperature for a perennial crop (ºC)	-40	0	1.1	0	-40	0	0	0
Radiation extinction coefficient	0.01	0.9	0.65	0.9	0.01	0.9	0.9	0.9
Canopy, LAI and Root Parameters								
Canopy cover coefficient	14	0.1	14	14	14	14	14	14
Parameter value for canopy height equation	23	1	23	3	23	3	3	3
Maximum canopy height (cm)	15	0.025	51	60	15	500	250	500
Maximum leaf area index	1	0.01	9	1	1	6	3	6
Maximum root depth (cm)	10	0.025	30	30	10	200	200	200
Root to shoot ratio (% root growth / % above ground growth)	33	33	33	33	33	33	33	33
Maximum root mass for a perennial crop	0.001	0	0.34	0.15	0.001	0.5	0.5	0.5

Plant Growth and Harvest Parameters	Cut slope	Bare soil	Continuous grass	Tall Prairie Grass	Road/ Forest	Disturbed/ Forest	2 yr Forest	20 yr Forest
(kg/m^2)								
Senescence Parameters								
Percent of growing season when leaf area index starts to decline	85	70	85	25	85	25	25	25
Period over which senescence occurs (days)	14	14	14	40	14	300	200	300
Percent canopy remaining after senescence	0.1	75	70	30	0.1	50	50	50
Percent of biomass remaining after senescence	1	70	90	25	1	70	70	70
Residue parameters								
Parameter for flat residue cover equation (m^2 kg^{-1})	5	5	5	5	5	5	5	5
Standing to flat residue adjustment factor (wind, snow, etc.) (%)	99	99	99	99	99	99	99	99
Decomposition constant to calculate mass change of above-ground biomass	0.0074	0.0065	0.009	0.0068	0.0074	0.006	0.006	0.006
Decomposition constant to calculate mass change of root biomass	0.0074	0.0074	0.009	0.0068	0.0074	0.006	0.006	0.006
Use fragile or non-fragile mfo values	Non-fragile	Non-fragile	Non-fragile	Non-fragile	Non-fragile	Non-fragile	Non-fragile	Non-fragile
Other Parameters								
Plant specific drought tolerance (% of soil porosity)	10	0	0	10	10	10	10	10
Critical live biomass value below which grazing is not allowed (kg m^{-2})	0	0	0.1	0	0	0	0	0
Maximum Darcy Weisbach friction factor for living plant	1	0	12	11	1	17	15	17
Harvest Units	Wepp WillSet	Wepp WillSet	Wepp WillSet	Wepp WillSet	Wepp WillSet	Wepp WillSet	Wepp WillSet	Wepp WillSet
Optimal yield under no stress conditions (kg m^{-2})	0	0	0	0	0	0	0	

Plant Growth and Harvest Parameters	Cut slope	Bare soil	Continuous grass	Tall Prairie Grass	Road/ Forest	Disturbed/ Forest	2 yr Forest	20 yr Forest
Bulk density after tillage (g cm^{-3})	1.0	1.6	1.1	1.1	1.0	1.1	1.1	1.1
Initial canopy cover (%)	0	0	50	30	0	90	50	90
Days since last tillage	0	200	200	1000	0	1000	1000	1000
Days since last harvest	0	2000	92	900	0	100	100	100
Initial frost depth (cm)	0	0	0	0	0	0	0	0
Initial interrill cover (%)	0	0	50	80	0	100	20	100
Initial residue cropping system	Fallow	Fallow	Perennial	Perennial	Fallow	Perennial	Perennial	Perennial
Cumulative rainfall since last tillage (mm)	420.1	19.69	500	1000	420.1	1000	1000	1000
Initial ridge height after last tillage (cm)	0.6	0	2	10	0.6	10	10	10
Initial rill cover (%)	0	0	50	80	0	100	20	100
Initial roughness after last tillage (cm)	0.6	0.1	2	10	0.6	10	10	10
Rill spacing (cm)	400.1	0	0	0	400.1	0	0	0
Rill width type	Temporary	Temp	Temp	Temp	Temp	Temp	Temp	Temp
Initial snow depth (cm)	0	0	0	0	0	0	0	0
Initial depth of thaw (cm)	0	0	0	0	0	0	0	0
Depth of secondary tillage layer (cm)	2.54	3.937	10	10	2.54	10	10	10
Depth of primary tillage layer (cm)	2.54	7.874	20	20	2.54	20	20	20
Initial rill width (cm)	0	0	0	0	0	0	0	0
Initial total dead root mass (kg m^{-2})	0	0	0.2	0.1	0	0.5	0.5	0.5
Initial total submerged residue mass (kg m^{-2})	0	0	0	0.1	0	0.5	0.5	0.5

Chapter 3: Applying Process-Based Models for Erosion and Sediment Control Design

ABSTRACT. *Sediment and erosion controls have been required on construction sites for many years, but are often not very effective in reducing sediment movement to streams. One approach to investigating the effectiveness of erosion and sediment controls is to use computer models to evaluate the individual and combined effect of sediment control measures. WEPP and GeoWEPP models were applied to determine the efficiency of planned controls on construction sites, and to create Best Management Practices (BMP) scenarios to meet North Carolina water quality standards. Two small watersheds (A & C) with plans for construction in Raleigh, NC were selected for modeling. Two sediment traps on watershed A were modeled as impoundments in WEPP, and a 15.2 m wide forested riparian buffer on watershed C was modeled with GeoWEPP. WEPP estimated trapping efficiencies within NC standards of 70 % trapping efficiency for particle sizes greater than 0.04 mm. WEPP predicted that the turbidity of runoff from the second sediment trap at the site outlet would be equal to or less than NC turbidity requirements of 50 Nephlometric Turbidity Units for 11 % of storm events. Turbidity standards were met on watershed A essentially by capturing the storm runoff, which was done by removing the outlet from sediment trap B and increasing the trap area 6-fold from 1 % to 8 % of the drainage area. Replacing rock check dams with culverts greatly reduced TSS concentrations, although the average turbidity level of 50 NTUs still exceeded standards. The GeoWEPP model predicted that planned riparian buffer would not meet the turbidity standard for any of the modeled storm event unless combined with other BMPs. Extending the design buffer in Watershed C decreased TSS concentration predicted with the design buffer by 57 %, while only increasing vegetation space on the construction site from 13 % to 22 %. Maintaining forested areas on highly erosive areas surprisingly had little impact on runoff volume or sediment yield, which may suggest a potential flaw within the GeoWEPP model.*

Keywords. *Erosion, Construction, Watershed, BMP, sediment, riparian buffer, WEPP model, GeoWEPP, GIS, Sediment, Runoff.*

Introduction

Because land-developing activities require vegetation removal and landscape reshaping, the soil surface is exposed to the elements and subjected to erosion. By 1980, construction activities had disturbed an estimated 1.7% of U.S. land (Toy and Hadley, 1987). Toy and Hadley (1987) also noted that land disturbance from mining, residential, commercial and highway construction can accelerate erosion by two or more orders of magnitude. In 1973, the Clean Water Act placed the responsibility of maintaining water quality from construction sites on state governments (Title II, section 208). In response, the state of North Carolina passed the Sedimentation Pollution Control Act of 1973, which required the approval of erosion control plans by the Sediment Control Commission of NC (NC General Statutes, 1973), with the distinction that discharge from the site would not exceed a turbidity of 50 Nephlometer Turbidity Units (NTUs). It was also stated that sediment traps are required to have 70 % settling efficiency for particles greater than or equal to 0.04 mm in diameter for a 2-year storm, which is 88.9 mm in Raleigh, NC.

To meet these standards, land developers and contractors must install sediment and erosion controls on their sites. Optimal placement of controls is dependent on topography, soil, and landcover. The traditional method for designing erosion and sediment control plans has been based on visual interpretations of contour maps, soil survey maps, and field surveys (Goldman et al., 1986). This method is labor and time intensive, and heavily dependent on the competency of the designer. Also, it can be difficult to account for interactions between elevation, soil, and landcover. Another method is computer erosion prediction modeling, which allows the user to identify erosive areas and to compare the effectiveness of different control measures (Goldman et al., 1986). Process-based erosion prediction models attempt to simulate significant processes going on in the environment by applying laws and theories of physical movement, and can be easily applied to a large variety of landscapes and situations (Doe and Harmon, 2001).

The Water Erosion Prediction Project, or WEPP, is a lumped-parameter process-based model designed to simulate erosion and deposition on agricultural areas, and is one of the most widely studied process-based erosion prediction models in current use (Flanagan and Nearing, 1995). The watershed version of WEPP can be used to simulate sediment controls such as sediment traps, rock check dams, and emergency spillways (Lindley et al., 1998). GeoWEPP, which provides a geographical information system GIS interface for WEPP, can be used to account for spatially variable erosion controls such as vegetative buffers, erosion mats on steeper slopes, and staged construction (Renschler, 2003).

GIS can also be used for designating optimal placement of BMPs (Best Management Practices) on watersheds. Tomer et al. (2003) applied GIS to determine optimal buffer width and placement for reducing nutrients in streams by designating riparian grid cells with large upslopes and low slopes as optimal sites for buffer placement.

There are several examples of computer models applied by researchers to test the effect of BMPs on controlling pollutants. Yuan et al. (2001) applied Ann AGNPs Annualized Agricultural Non-Point Source to test impoundments and winter cover crops as BMPs for reducing sediment loads on a large watershed. Wright et al., 1992, used CREAMS-DRAINMOD (Chemicals, Runoff, and Erosion from Agricultural Management Systems - Drainage Simulation Model) to evaluate the effects of different types of water table management runoff, erosion, and nitrogen losses. Gerwig et al., 2001 examined the effect of riparian buffers using GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) and REMM (Riparian Ecosystem Management Model) on phosphorous and nitrogen transport from agricultural fields receiving swine effluent.

The objective of this research is to experiment with WEPP and GeoWEPP as land planning tools by determining the efficiency of planned erosion and sediment controls on sample construction sites, applying erosion controls to erosive areas designated by GeoWEPP, and creating BMP scenarios on sample construction sites to meet North Carolina water quality standards.

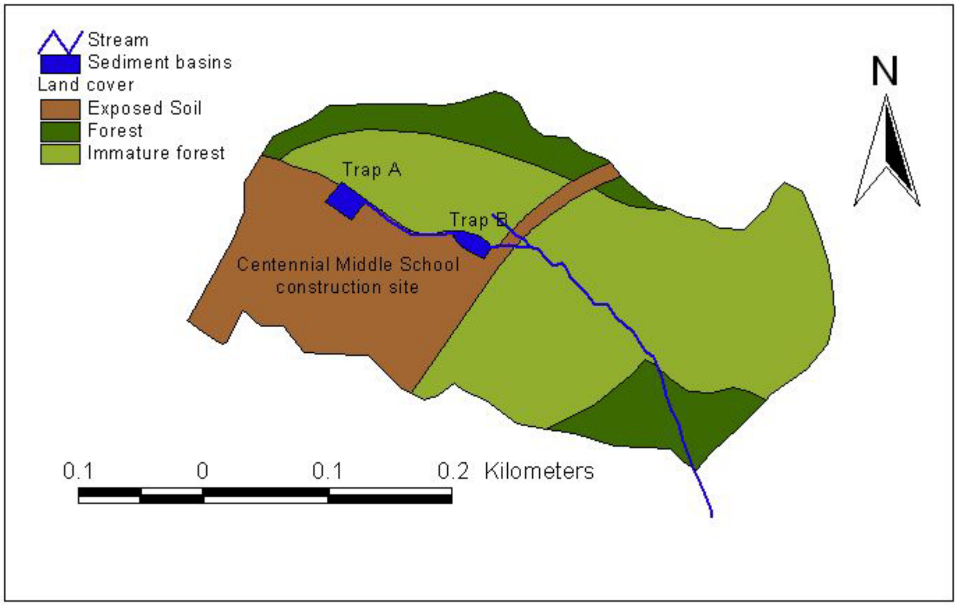
METHODS AND MATERIALS

SITE DESCRIPTION

Two watersheds in Wake County, NC, were selected for modeling purposes. Detailed site descriptions are listed in Table 3-1. Both watersheds (referred to as watersheds A & C) are located on North Carolina State University's Centennial Campus in Raleigh, NC. Watershed A was modeled using erosion and sediment control plans that were applied during the development of the Centennial Campus Middle School. The N.C. Sediment Control Commission (1988) state that sediment storage volume must be at least 126 m^3 ha^{-1} of the total disturbed area draining into the sediment trap. Thus, sediment trap A had storage volume of 165 m^3 for a drainage area of 1.31 ha and sediment trap B had storage volume of 281.4 m^3 for a drainage area of 2.23 ha (Figure 3-1). Both sediment traps contain rock check dam outlets. Watershed C was modeled using projected erosion control plans for the development of the Centennial Campus Golf Course. Because of the presence of streams, these plans included a 15.2 m width of undisturbed forested buffer from the perennial portion of the stream to remain during and after construction in order to comply with Neuse Buffer Rules (Figure 3-1).

