WATERSHED MODELING AND UNCERTAINTY ANALYSIS FOR

THE NORTH FORK BROAD RIVER, GEORGIA, USA

by

PATRICIA J. HAYES

(Under the Direction of David Radcliffe)

ABSTRACT

Erosion and the resulting sediment are major issues facing the environment. High sediment loads can cause water quality problems, such as damaging biota habitat and recreational use. Georgia's North Fork Broad River has been listed as an impaired stream segment for sediment. Our objective was to use Water Characterization System's (WCS) Sediment Tool to model the sediment movement in the North Fork. The model uses USLE to determine erosion and four delivery ratios (DR) to determine sediment yield. Another objective was to determine model sensitivity and uncertainty. We have implemented WCS in an Excel spreadsheet coupled with @Risk software, a commercial plug-in to Excel. Our modeling efforts show that the North Fork does have a sediment problem. Sediment is greatly affected by DR. Land use changes can also affect the sediment yield. Using WCS, there is large uncertainty in sediment delivery prediction, but much less uncertainty in erosion prediction.

INDEX WORDS: Erosion Modeling, Model Uncertainty Analysis, Sediment Modeling, Sediment Yield, TMDL, Watershed Modeling

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DEDICATION

I would like to dedicate this thesis to my mom, Billie Patrick Hayes, and my dad, Tim Hayes. They taught me to always follow my dreams, to find the positive in everything and most of all to not worry about things I cannot control. Thank you for your patience, guidance and love.

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

Chapter 1

Introduction

Erosion is a major issue facing the environment today. The resulting sediment can cause severe problems for streams. Sediment is defined as "particles derived from rocks or biological materials that have been transported by fluid or solid material suspended in or settled from water" (Faye et al., 1980). High sediment loads cause critical water quality problems within the stream, such as damaging the biota habitat, aiding in the transport of carrying other pollutants, and filling ponds, lakes and reservoirs. Measuring stream sediment and setting a general standard for a healthy stream can be a complex task. Not only must the current stream health and sediment load be considered, but also the stream history as well as future growth and change. Many U.S. waters do not meet water quality standards set forth by the EPA; 17% of these streams have excessive sediment load (Radcliffe, 2002).

In 1979, the total U.S. sediment yield was estimated at about 3.6 billion metric tons/year (Robinson, 1979). Given that stream sediment is a major issue across the nation as well as the various other stream pollutant problems, the federal government included the Total Maximum Daily Load (TMDL) program in the Clean Water Act. This program is a watershed-based plan for protecting and improving water quality in streams that no longer meet their designated use. While TMDL programs provide guidelines and directions, there is no set amount for the total maximum daily load of sediment allowed in a stream, usually due to limited water quality data. Gathering monitored data for a stream is the best possible solution to setting a sediment load. However, one cannot assume every stream across the United States can be monitored in order to determine its sediment load; this would be time consuming and costly.

Scientists must find a way to determine the erosion yield, sediment yield and sediment load for a particular stream type and use these data for similar streams. Collecting measured data for a limited number of stream types across the nation, and then using watershed-modeling programs coupled with geographical information systems (GIS) to analyze and interpret that data, will allow sediment loads to be set more quickly and economically. The type of land use and terrain can help determine which model will be most appropriate for a given region.

The objective of this study was to use one such watershed model, the Water Characterization System's (WCS) Sediment Tool (Tetra Tech, Pasadena, CA), to determine sediment load in the North Fork Broad River in the Piedmont Region of Georgia. The sediment load was determined by modeling erosion and sedimentation processes in the watershed. @Risk software (Palisade Corporation, Newfield, NY) was used to quantify the model uncertainty.

Chapter 2

Literature Review

Total Maximum Daily Load (TMDL)

The 1972 Clean Water Act required states, territories, and authorized tribes to develop impaired waters lists. These impaired waters do not meet water quality standards set by the state, territory, or authorized tribe. The latest information from EPA states that 40% of the assessed waters still do not meet the published water quality standards (USEPA, 2002b). In order to improve the water quality in the nation, EPA is now enforcing the Total Maximum Daily Load (TMDL) provisions in the 1972 Clean Water Act creation (USEPA, 2002b).