Table 3-1. General site description of watersheds A & C on North Carolina State University's Centennial Campus in Raleigh, North Carolina.

	Watershed A	Watershed C
Elevation above mean sea level (m)	98 - 115	97 - 128
Area (ha)	9.3	11.8
Soil	13 % Pavement 29 % Appling 58 % Cecil	1 % Pavement 90 % Cecil 9 % Colfax
Construction period	1998 - 1999	Pending



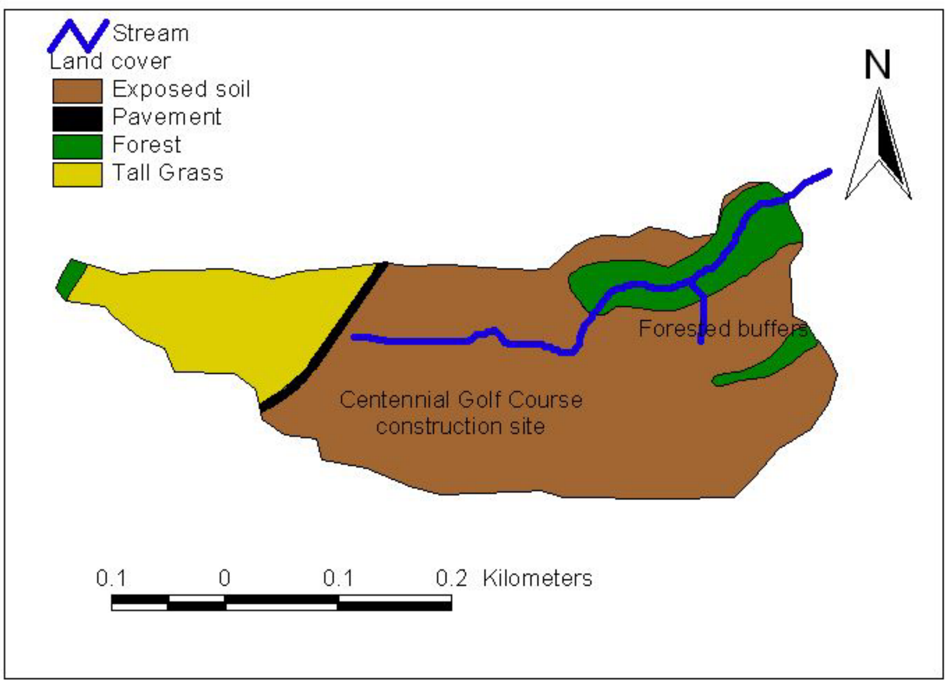


Figure 3-1. Landcover during construction on watersheds A (upper) and C (lower) watersheds A & C on North Carolina State University's Centennial Campus in Raleigh, North Carolina.

Model Descriptions

WEPP

Water Erosion Prediction Project (WEPP) is a lumped parameter, one-dimensional, process-based erosion model that simulates the detachment, transport, and deposition of sediment on rectangular hillslopes during runoff events, predicting sediment yield and runoff volume during storm events (Flanagan and Nearing, 1995). Figure 3-2 illustrates how landcover in Watershed A is simplified into one lumped parameter for each hillslope in WEPP. General soil, landcover, and slope information for each hillslope is listed in Table A3-1.

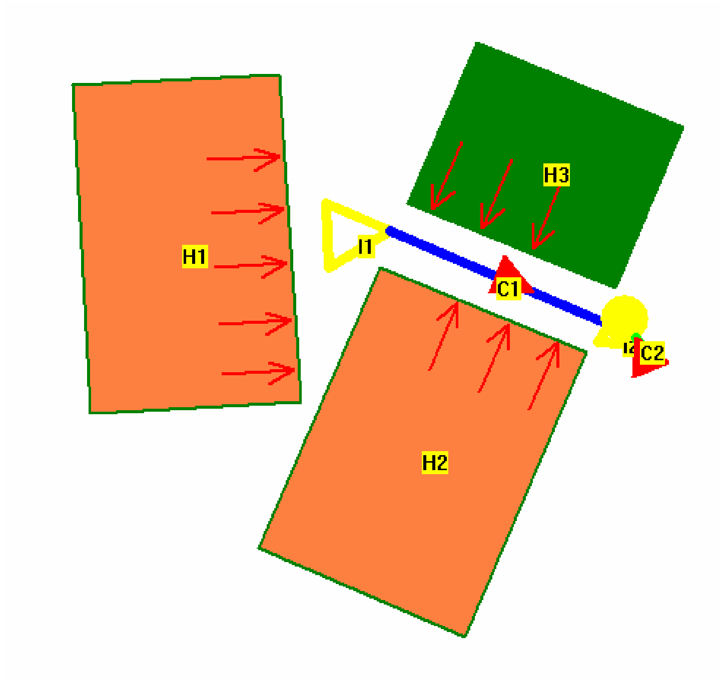


Figure 3-2. WEPP Watershed view of the three hillslopes (H1, H2, and H3), two channels (C1 and C2), and two impoundments (I1 and I2) modeled in watershed A. Hillslopes H1 and H2 are orange to represent exposed soil; hillslope H3 is green to represent forest.

WEPP has been validated for agricultural fields, (Zhang et al., 1995a; Zhang et al., 1995b; McIsaac et al., 1992; Lienbow et al., 1990), rangelands (Savabi et al., 1995; Simanton et al., 1991; Wilcox et al., 1990; Nearing et al., 1989), impoundments (Lindley et al., 1998), and calibrated for forested areas (Elliot and Hall, 1997). Watershed A was modeled using WEPP Watershed Version 2002.70, which provides input parameters for impoundments with outlet structures such as culverts, rock check dams, and straw bales. Sedimentation algorithms for WEPP impoundments were developed by Lindley et al. (1998) and are based upon principle of conservation of mass for as follows:

$$\frac{dM}{dt} = Q_i C_i - Q_O C_O - \frac{dDep}{dt} \quad (1)$$

where

M = Mass in the impoundment (kg)

C_i = Incoming sediment concentration (kg m^{-3})

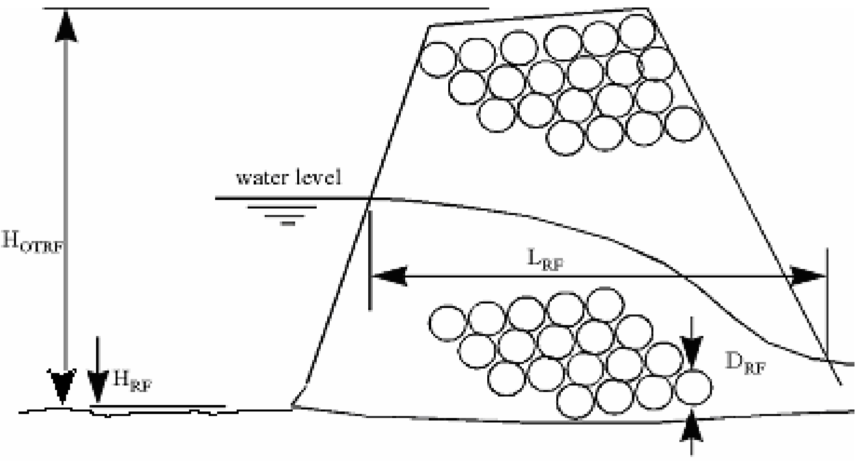
C_o = Outgoing sediment concentration (kg m^{-3})

Dep = Deposition (kg)

Q_i = Inflow rate (m^3 sec^{-1})

Q_o = Outflow rate (m^3 sec^{-1})

While sediment algorithms apply to all impoundments, flow rate equations in WEPP are specific to impoundment outlets. Figure 3-3 illustrates the equation used to predict flow rates for the rock check dam outlets in sediment traps A & B.



$$Q_{RF} = W_{RF}\left[\frac{H}{aL_{RF}}\right]^{1/b}$$

Q_{RF} - Flow rate through check dam ($m^3\ s^{-1}$)
W_{RF} - Cross-sectional width of check dam (m)
H - Head loss through check dam (H_{OTRF} - H_{RF}) (m)
L_{RF} - Average flow length of rock check dam (m)
a and b- Coefficients, function of rock diameter (D_{RF}) and flow length (L_{RF})

Figure 3-3. Schematic of the rock check dam impoundment as modeled by WEPP (from Lindley et al., 1998).

GeoWEPP

GeoWEPP ArcX 2004.3 is an ESRI-ArcView extension that directly links GIS to WEPP (Renschler, 2003). GeoWEPP allows the user to model raster cells as individual hillslopes, thus accounting for spatial variability among slope, soils, and landcover. Although currently GeoWEPP is not designed to simulate impoundment hydrology, it is an effective tool for detecting specific erosive and depositional areas around vegetative BMPs such as riparian buffers. It should also be noted that GeoWEPP is not a validated model, and therefore must be validated by the individual user. As the primary BMP for Watershed C was a forested buffer, erosion processes were simulated using GeoWEPP. Figure 3-4 illustrates how landcover in Watershed C is distributed into one parameter for each raster cell in GeoWEPP.

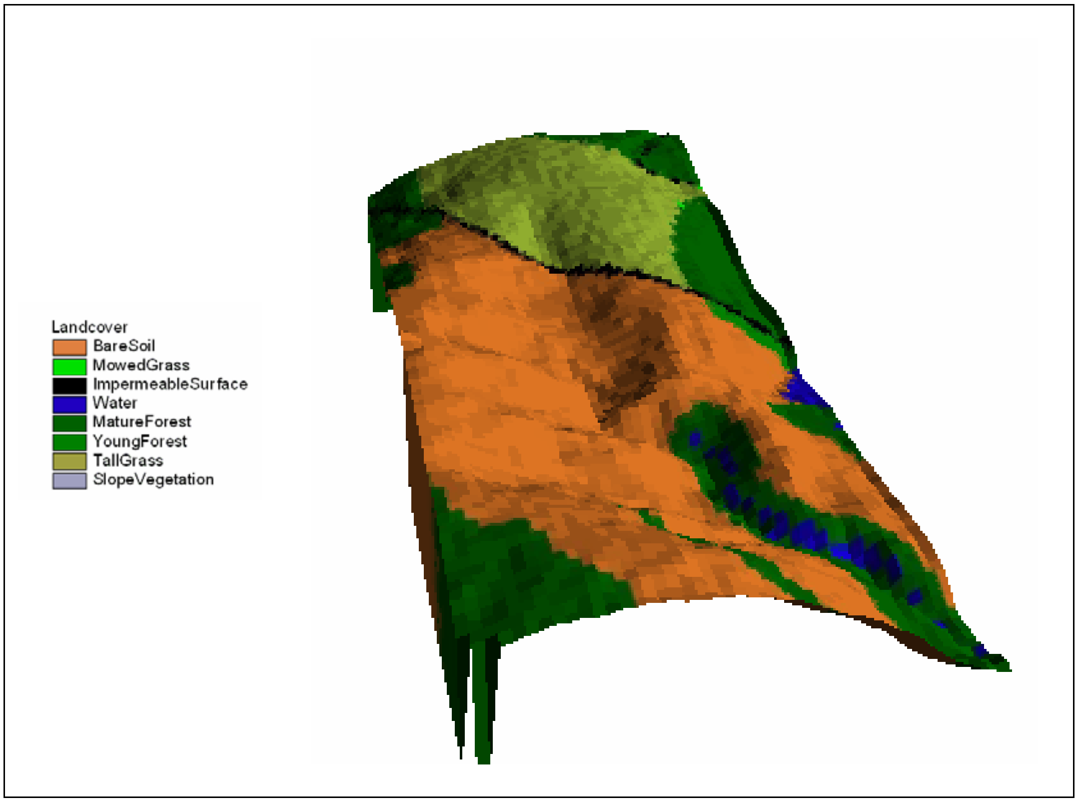


Figure 3-4. Landcover input map for GeoWEPP simulating a forested buffer designed to meet Neuse River Basin Rules, on Watershed C during construction.