A TMDL is commonly referred to in two separate but integrated ways. One is a "calculation of the maximum amount of pollutant that a water body can receive and still meet water quality standards" (USEPA, 2002a). This calculation is the sum of all loads of a single pollutant entering the body of water from all point and nonpoint sources. This number must account for seasonal variations and include a margin of safety. Allowing for these possible deviations enables the use of the stream to be maintained at its given classification, such as scenic or recreational. It is important to include current wasteload allocations from point sources, load allocations from nonpoint sources, and any possible natural or background conditions in the analysis (USEPA, 2002b). Including these in the calculation and assessment will aid in determining possible ways to improve water quality as well as how quickly the improvement can and will actually happen. These TMDLs can be created for any number of pollutants or impairments, including sediment, nutrients, and chemical toxins. The inherent problem for creating a TMDL for a specific impaired stream is the lack of data. Water quality monitoring and data collection are expensive and time consuming, and not all streams will immediately have sufficient data to create a reliable target load. Therefore a plan to improve the quality of the water body is difficult to develop.

The second way the term TMDL is commonly used is actually a TMDL Implementation Plan or TMDL program. This program includes identifying impaired waters, establishing a TMDL (calculating a target load), developing ways to reduce the impairment, and assessing all aspects of the implementation (Conservation Technology Information Center, 2002). It is up to the local jurisdictions to create these TMDL programs and to monitor and improve the water quality of their water bodies. However, the EPA must approve each impaired list and TMDL. This process can take anywhere from two to five years, with each cycle period allowing new monitoring data and water quality improvement to remove a water body from the impaired list. The TMDL program requires each state, territory, and authorized tribe to create a priority list based on the severity of pollution and develop a TMDL (calculation) within two years. A TMDL, utilizing all obtainable data, must be created for each impairment within a water body (USEPA, 2002b).

The EPA has set goals for the TMDL program. These goals include improving monitoring and assessment programs, increasing stakeholder participation, strengthening existing watershed planning processes to aid in TMDL implementation, and enhancing opportunities for innovation. These goals should aid each state, territory, and authorized tribe in improving their water quality standards and monitoring (USEPA, 2002c). Determining the TMDL and starting the TMDL process are vital to the health and improvement of U.S. waters.

Erosion and Sediment

Erosion is "the wearing away of the land surface by detachment and movement of soil and rock fragments through the action of moving water and other geological agents" (Cline et al., 1981). Erosion is important in terms of streams because the amount of erosion occurring highly impacts the amount of sediment being transported to a stream. Erosion has always been an important concern in agriculture due to losses in productivity; now, due to impacts on stream and water quality, it has become increasingly important to be able to measure and predict erosion and stream sediment yield to enable better understanding of how construction, urbanization, agriculture, silviculture and other land-uses affect water quality.

Sediment is defined as "particles derived from rocks or biological materials that have been transported by fluid or solid material suspended in or settled from water" (Faye et al., 1980). In other words, sediment is erosion that has reached a stream. Sediment can be composed of a multitude of materials, including aggregates, organic materials, and associated chemicals (Haan et al., 1994). The materials can be derived from cultivated or grass lands, forests, construction sites, roadways, urban areas, stream channels or active gullies (Robinson, 1979). Sediment yield is not only affected by erosion and the factors that influence it, but also by the ability of the field, stream or watershed to transport those eroded particles. Another challenging issue with this type of nonpoint source pollution is that the pollution may take weeks or months to enter the stream (Birkeland, 2001). Nonpoint source pollution, a diffuse type of pollution, is the leading source of water quality problems across the nation (FitzHugh and Mackay, 2001).

Once sediment reaches a stream, it affects the health of the stream and is a key issue in Georgia waters. To control sediment issues in a stream, three issues must be addressed: quantifying stream sediment, predicting future erosion and sediment sources in the watershed, and setting regulatory limits. When TMDLs are created, time is fundamental in determining how quickly the stream can be termed healthy, and therefore be de-listed. First, quantifying stream sediment includes not only suspended but also bedload sediment (discussed in next section). Second, being able to predict future erosion and sediment in the watershed will allow TMDL program organizers the opportunity to plan for future growth and changes within the watershed and include that in the regulatory limits.

Setting regulatory limits and target loads for TMDLs is also important to addressing sediment pollution problems. Currently the federal government has not set limits on suspended sediment or bedload. In Georgia, streams with sediment TMDLs are typically listed due to low scores on biotic indices. This impairment is linked to high sediment load; however, sediment measurements were usually not made (Radcliffe, 2002). There is a narrative water quality standard for sediment: "maintain biological integrity of the waters of the State" (Georgia Department of Natural Resources

Environmental Protection Division, 2000). However, once a stream is listed, the TMDL program must include an actual target sediment load, determined on the basis of references streams, monitoring, and possibly modeling.

Sediment Measurements

Quantifying stream sediment involves measuring two fractions of sediment, suspended particles and bedload. Assessing the suspended fraction of sediment is complicated, as there are many methods of determination. Suspended sediment is the particulate matter suspended within the water column. This suspended sediment concentration varies with depth and time (Haan, 1994). Flow also affects the suspended sediment concentration, as sections of the stream will have greater velocity, therefore greater carrying capacity. This variability makes it difficult to determine where to sample in the water column. There are three common ways to measure suspended sediment. The U.S. Geological Survey (USGS) typically uses suspended sediment concentration (SSC). The SSC measurement analyzes all sediment and the mass of the entire water-sediment sample (Gray et al., 2000). There are three laboratory methods the USGS uses to determine SSC. One method uses evaporation and a dissolved-solids correction is needed if the dissolved-solids concentration exceeds 10% of the total SSC. The second method uses filtration and is used on samples with concentrations of sand-size material less than 10,000 mg/L. No dissolved-solids correction is required. The final method is wet-sieving filtration and is used if one wants to quantify the percentage of material larger than sand-size particles. A dissolved-solids correction may be required depending on the fine fraction analysis. Each of these methods requires drying at 103°C ±2°C and then weighing the sediment.

Another common method to determine suspended sediment is total suspended solids (TSS), similar to the SSC method except an aliquot is used instead of a full water sample (Gray et al., 2000). This method uses a predetermined volume of the original sample that is mixed with a magnetic stirrer. The aliquot (usually 0.1 L) is withdrawn with a pipette and then passed through a filter, which can range from 11 to 125 mm. The filter and sediment are then dried at 103°C ±2°C and weighed. A correction for dissolved-solids is not needed. Problems with TSS arise when a significant amount of the material is sand-size and the sub-sample (aliquot) rarely yields the same value as SSC due to settling of particles. Also, the pipette can collect at different depths in the sample and therefore sample different amounts, giving a variable TSS value.

Finally, a third method is the measurement of turbidity in Nephelometric Turbidity Units (NTU) (USGS, 2000). This method measures the "cloudiness" of water, rather than the actual weight of dried sediment from the sample. The NTU is the "optical measurement of scattered light resulting from the interaction of incident light with particulate material in a liquid sample" (Sadar, 2002). These suspended solids can be silt, clay, algae, organic matter, or even microorganisms. The light that is scattered by this particulate matter then returns to the detector and a turbidity level is given. The more scattered light reaches the detector, the higher the turbidity of the sample.

Each method has its problems and further research is needed to determine which method is best for quantifying suspended sediment. For example, the TSS method was originally devised for wastewater and has not proven its reliability with natural-water samples (Gray et al., 2000). Also, the two final methods seem to underestimate sediment concentration in samples with high sand content due to the sand fraction settling more quickly (Radcliffe, 2002). Suspended sediment is highly variable across a stream section and therefore depth-integrated samples are commonly collected at various points across a stream (Faye et al., 1980).

Another issue for quantifying stream sediment is bedload. Bedload is the "sediment that moves by saltation (jumping), rolling, or sliding in the flow layer just above the bed" of the stream (Haan et al., 1994). The transport of bedload is related to the variability in stream velocity, not the average stream velocity. Streams have normal ebb and flow, shown in pools and rapids. Through the stream velocity changes, the amount of bedload that can be carried is directly related to the with the velocity of the stream. The faster parts of a stream can carry more bedload.