MODEL INPUTS

WEPP

Climate, soil, landcover, and slope input are required by WEPP for modeling. Input parameters for both WEPP and GeoWEPP simulations were created in WEPP. All climate information was retrieved from the RDU airport weather station for the years of 1998 and 1999 for both watersheds and submitted into WEPP CLIGEN format (Table A3-2) (SCONC, 2004). The climate parameter also includes climate data for 1997, to allow the water balance to equilibrate before modeling the target storm events. Soil parameter information required by WEPP is listed in Table 3-2. Appling and Cecil soil series were not included in the WEPP database, therefore soil parameters originating from these series were created using the NRCS soil series descriptions (USDA - NRCS, 2002) and equations from the WEPP manual (Alberts et al., 1995).

Table 3-2. WEPP input soil parameters for watersheds A & C on North Carolina State University's Centennial Campus in Raleigh, North Carolina.

Soil description	Soil Texture[a]	Interrill erodibility (Ki)	Rill erodibility (Kr)	Critical shear stress (tau)	Effective Hydraulic conductivity Kef	Sand	Clay	CEC	Rock
		kg sec m^{-4}	sec m^{-1}	Pa	mm h^{-1}	%	%	meq/ 100 g	%
Appling	SL	4.97 x 10^6	1.02 x 10^{-2}	2.5	4.4	65	15	3.0	3
Appling subsoil	CL	4.31 x 10^6	4.80 x 10^{-3}	4.7	4.4	45	40	8.0	4
Cecil	L	5.43 x 10^6	8.50 x 10^{-3}	3.3	4.8	50	12	7.3	3
Cecil subsoil	L	5.43 x 10^6	8.50 x 10^{-3}	3.3	4.4	45	25	5.5	4
Colfax	L	5.31 x 10^6	7.00 x 10^{-3}	3.1	7.1	41	19	7.3	3
Colfax subsoil	L	5.31 x 10^6	7.00 x 10^{-3}	3.1	7.1	48	27	5.5	4
Pavement	SL	1.00 x 10^3	1.00 x 10^{-4}	100.0	0.1	10	70	25	90

[a] SL - Sandy loam, L - Loam, CL - Clay loam

Complete WEPP landcover input parameters are listed in Table A3-3. Select WEPP landcover parameters in Table 3-3 were chosen based on degree of sensitivity, using parameters as suggested by Nearing et al., 1990. In Chapter 2, we found that the subsoil soil series input parameters used in combination with the WEPP landcover "Cutslope" parameter resulted in a satisfactory runoff efficiency (E = 0.78) when compared to measured runoff data from a construction site near Raleigh, NC. Construction site soil conditions were modeled using soils on Watersheds A & C altered in this manner. Forest and tall grass landcover parameters from WEPP were selected based on the highest runoff efficiency achieved (E =

0.21) for stable watersheds, as determined in Chapter 2. Slope information was derived manually from contour maps of the area, assuming a simple uniform slope for each hillslope.

Table 3-3. Selected WEPP landcover input parameters for watersheds A & C on North Carolina State University's Centennial Campus in Raleigh, North Carolina.

Plant Growth and Harvest Parameters	Cut slope	Tall Prairie Grass	Disturbed/Forest
Maximum Darcy Weisbach friction factor for living plant	1	11	17
Initial canopy cover (%)	0	30	90
Days since last tillage	0	1000	1000
Days since last harvest	0	900	100
Initial interrill cover (%)	0	80	100
Initial residue cropping system	Fallow	Perennial	Perennial
Initial rill cover (%)	0	80	100
Initial roughness after last tillage (cm)	0.6	10	10
Initial total dead root mass (kg m^{-2})	0	0.1	0.5

Sediment trap information was imported from the sediment trap characteristics in the erosion and sediment control design for the Centennial Campus Middle School (Table 3-4). Check dam length and cross-sectional width was based on the minimum requirements in the NC Sediment and Erosion Control Design Manual. The infiltration rate of the sediment traps was assumed to be the same as infiltration rates for the Cecil subsoils on this site.

Table 3-4. WEPP impoundment inputs for designed sediment traps A & B on North Carolina State University's Centennial Campus in Raleigh, North Carolina.

WEPP Impoundment inputs	Sediment trap A	Sediment trap B
L_{RF} (m)	1.52	1.52
H_{RF} (m)	0.0	0.0
W_{RF} (m)	1.52	1.52
D_{RF} (m)	0.23	0.23
H_{OTRF} (m)	0.91	1.52
H_{FULL} (m)	0.46	0.76
Infiltration rate (Q_{inf}) (m day^{-1})	0.11	0.11
Bottom stage area (m^2)	131.5	105.9
Top stage area (m^2)	237.5	286.1
Bottom stage length (m)	18.0	17.4
Top stage length (m)	21.6	23.5

GeoWEPP

Data layers for GeoWEPP Arc X 2004.3 were constructed and modified using ArcView GIS 3.2a and GRASS 5.0. The digital elevation models (DEMs) were created by implementing a spline algorithm in GRASS (Neteler and Mitasova, 2000) to interpolate 2 ft (0.6 m) interval contour maps to 7 m resolution grids for both watersheds. Soil maps, scaled at 1:24,000, were downloaded from the USDA-NRCS Soil Survey Geographic Database (Figure A3-1) (USDA-NRCS, 2000). The landcover map for watersheds A & C watersheds was derived from aerial photos of the site. Soil, landcover, and DEMs were exported from grid format to the ASCII format required by GeoWEPP.

METHODS FOR OPTIMIZING BMPS

New erosion control plans for Watersheds A & C were created with the goal of meeting NC standards for sediment. Specifically, our goal was to reduce turbidity levels to 50 NTUs in runoff leaving the site, and to design sediment traps with a minimum of 70 % retention efficiency as mandated by the Sediment Control Act of NC. A second-order polynomial was developed with the SAS procedure PROC NLIN using TSS and turbidity data retrieved from 1/23/02 to 4/1/02 (Figure 3-5) (SAS, 1999). Following this relationship, TSS concentrations of 16.6 mg L^{-1} were assumed to be equivalent to 50 NTUs, with the understanding that their TSS concentrations range greatly at each turbidity level. In this case TSS concentrations ranged from 2.0 to 22.7 mg L^{-1} for turbidity values between 45 and 55 NTUs.

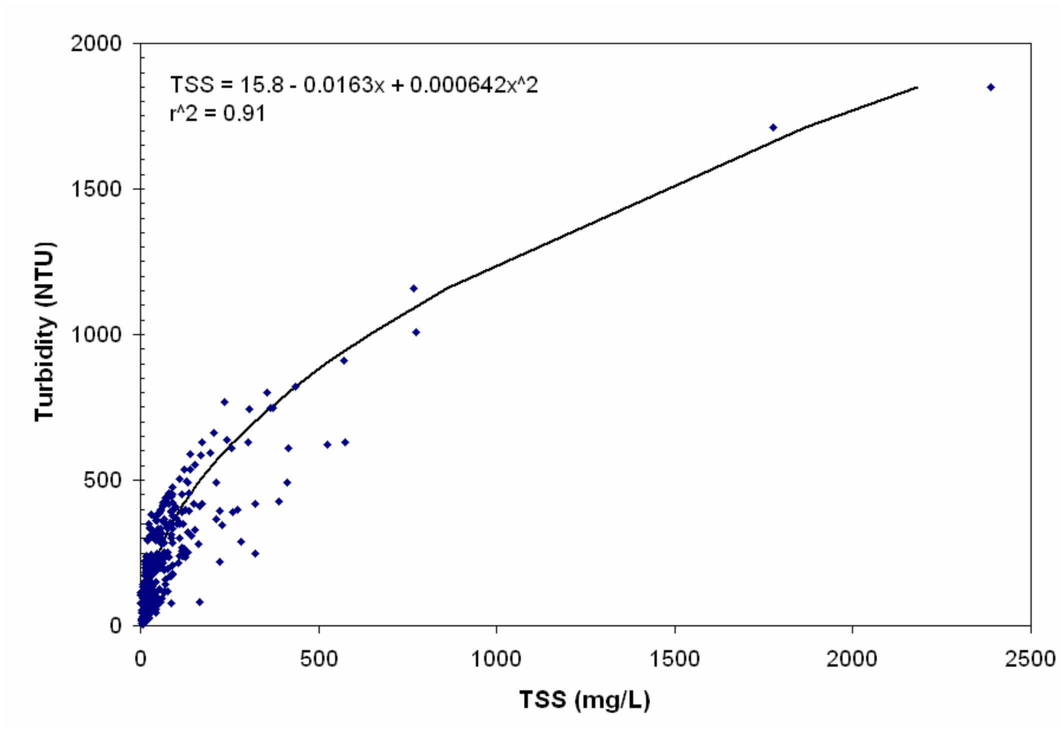


Figure 3-5. Relationship between TSS and turbidity in runoff samples collected from outlets on watersheds A & C on North Carolina State University's Centennial Campus in Raleigh, North Carolina.

GeoWEPP was applied to create erosion control coverage on the Watershed C construction site in areas of high soil loss, with the objective of optimizing the efficiency of vegetative cover by allowing the existing forest to remain standing on the most erosion sensitive areas on the site. GeoWEPP simulations were used to identify erosive areas, applying a landcover input map representing the construction site without vegetated buffers. Cells that had an estimated soil loss greater than either 128 or 256 tonnes ha^{-1} were used to create forested areas on the landcover input map (Figure 3-6). These soil loss tolerance levels were selected to simulate what we considered to be the upper and lower limits of maintaining a reasonable amount of space for construction while significantly reducing erosion losses, and were labeled as high and low cover, respectively. To save on time and effort, the newlandcover.aml script was developed to convert highly erosive cells from GeoWEPP output map to landcover on high erosion areas in the landcover input map, based on a soil loss tolerance which can be determined by the user (Script A3-1).

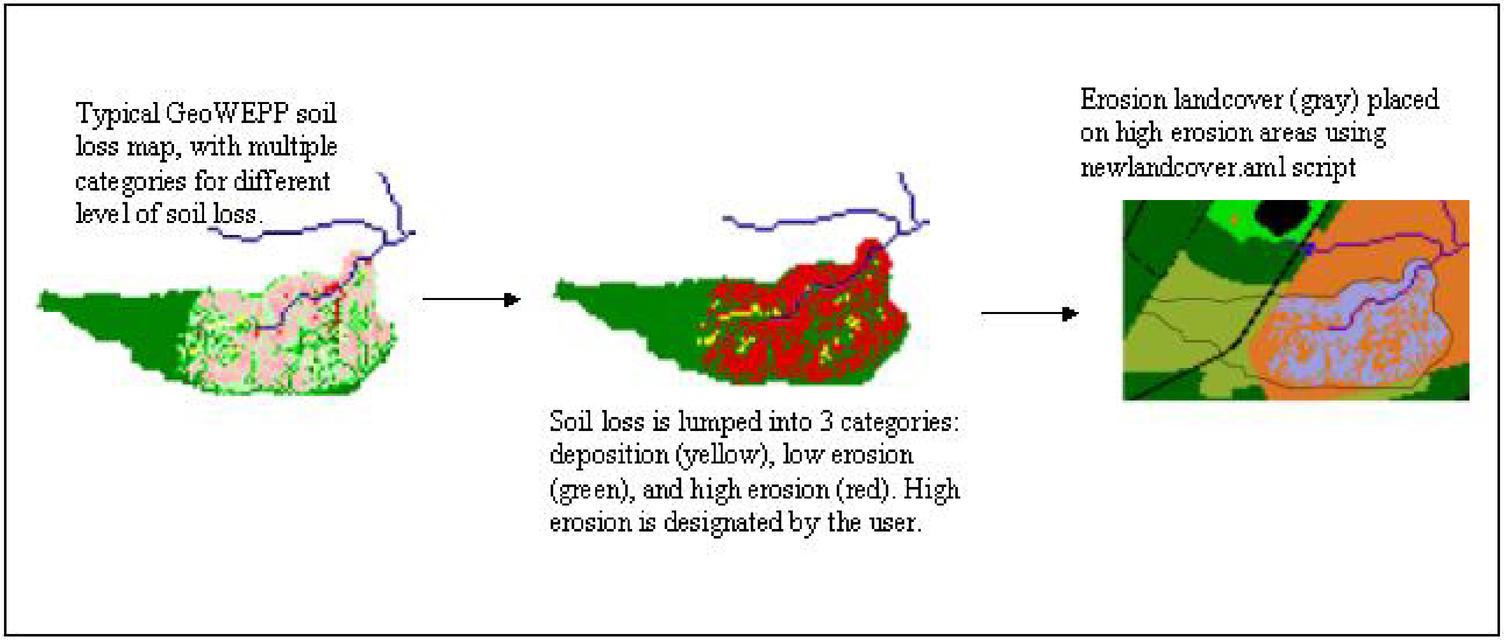


Figure 3-6. Creating landcover on high erosion areas detected by GeoWEPP.