Bedload may be measured using a bedload sampler or a sediment trap, both labor-intensive methods (Radcliffe, 2002). The bedload sampler simply contains a porous bag, which collects sediment along the bed of the stream. The sediment trap method requires creating sediment traps in the stream and measuring the amount of sediment collected. Due to the natural flow changes of the stream, sediment and bedload fractions of the stream sediment load vary widely. Therefore, sampling must occur at all flow levels to determine the cycle of the stream sediment transport.

Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) is used to determine the average rate of soil erosion based on soil type, rainfall pattern, crop system, management practices, and topography (Wischmeier and Smith, 1978). This equation is designed to calculate only sheet and rill erosion; it does not predict erosion from gully, streambanks or streambeds. The USLE was developed using over 10,000 plot studies for basic runoff and soil loss data from agriculture experiment stations all over the U.S.

The USLE equation is defined from Wischmeier and Smith (1978) as

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

where

A is the soil loss per unit area. Units are from *K* and *R*. Typically, the units are tons per acre per year, but other units can be used.

R is the rainfall and runoff factor. For the Southeast Piedmont in Georgia, a typical R factor would be from 250 to 300. (time interval, usually year)

K is the soil erodibility factor. (tons/acre)

L[1] is the slope-length factor. (dimensionless)

S[1] is the slope-steepness factor. (dimensionless)

C is the cover and management factor. (ratio and dimensionless)

P is the support practice factor, deals with stripcropping, terracing and contouring. (ratio and dimensionless)

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[1] In the field, sometimes it is easier to consider these two factors (L and S) as a single factor, *LS*. It is typical to see these as one variable.

The *LS* factor accounts for much of the variation in erosion yield (Williams and Berndt, 1976). For a watershed such as the North Fork Broad River (fairly small in area), *R*, *K* and *P* may not have much variability. However, the cover and length-slope factors may create the most variability and therefore have the most effect on the total erosion yield. Wischmeier (1976) notes that for a complex watershed, the entire watershed should be broken down into sub-watersheds so the six factors can be better defined and allow for variability within the watershed. The sum of each of the sub-watershed USLE calculations would then be the total erosion estimation.

In Faye et al.'s (1980) study of the Upper Chattahoochee River Basin, *R* factors ranged from 270 to 340 (erosion potential of long-term, average annual rainfall) depending on the location of weather station (where periodic rainfall-data collection occurred). *K* factors were obtained from the Georgia State Soil and Water Conservation Committee and ranged from 0.18 to 0.34 (tons/acre/year). *LS* factors ranged from 0.11 to 14.30. *C* factors were 0.00 for industrial and transportation, 0.0005 for undisturbed forest, 0.01 for confined feeding operations and residential, 0.05 for other urban, 0.07 for pasture, 0.30 for orchards, 0.34 for cropped woodland, 0.50 for transitional areas, and 0.52 for row crop. Finally, the *P* values were 1.0 for land uses other than cropland and ranged from 0.4 to 0.9 for cropland, based on slope.

The USLE can be greatly enhanced through geographic information systems (GIS), enabling the user to get greater resolution of data. "GIS is designed to store, retrieve, manipulate, and display large volumes of spatial data" (Yitayew et al., 1999). USGS quads, Digital Elevation Maps (DEM), weather data, soil data and other information sources can be used to determine the USLE factors. One can also use GIS to enable quicker determination of erosion rates and be able to compare differences within a year or even a season. In GIS, locating the closest weather station to the study site can be done easily to find the *R* factor. Variations in the GIS soil layer can be used to determine the soil erodibility factor, *K*. If the watershed is in a large enough area, the soil may change and therefore the *K* factor may change. However, typical soil layer data for GIS is not detailed enough to show these changes over a watershed area. The *C* factor can greatly be expanded through GIS. Land use data can allow the modeler to determine *C* factors for each land use and easily apply these to sections or grid cells within the watershed. The *P* factor is very similar to the *C* factor in terms of GIS accessibility.