RESULTS AND DISCUSSION

EFFICIENCY OF PLANNED BMPS

WEPP Impoundments

Trap efficiency, average TSS, peak outflow, inflow and outflow runoff volumes, and number of days that traps were overtopped were estimated on a yearly basis using WEPP (Table 3-5). Yearly output was averaged over 1998 and 1999, because there was little difference between them. Both sediment traps were predicted to have greater than 70 % trapping efficiencies for particle sizes larger than 0.05 mm in diameter (Table 3-5), suggesting that the sediment traps would have been within NC sediment trap efficiency standards. Sediment trap A had a higher trapping efficiency than trap B, despite the fact that sediment B was 1.7 times larger in storage volume than sediment trap A. Peak outflow rates were 8 times greater for trap B than trap A (Table 3-5), as sediment trap B received water from sediment trap A in addition to water from its own surrounding drainage area (Figure 3-2), which would reduce sediment settling. It should be noted that Line and White (2001) measured an average sediment trap efficiency of 59 % from a standard-sized trap on a construction site in Wake County, N.C., similar to what we predicted for total sediment trap efficiency in sediment trap B.

Table 3-5. WEPP impoundment output averaged over 1998 and 1999 precipitation events on watersheds A & C on North Carolina State University's Centennial Campus in Raleigh, North Carolina.

	Trap efficiency (%)	Trap efficiency, particles > 0.05 mm	Avg. TSS, outflow (mg L-1)	Peak outflow rate (m^3 sec^{-1})	Total inflow volume (m^3)	Total outflow volume (m^3)	# Days overtopped
Sediment trap A	85	92.0	3460	0.114	2790.0	2781.3	2
Sediment trap B	52	74.1	1400	0.908	6329.2	6319.2	3

TSS concentration was predicted on a storm event basis for both sediment traps. WEPP produces output for watersheds with impoundment outlets on a yearly basis, and on an event-by-event basis for channel outlets. To produce sediment yield information on a storm event basis from sediment trap B, a small channel with a length of 1.5 m was attached to the outlet of sediment trap B in the model. This allowed WEPP to produce sediment yield results for runoff exiting sediment trap B for individual storms (Figure 3-2).

WEPP predicted that runoff leaving the construction site from sediment trap B would meet turbidity standard of 50 NTUs for only 11 % of the 53 storm events that occurred from 1998 to 1999 (Figure 3-7). Acceptable turbidity levels were predicted to occur during light precipitation events (20 mm or less). When the site was modeled without sediment traps, turbidity levels exceeded 50 NTUs for all storm events. From these results we concluded that while the sediment traps could potentially reduce sediment yields and would most likely meet NC trap efficiency standards, they would not be effective for meeting NC turbidity standards without additional BMPs.

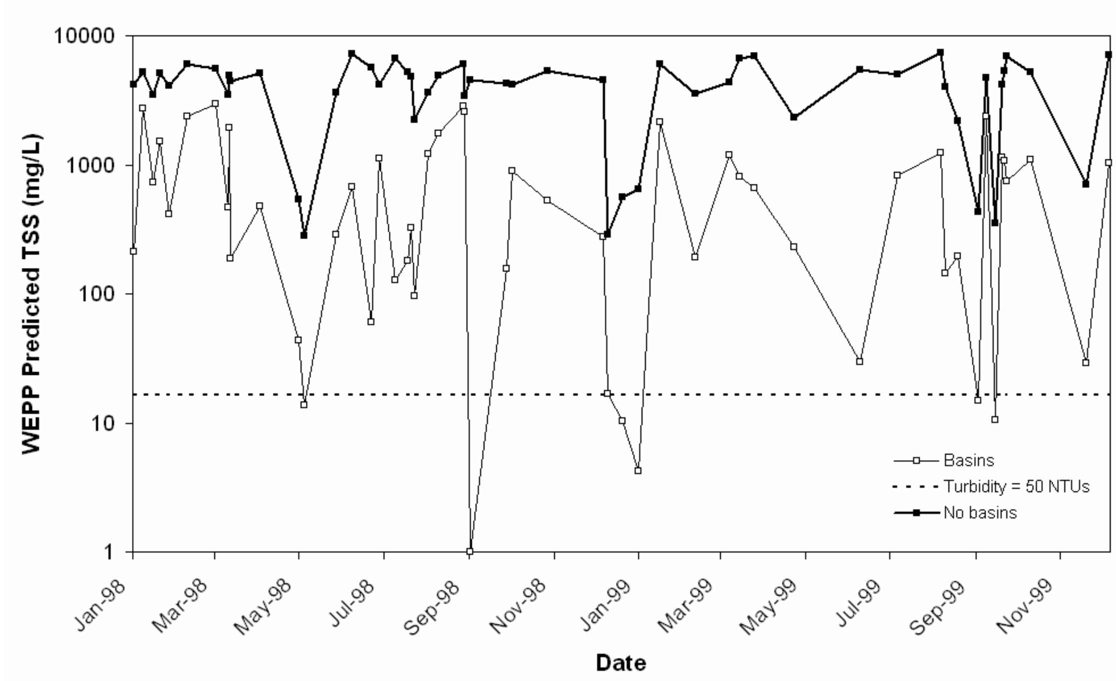


Figure 3-7. Predicted TSS in outlet directly below sediment trap B during construction, with and without the addition of two planned sediment traps.

GeoWEPP Vegetation

The GeoWEPP model predicted that the planned forested riparian buffers were not able to meet the NC 50 NTU turbidity standard for storm events that occurred during 1998 and 1999, with the lowest turbidity of 715 NTUs (304 mg L^{-1}) occurring during a snow melt event (Figure 3-8). The addition of the design buffer did reduce TSS concentrations for all storms by 62 % and sediment yield by 47 % compared to no buffer at all, illustrating that the forested buffers would significantly reduce sediment loads entering the stream. These sediment capture rates are similar to those found in sediment traps (Line and White, 2001), suggesting that maintaining natural vegetation around stream banks on developing sites would be as effective for reducing sediment yields as installing sediment traps. However, assuming GeoWEPP estimates are valid, the 15.2 m wide buffer required for this site would most likely need to be used in combination with impoundments such as sediment traps and check dams to meet the state water quality standard.

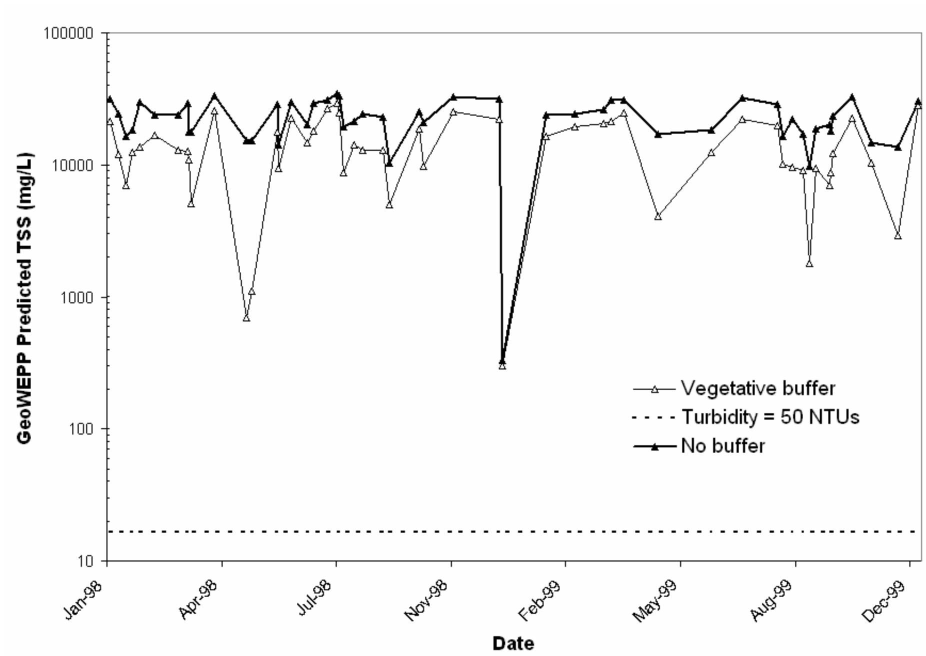


Figure 3-8. Predicted TSS in Watershed outlet C during construction, with and without the addition of the design riparian buffer.

GeoWEPP predicted that sediment would be deposited as runoff enters the buffer from the construction site, according to the GeoWEPP soil loss output map (Figure 3-9). The deposition of sediment occurs when there is a decrease in runoff velocity. Changes in WEPP landcover parameters from exposed soil to forest include an increase in surface roughness from 0.6 cm to 10 cm and in rill cover from 0 to 100 % (Table 3-3), and would reduce runoff velocities. GeoWEPP did not predict the formation of rills through the buffer (Figure 3-9). However, GeoWEPP would most likely not illustrate the formation of these rills, because the 7 m cell size that we used for our maps is larger than the general expected width of rills forming in buffers. Continuous erosion prediction models, such as SIMWE, would be more effective for smaller scale changes in the landscape (Mitasova and Mitas, 2001) .

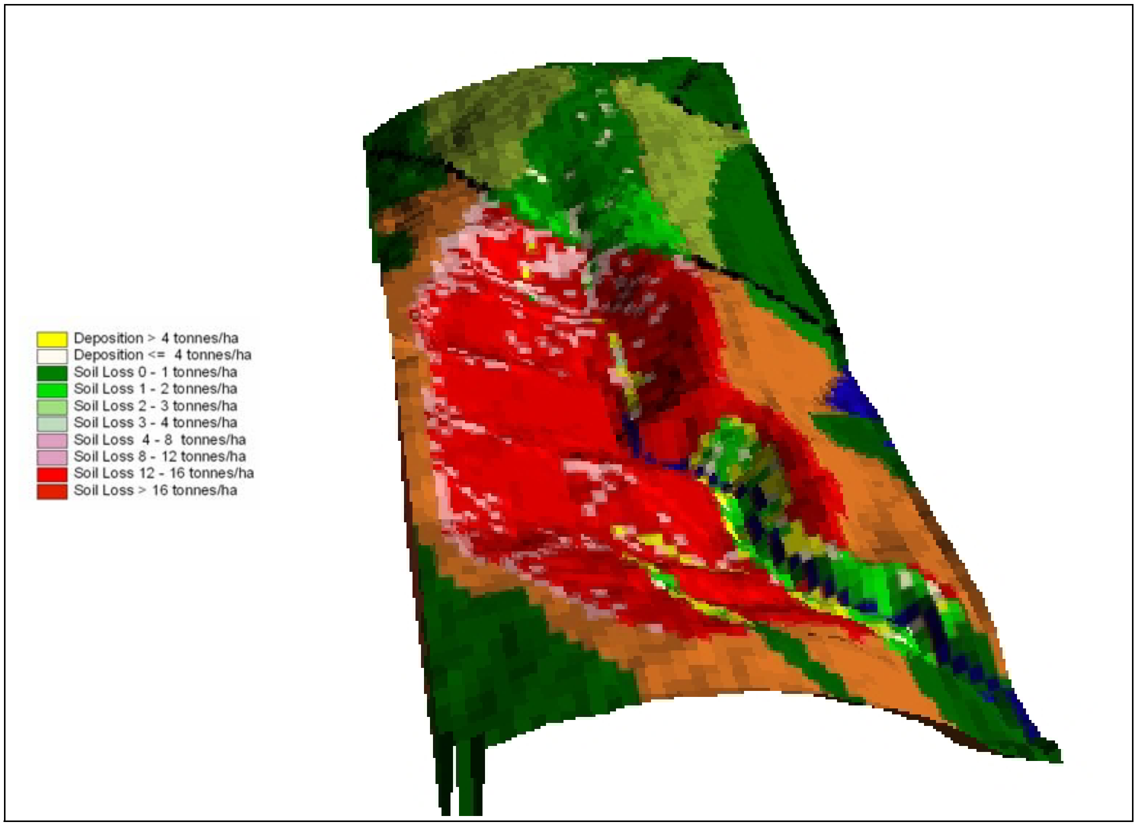


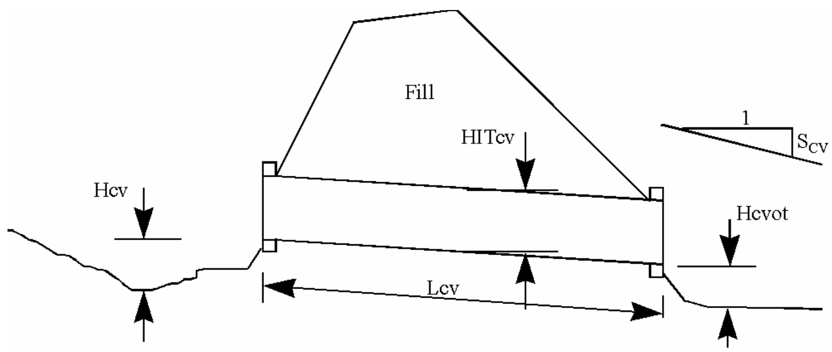
Figure 3-9. GeoWEPP soil loss map for Watershed C during construction, with the design buffer landcover draped over a 7m DEM. (DEM elevations exaggerated 5X to clearly illustrate topographical characteristics).

USING MODELS TO MEET NC WATER QUALITY STANDARD

WEPP Impoundments

Sediment trap sizes and outlets were adjusted to meet the 50 NTU standard by targeting TSS concentrations 16.6 mg L^{-1} or less in runoff exiting the traps. Sediment trap area was increased two, six, and eight-fold for Sediment trap B, and two-fold for Sediment trap A, thus increasing storage volume and settling time between the trap inlet and outlet. Area was increased while maintaining the flow length to basin width ratio of 2:1, as described in

NCSCC (1988). The six-fold and eight-fold area simulations of sediment trap B were also modeled without an outlet to simulate pond hydrology. Culvert outlets with standing pools of 0.46 – 0.76 m were used in place of rock check dams to allow the more sediment laden water to remain in the trap (Figure 3-10). Culvert inputs were retrieved from default culvert parameters in WEPP and adjusted to account for sediment trap depth (Table 3-6). This basin design will be called a "standing pool" hereafter.



N_{CV} - Number of identical culvert outlet structures
A_{CV} - Cross-sectional area of culvert (m^2)
HIT_{CV} - Cross-sectional height of culvert (m) for square conduits or diameter for circular conduit
H_{CV} - Stage of culvert inlet (m).
L_{CV} - Flow length of culvert (m)
S_{CV} - Slope of culvert (m/m).
H_{CVOT} - Height of culvert outlet above the outlet channel bottom (m)

Figure 3-10. Schematic of culvert impoundment as modeled by WEPP (from Lindley et al., 1998).

Table 3-6. WEPP impoundment inputs for sample culvert outlets for sediment traps A & B.

WEPP Impoundment inputs	Culvert parameters
N_{CV}	1
A_{CV}	0.023
HIT_{CV}	0.30
H_{CV}	0.46 for Sediment trap A, 0.76 for Sediment trap B
L_{CV}	1.83
S_{CV}	0.01
H_{CVOT}	0.30

Average TSS concentrations and sediment yields in relation to trap size and outlet type are illustrated in Figure 3-11. Doubling the size of sediment traps A and B had little effect on sediment yield and runoff volume (Figure 3-11), suggesting that increasing the flow length of the basin is not an effective method on this site for significantly reducing sediment yield or runoff. Standing pools with culvert outlets reduced runoff and TSS concentrations in comparison to the rock check dam outlets (Figure 3-11). Runoff volume for the pool/culvert design is decreased because runoff remaining in the trap below the culvert outlet exits by evaporation and infiltration, creating storage for the next storm. TSS concentrations are reduced because the upper portion of the water column is drained, instead of the entire water column, as is the case for rock outlets. It should be noted that while culverts do reduce TSS concentration, the turbidity (550 NTUs, estimated from TSS = 200.5 mg L^{-1}) still far exceeds the turbidity standard of 50 NTUs. It should also be noted that skimmer outlets are considered to be far more effective for draining sediment traps than culverts by draining water consistently from the top portion of the water column (Fennessey and Jarrett, 1997). Also, skimmers drain the trap until all liquid is removed, allowing for more runoff storage space for the next storm event. Unfortunately skimmer outlets are not modeled by WEPP, and are in general difficult to model because the outlet position does not remain constant.

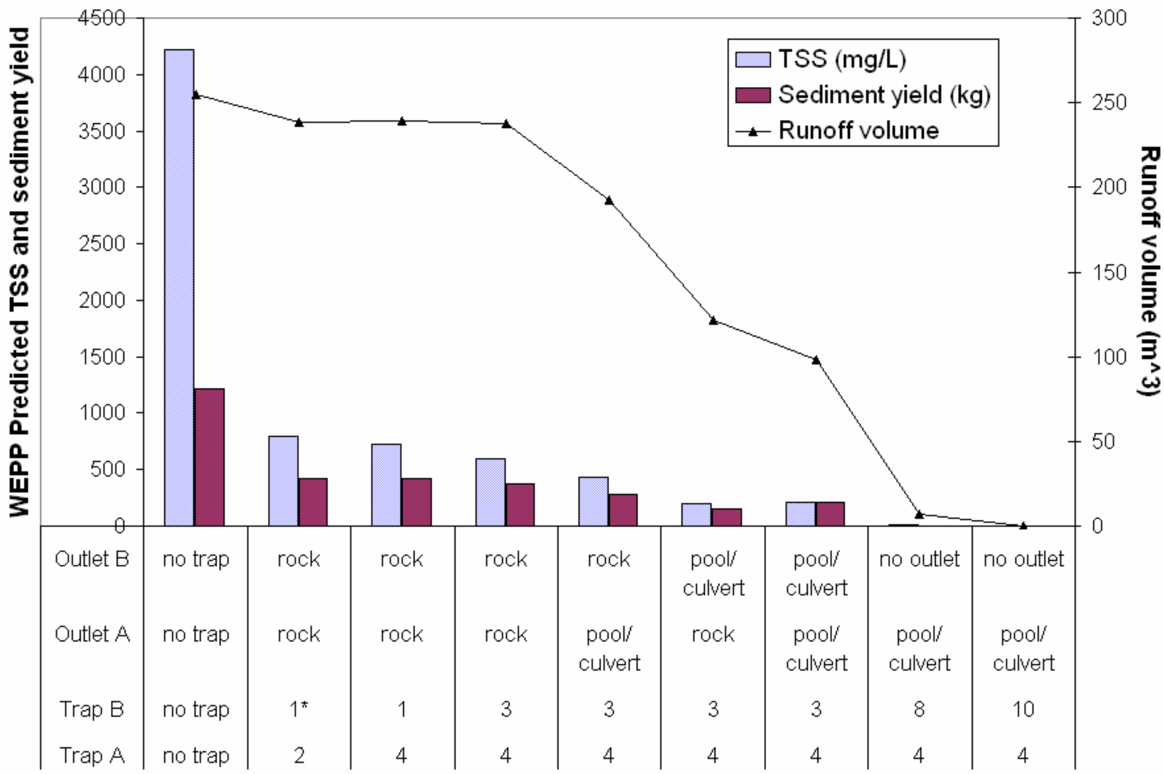


Figure 3-11. Predicted average TSS and sediment in outlet directly below sediment trap B during construction. *Percent of drainage area taken up by the trap.

The N.C. turbidity standard was met when we increased area in trap B 6-fold and 8-fold and removed the outlet, with turbidity level less than 14 NTUs. When there are no outlets established for an impoundment in WEPP, runoff exits by overtopping the impoundment. This was because increasing the area of trap B 6-fold and 8-fold either greatly reduced or eliminated runoff exiting the trap (Figure 3-11). However, increasing trap area 6-fold would take up 8 % of the drainage area, and an 8-fold increase would take up 10 % of the drainage area, which may provide a challenge to most developers.

GeoWEPP Vegetation

We attempted to meet the 50 NTU water quality standard in Watershed C by both adding forest cover to highly erosive areas and by surrounding the entire stream length with a riparian buffer to prevent sediment from entering the channel. We designed an extended buffer while maintaining the 15.2 m width set by the original developers, and stretched the buffer to follow the length of the stream network as delineated by TOPAZ in GeoWEPP. Forested landcovers for highly erosive areas on the construction site, as detected by GeoWEPP, were constructed following the method described in Figure 3-6. The landcover was divided for each scenario as listed in Table 3-7.

Table 3-7. Percent cover of various landcovers in Watershed C.

Landcover	No buffer	Design buffer	Long buffer	Long buffer + Low cover	Long buffer + High cover	No construction
Forest and forest buffer	0	11	23	23	23	55
Forested erosion cover	0	0	0	12	32	0
Pavement	1	1	1	1	1	1
Tall grass	21	16	16	16	16	44
Exposed soil surface	78	72	60	48	28	0

Average yearly TSS and sediment yields for various combinations of buffers and erosive area landcovers are illustrated in Figure 3-12. Extending the design buffer decreased TSS concentration in comparison to the design buffer by 57 %, and sediment yield by 68 %, while only increasing vegetation space on the construction site from 13% to 22 %. The large concentration of yellow raster cells surrounding the channel on the GeoWEPP soil loss map indicates considerable deposition, thus reducing the amount of sediment reaching the stream

(Figure 3-13, Figure 3-14). As mentioned earlier, runoff entering the buffer slows down as a result of the increased roughness associated with forest landcover, reducing runoff velocities and increasing deposition. Also providing a vegetative barrier between the exposed soil and the stream along the length of the stream instead of only the perennial portion (as was recommended by the developers) prevents direct sediment delivery at the upper half of the stream. We assumed that the turbidity would far exceed the turbidity standard of 50 NTUs, as WEPP-predicted TSS concentrations were greater than measured TSS concentrations used to estimate turbidity using our turbidity-TSS model for this site (Figure 3-5). Overall, extending the buffer appears to be an effective method for dramatically reducing sediment yields with minimal use of space, but not effective for meeting water quality standards.

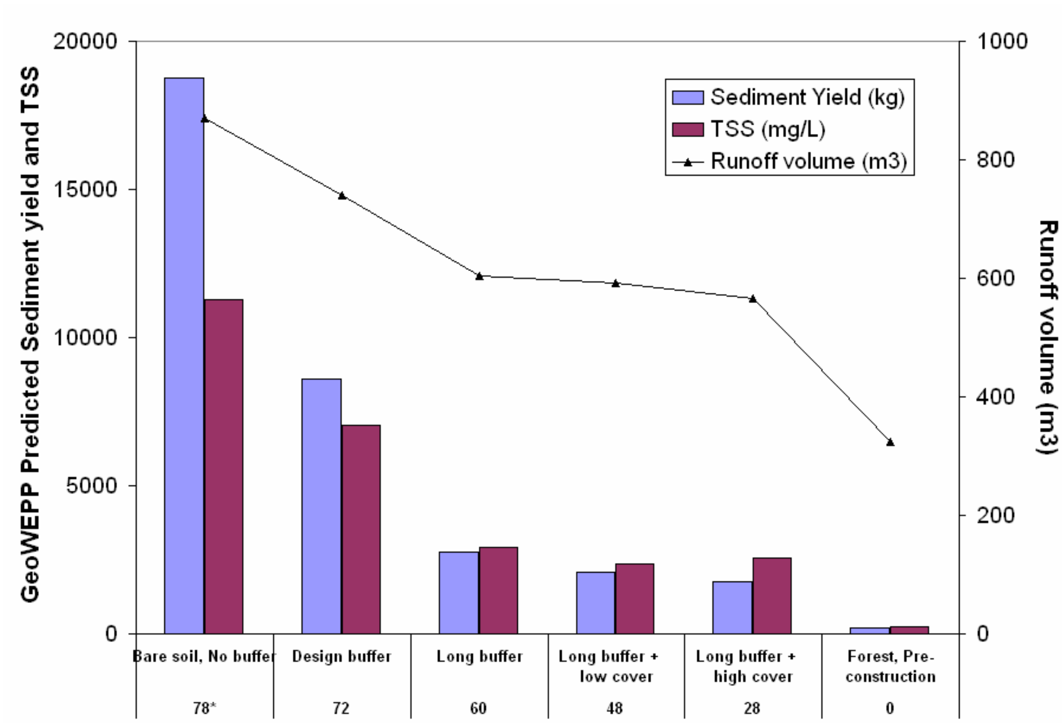


Figure 3-12. Predicted average TSS and sediment in outlet during proposed construction. *Percent of exposed surface on Watershed C for each landcover scenario.

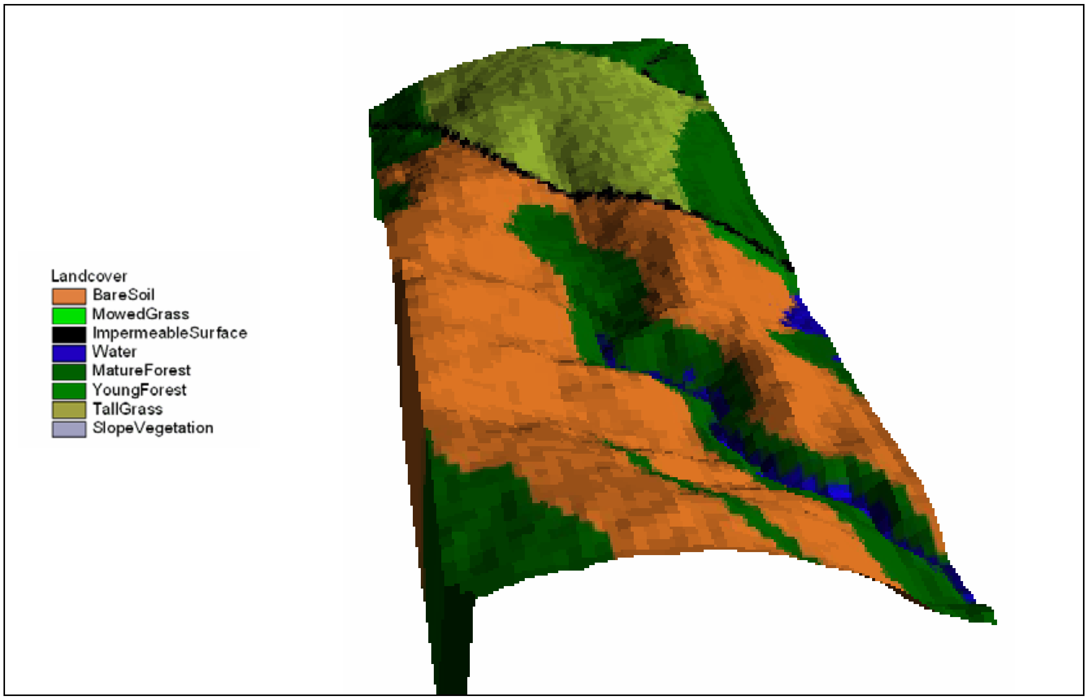


Figure 3-13. Landcover input map for GeoWEPP, simulating a forested buffer extending the length of the stream on Watershed C during construction.

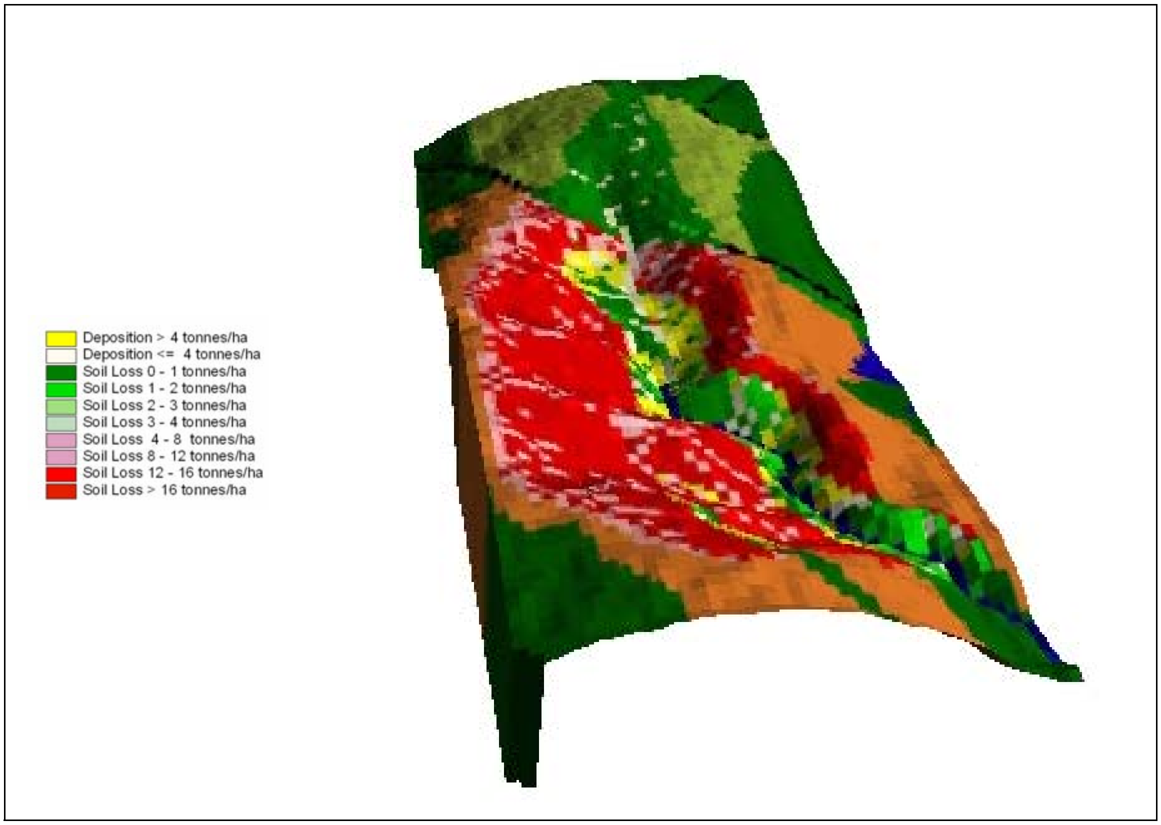


Figure 3-14. GeoWEPP predicted soil loss map, simulating a forested buffer extending the length of the stream on Watershed C during construction.

GeoWEPP predicted that adding landcover to erosive areas on this site provided little benefit to reducing sediment yield and TSS (Figure 3-12), which was surprising, as 20 % and 53 % of the previously exposed soil was covered with forest for the low and high cover scenarios, respectively. This finding may suggest a problem within the GeoWEPP model. It appears in Figure 3-12 that sediment yield is controlled by runoff volume, and because runoff volume does not seem to be effected by the addition of cover on erosive areas, then sediment yield also remains unaffected. In Figure 3-15, Figure 3-16, Figure 3-17, and Figure 3-18, there appears to be either deposition or soil loss less than 1 tonne ha^{-1} in the areas of remaining forest, which would be expected, as the increased roughness from bare soil to forest would reduce runoff and increase deposition.

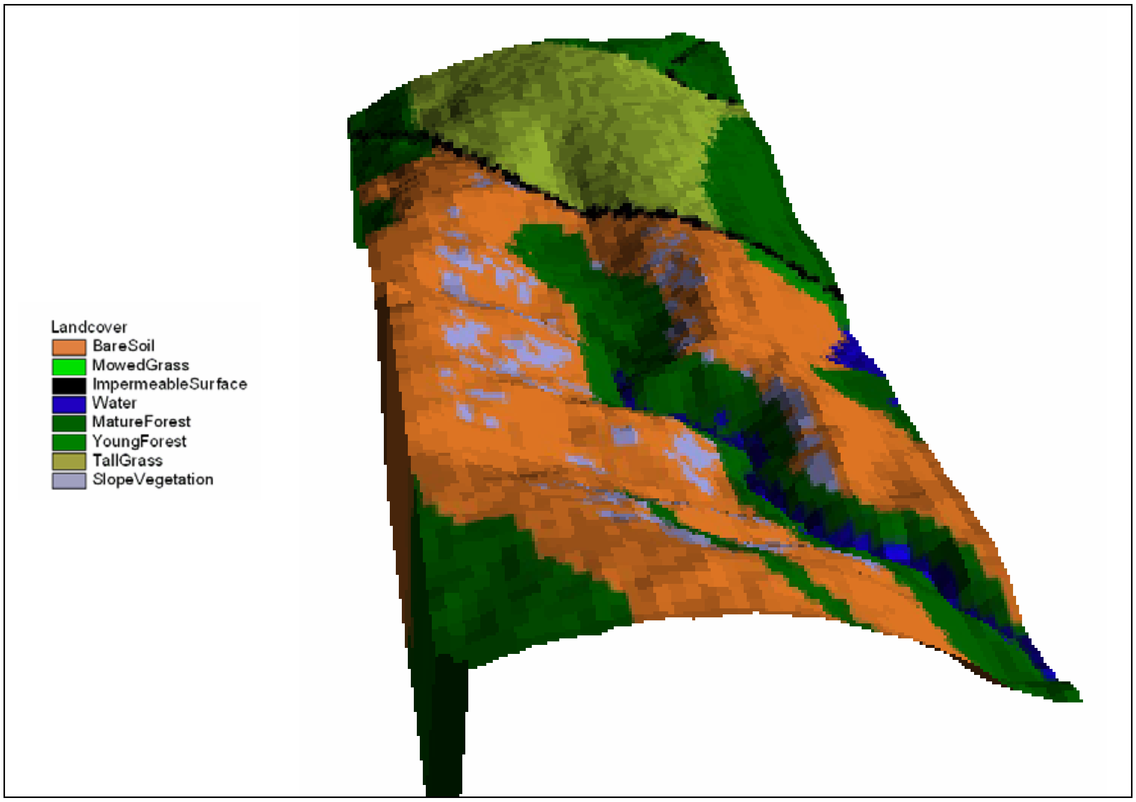


Figure 3-15. Landcover input map for GeoWEPP, simulating a forested buffer extending the length of the stream along with forest remaining on moderately erosive areas on Watershed C during construction.

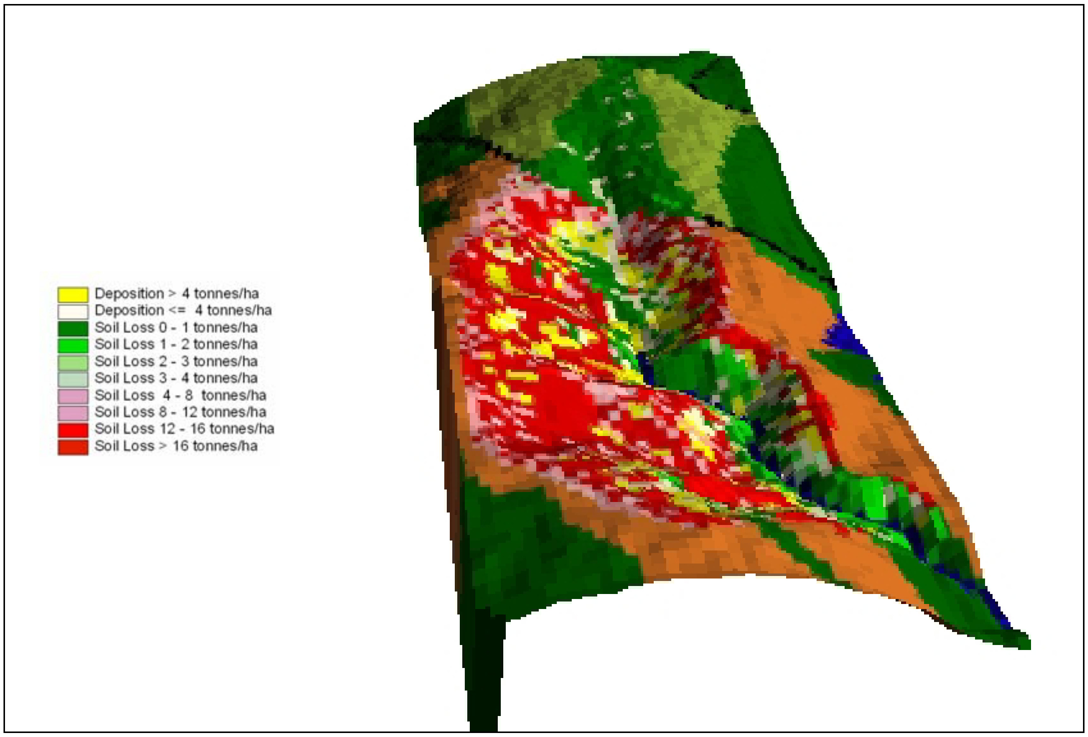


Figure 3-16. GeoWEPP predicted soil loss map, simulating a forested buffer extending the length of the stream along with forest remaining on moderately erosive areas on Watershed C during construction.

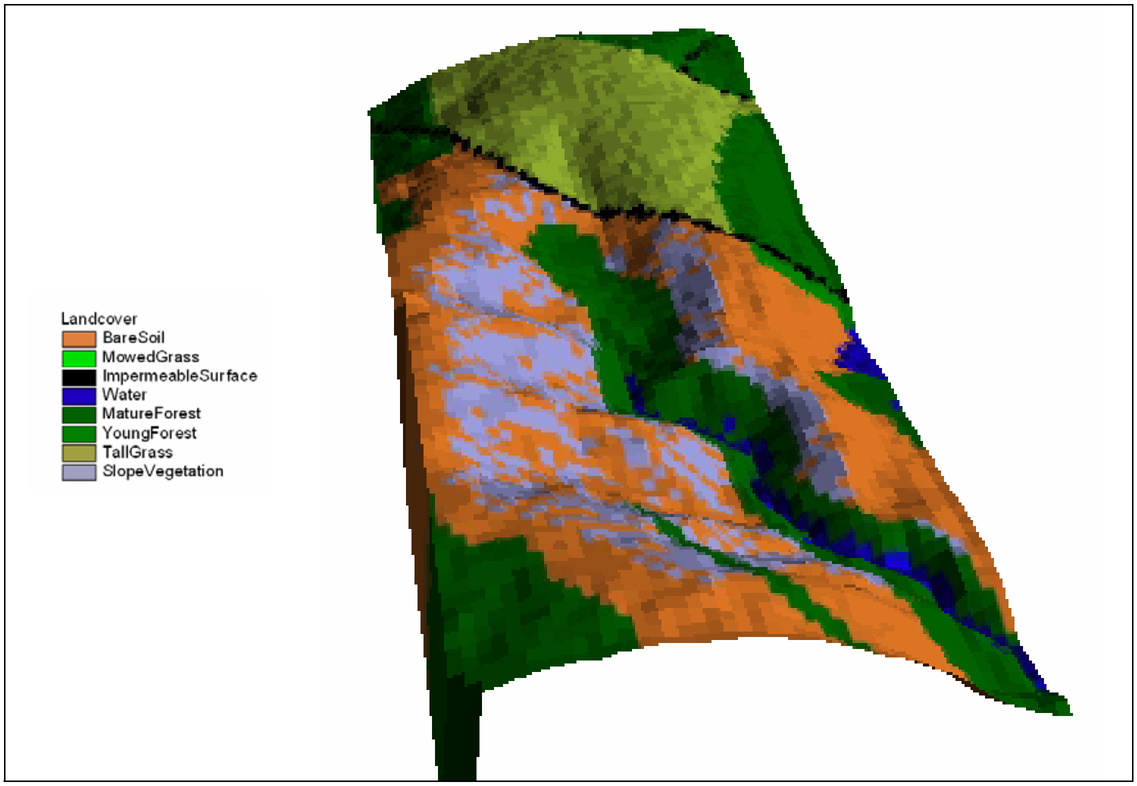


Figure 3-17. Landcover input map for GeoWEPP, simulating a forested buffer extending the length of the stream along with forest remaining on highly erosive areas on Watershed C during construction.

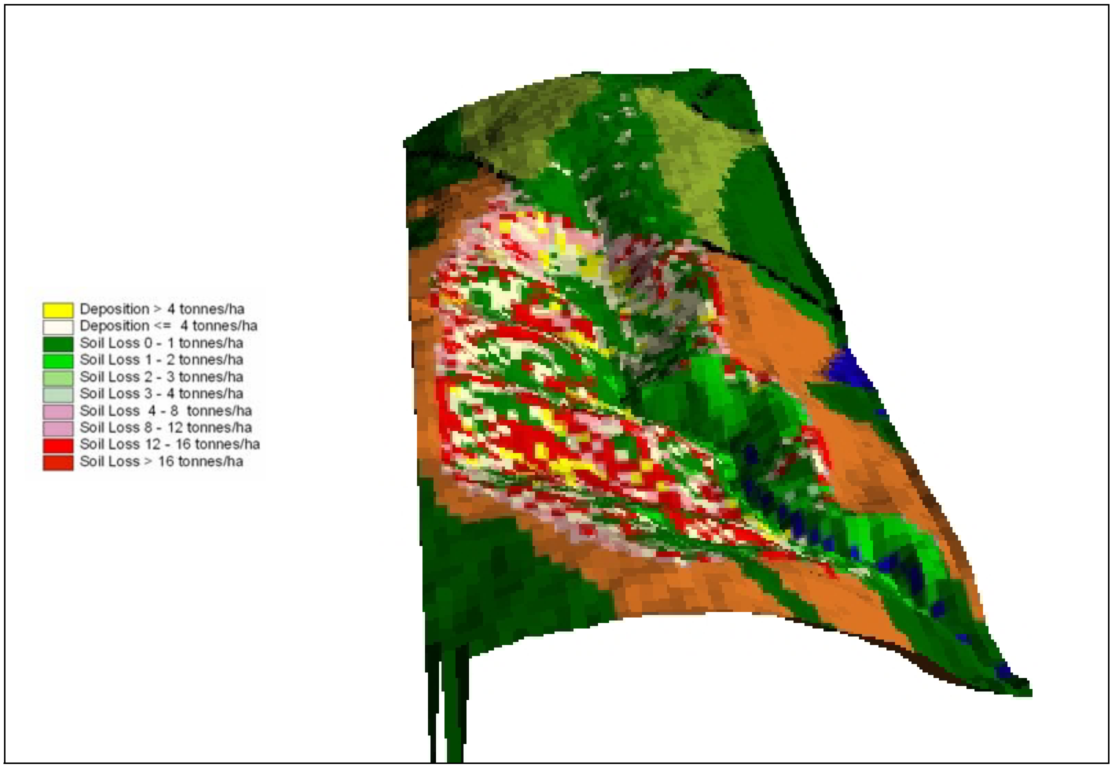


Figure 3-18. GeoWEPP predicted soil loss map, simulating a forested buffer extending the length of the stream along with forest remaining on highly erosive areas on Watershed C during construction.

Watershed C was modeled under the existing forested conditions to both evaluate predicted runoff and sediment under pre-construction conditions and to compare to previously measured runoff and sediment data from that watershed (Figure 3-19). Average TSS was predicted to be 235.8 mg L^{-1} (556 NTUs), while the TSS measured in runoff from Watershed C over 5 storm events averaged at 25.1 mg L^{-1} (134 NTUs), suggesting that GeoWEPP is overpredicting sediment concentration in the runoff. This finding is supported by data generated in Chapter 2, which showed an overestimation of sediment yield on both Watersheds A and C.

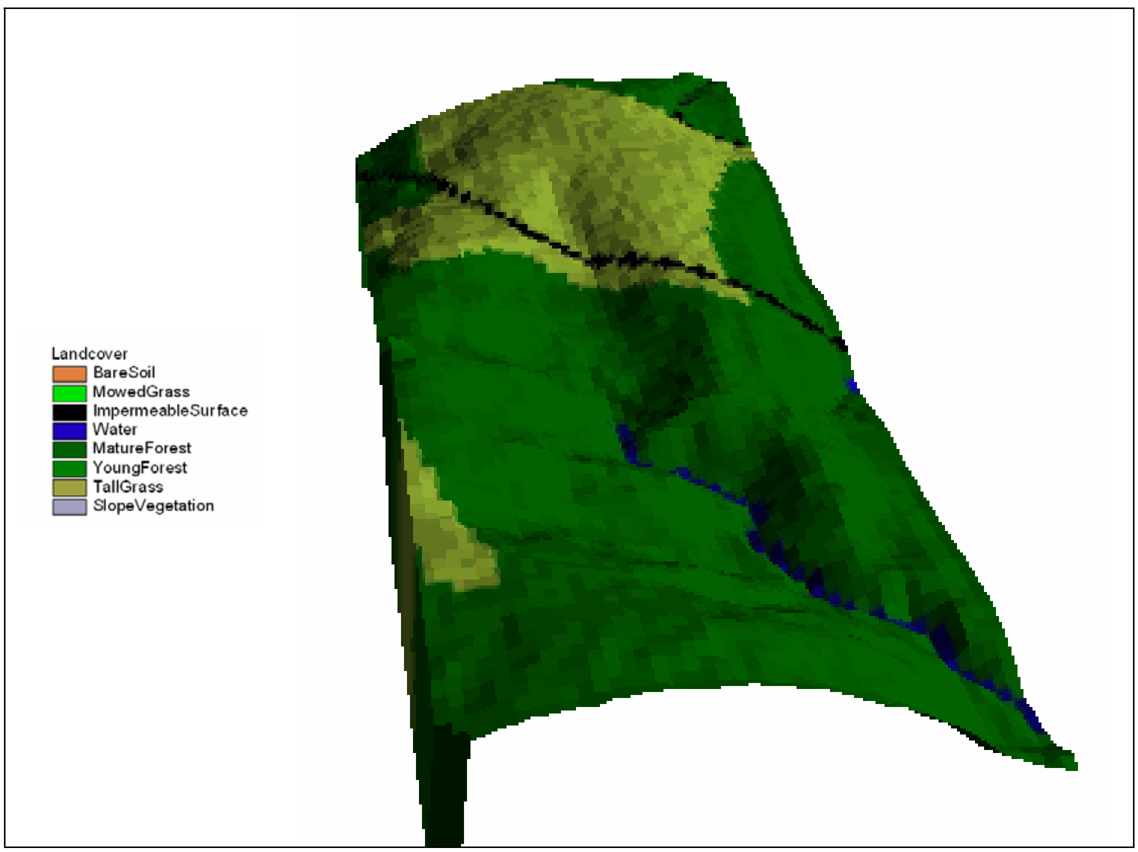


Figure 3-19. Landcover input map for GeoWEPP, simulating a forested cover on Watershed C before construction.

Soil loss was less than 1 tonne ha^{-1} on shallow slopes in forested areas, and between 1 and 2 tonne ha^{-1} on steeper slopes and some areas of tall grass (Figure 3-20). These patterns most likely occurred due to higher runoff velocities on steeper slopes and lower values for friction factor and interrill cover for tall grass. It should be mentioned that there is not yet an effective method developed for validating the spatial distribution of erosion on a watershed, which is why we must use logic and field observations to determine the validity of GeoWEPP soil loss output maps.

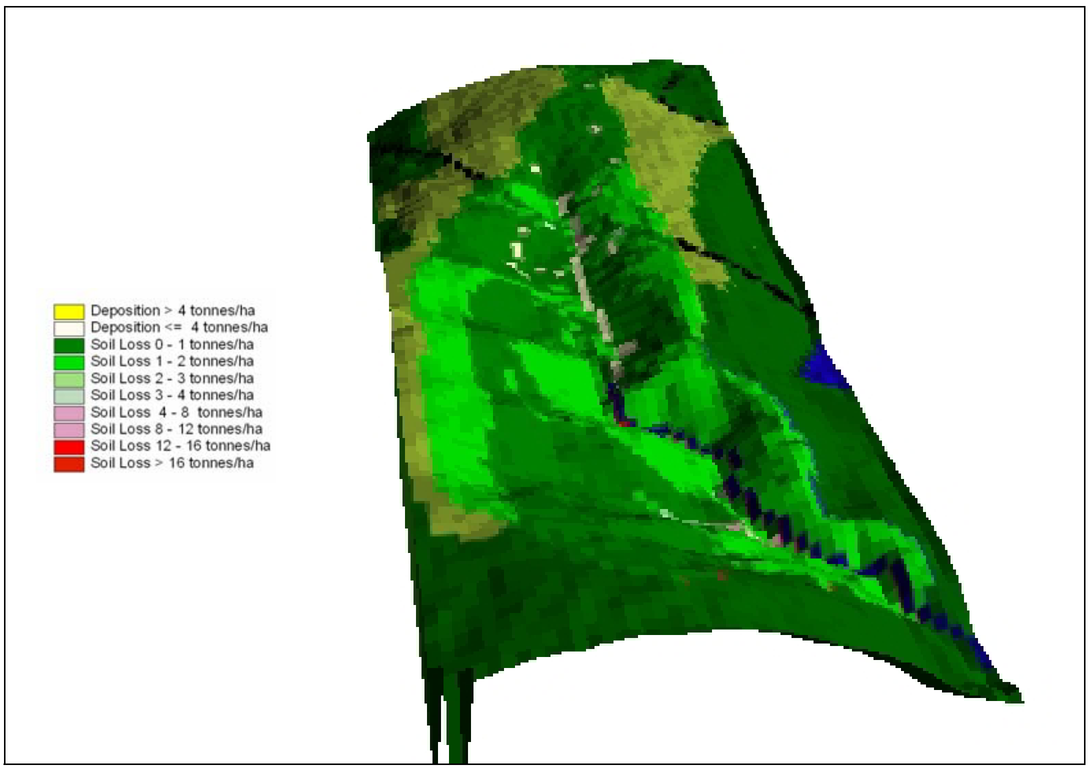


Figure 3-20. GeoWEPP predicted soil loss map, simulating a forested cover on Watershed C before construction.

CONCLUSION

WEPP and GeoWEPP models were applied to determine the efficiency of planned controls on construction sites and to create BMP scenarios to meet North Carolina water quality standards. WEPP estimated trapping efficiencies within NC standards of 70 % trapping efficiency for particle sizes greater than 0.04 mm. WEPP predicted that the runoff turbidity from the second sediment trap at the site outlet would be equal to or less than NC turbidity requirements of 50 Nephlometric Turbidity Units for 11 % of storm events. The GeoWEPP model predicted that planned riparian buffers on Watershed C were not able to meet the turbidity standard for any of the modeled storm events, and would need to be combined with other BMPs to decrease the turbidity.

Turbidity standards were met on watershed A by removing the outlet from the second sediment trap and increasing the trap area 6-fold. Replacing rock check dams with standing pools with culvert outlets greatly reduced TSS concentrations, although the average turbidity level of 550 NTUs still exceeded standards. Extending the design buffer decreased TSS concentration predicted with the design buffer by 57 %, while only increasing vegetation space on the construction site from 13 % to 22 %. Maintaining forested areas on highly erosive areas surprisingly had little impact on runoff volume or sediment yield, which may suggest a potential flaw within the GeoWEPP model.

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APPENDIX

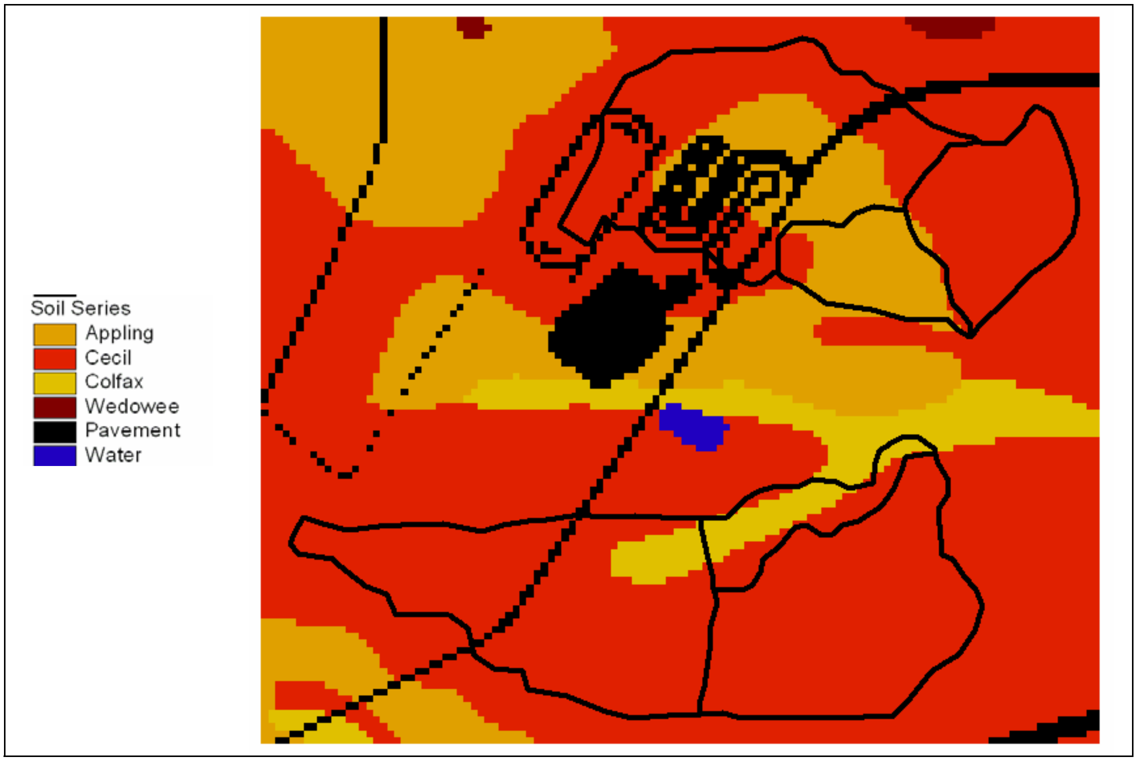

Figure A3-1. Soil grid map at 7 m resolution for watersheds Centennial A (above) and Centennial C (below). Watersheds are divided into three hillslopes by GeoWEPP.

Table A3-1. WEPP watershed characteristics for Centennial watershed.

	Left hillslope	Top hillslope	Right hillslope	Channel
Soil	Appling subsoil	Cecil subsoil	Cecil	Cecil subsoil
Landcover	Cutslope	Cutslope	Forest	Cutslope
% Slope	4	10	2	8
Length (m)	94.0	63.4	53.3	72.1
Width (m)	68.7	100.0	68.7	N/A

Table A3-2. Rainfall measurements from the RDU airport weather station near Raleigh, NC from 1998 to 1999.

Date	Rain (mm)
1/8/98	18.8
1/15/98	53.6
1/18/98	24.9
1/22/98	29.7
1/27/98	47.2
2/3/98	23.4
2/16/98	58.7
2/22/98	11.7
3/8/98	60.5
3/17/98	26.9
3/18/98	98.8
4/4/98	11.1
4/9/98	22.4
5/7/98	21.6
5/11/98	29.0
5/23/98	17.0
6/3/98	20.1
6/15/98	26.7
7/4/98	38.9
7/27/98	20.3
7/30/98	15.7
8/9/98	39.9
8/10/98	11.2
8/16/98	41.2
9/3/98	61.7
9/8/98	12.2
10/4/98	15.2
10/8/98	40.9
11/3/98	24.4
11/4/98	10.9
11/14/98	9.4
11/16/98	12.9
11/26/98	5.6
12/13/98	21.6
12/16/98	17.3
12/24/98	33.0
1/2/99	45.0
1/15/99	10.7
1/18/99	16.0
1/23/99	52.3
2/1/99	14.2
2/17/99	14.2
2/19/99	10.9
3/14/99	40.9
3/21/99	27.9
4/1/99	21.6
4/30/99	42.2
7/13/99	36.1
8/14/99	34.8
8/26/99	21.6
9/4/99	168.2
9/15/99	123.4
9/22/99	15.7
9/27/99	43.7
9/28/99	33.0
9/30/99	19.6
10/17/99	34.8
10/20/99	12.7

Date	Rain (mm)
11/2/99	8.1
11/26/99	18.3
12/13/99	29.7

Table A3-1. Complete list of WEPP landcover input parameters for watersheds A & C on North Carolina State University's Centennial Campus in Raleigh, North Carolina.

Plant Growth and Harvest Parameters	Cut slope	Tall Prairie Grass	Disturbed/Forest	20 yr Forest
Biomass energy ratio (kg MJ^{-1})	2	13	150	150
Growing degree days to emergence (ºC day)	30	5	5	5
Growing degree days for growing season (ºC day)	0	0	0	0
In-row plant spacing (cm)	499.9	10	200	200
Plant stem diameter at maturity (cm)	0.1	1	25	25
Height of post-harvest standing residue; cutting height (cm)	1	10	2000	2000
Harvest index (dry crop yield/total above ground dry biomass) (%)	42	42	42	42
Temperature and Radiation Parameters				
Base daily air temperature (ºC)	2	2	2	2
Optimal temperature for plant growth (ºC)	12	20	20	20
Maximum temperature that stops the growth of a perennial crop (ºC)	32	40	40	40
Critical freezing temperature for a perennial crop (ºC)	-40	0	0	0
Radiation extinction coefficient	0.01	0.9	0.9	0.9
Canopy, LAI and Root Parameters				
Canopy cover coefficient	14	14	14	14

Plant Growth and Harvest Parameters	Cut slope	Tall Prairie Grass	Disturbed/Forest	20 yr Forest
Parameter value for canopy height equation	23	3	3	3
Maximum canopy height (cm)	15	60	500	500
Maximum leaf area index	1	1	6	6
Maximum root depth (cm)	10	30	200	200
Root to shoot ratio (% root growth / % above ground growth)	33	33	33	33
Maximum root mass for a perennial crop (kg/m^2)	0.001	0.15	0.5	0.5
Senescence Parameters				
Percent of growing season when leaf area index starts to decline	85	25	25	25
Period over which senescence occurs (days)	14	40	300	300
Percent canopy remaining after senescence	0.1	30	50	50
Percent of biomass remaining after senescence	1	25	70	70
Residue parameters				
Parameter for flat residue cover equation (m^2 kg^{-1})	5	5	5	5
Standing to flat residue adjustment factor (wind, snow, etc.) (%)	99	99	99	99
Decomposition constant to calculate mass change of above-ground biomass	0.0074	0.0068	0.006	0.006
Decomposition constant to	0.0074	0.0068	0.006	0.006

Plant Growth and Harvest Parameters	Cut slope	Tall Prairie Grass	Disturbed/Forest	20 yr Forest
calculate mass change of root biomass				
Use fragile or non-fragile mfo values	Non-fragile	Non-fragile	Non-fragile	Non-fragile
Other Parameters				
Plant specific drought tolerance (% of soil porosity)	10	10	10	10
Critical live biomass value below which grazing is not allowed (kg m^{-2})	0	0	0	0
Maximum Darcy Weisbach friction factor for living plant	1	11	17	17
Harvest Units	WeppWillSet	WeppWillSet	WeppWillSet	WeppWillSet
Optimal yield under no stress conditions (kg m^{-2})	0	0	0	0
Bulk density after tillage (g cm^{-3})	1.0	1.1	1.1	1.1
Initial canopy cover (%)	0	30	90	90
Days since last tillage	0	1000	1000	1000
Days since last harvest	0	900	100	100
Initial frost depth (cm)	0	0	0	0
Initial interrill cover (%)	0	80	100	100
Initial residue cropping system	Fallow	Perennial	Perennial	Perennial
Cumulative rainfall since last tillage (mm)	420.1	1000	1000	1000
Initial ridge height after last tillage (cm)	0.6	10	10	10
Initial rill cover (%)	0	80	100	100
Initial roughness after last tillage (cm)	0.6	10	10	10
Rill spacing (cm)	400.1	0	0	0
Rill width type	Temporary	Temporary	Temporary	Temporary

Plant Growth and Harvest Parameters	Cut slope	Tall Prairie Grass	Disturbed/Forest	20 yr Forest
Initial snow depth (cm)	0	0	0	0
Initial depth of thaw (cm)	0	0	0	0
Depth of secondary tillage layer (cm)	2.54	10	10	10
Depth of primary tillage layer (cm)	2.54	20	20	20
Initial rill width (cm)	0	0	0	0
Initial total dead root mass (kg m^{-2})	0	0.1	0.5	0.5
Initial total submerged residue mass (kg m^{-2})	0	0.1	0.5	0.5

Script A3-1. Newlandcover.aml avenue script for converting raster cells to landcover using soil loss categories; for this example, we selecteed soil loss categories greater or equal to 6 for designating highly erosive areas on the landscape. This script was developed by Robert Austin at NC State University.

```
&args landcov model_cov out_cov
&if [null %out_cov%] &then
  &return &inform Usage new_landcov.aml <landcov> <model_cov> <out_cov>

&TYPE
&TYPE Starting creation of new landcover....
&TYPE

grid

/*** Set the size of the analysis environment to the largest extent ***/
setwindow %landcov%
setcell %landcov%
mapextent %landcov%

/*** turn the floating point grid into an integer grid ***/
intgrd = int( %model_cov% )

/*** create a grid with just the 0=not included and 1=included values ***/
selgrid = test( intgrd, 'value <= 10 AND value >= 6' )

/*** fill the nodata values with 0 ***/
bingridfill = con (isnull (selgrid), 0, selgrid)

/*** if the boolean grid contains a 1 set it to new class = 10, otherwise keep it the same
***/
%out_cov% = con ( bingridfill == 1, 10, %landcov% )

kill intgrd all
kill selgrid all
kill bingridfill all

&TYPE
&TYPE Finised creating %out_cov%....
&TYPE

quit
&return
```