The *K* factor can be derived from two different commonly available GIS layers. The first is the State Soil Geographic database (STATSGO). This database is "produced by generalizing the detailed soil survey data" (NRCS, 2004b). STATSGO is mapped at a 1:250,000 scale and is to be used for broad-based planning. The second GIS layer is the Soil Survey Geographic Database (SSURGO). This level of GIS soil mapping is the most detailed at a range from 1:12,000 to 1:63,360 (NRCS, 2004a). SSURGO is to be used by landowners, townships, and county natural resource planning. SSURGO is much more detailed than STATSGO, however it is not always available.

The most dynamic parameter to determine using GIS is the *LS* factor. Yitayew et al. (1999) discuss four methods for calculating the *LS* factor. The first method used a photogrammetric corrected orthophoto with 0.305 m elevation contour intervals. The watershed was subdivided into 38 units and slope steepness and length were measured by digitizing in GIS. The second method used USGS 7.5-min quads with 7.6 m elevation contour intervals. Slope steepness and length were determined based on the contours and average flow length of each area. The third calculation used a 15 m x 15 m DEM and derived 200 grids covering the watershed. This method computed length based on existing slope steepness. The fourth method used the same 15 m x 15 m DEM and modeled overland flow. The results showed a variance in *LS* based on different data and different methods to calculate the *LS*. The results were as follows:

Method	*LS* Factor
0.305 m	1.95
7.5-min quad	1.82
15 m DEM (1)	1.22
15 m DEM (overland flow)	2.19

Sediment and Erosion Amounts

According to Robinson (1979), total sediment yield is generally reported as 3.6 billion metric tons/year for the entire U.S. The biggest contributors were agriculture (40%), stream bank erosion (26%), pasture and rangeland (12%) and forestlands (7%). The remaining 15% was from other federal lands, urban, roads, mining and other.

The North Fork of the Broad River is located in the Southern Piedmont region. Sheet erosion is the biggest source of erosion in the southeastern U.S. (Roehl, 1962). Erosion in Southern Piedmont is estimated to be 66 to 100% sheet erosion and 0 to

34% channel or gully erosion. Therefore, the USLE can predict the major component of erosion in the Southern Piedmont. The Upper Chattahoochee River Basin is also in the Southern Piedmont and includes the Chestatee River near Dahlonega (Faye et al., 1980). For the Chestatee basin a 97,930-acre drainage area (39,631 ha), the average annual sheet erosion (estimated from the USLE) was 437,260,760 kg/year (11,033 kg/ha/yr). The calculated suspended sediment load for the Chestatee River was 47,445,514 kg/year (1,198 kg/ha/yr). For a much smaller watershed, the Nancy Creek at Atlanta that has a 22,272-acre drainage area (9,013 ha), the average annual sheet erosion calculated from the USLE was 27,668,990 kg/year (3,081 kg/ha/yr). The calculated suspended sediment load at Nancy Creek was 17,962,164 kg/year (1,994 kg/ha/yr). The calculated suspended sediment yields ranged from 301 to 3,005 kg/ha/yr, while the calculated average annual erosion yield ranged from 3,012 to 23,937 kg/ha/yr per sub-watershed.

Van Lear, et al. (1985) researched sediment concentrations in the Piedmont of South Carolina. The study looked at burned and harvested pine watersheds. For the control site, during a calibration period, the sediment export averaged 25.5 kg/ha/yr. The harvest site averaged 57.7 kg/ha/yr during the same period. The control site, during calibration, had an average suspended sediment concentration (SSC) of 24 mg/L and the harvest site had an average of 37 mg/L.

Simmons (1976) researched sediment in streams of the Eastern Piedmont and Western Coastal Plain in North Carolina. Over four-fifths of the study area was located in the Piedmont region. The average annual sediment yield, during the period of 1969-

73, ranged from 42 to 1,166 kg/ha/yr for different watersheds in the study area. On the low end of the spectrum, suspended sediment concentration ranged from 0 to 37 mg/L (equaled or exceeded 95% of the time). On the higher end, suspended sediment concentration ranged from 34 to 690 mg/L (equaled or exceeded 1% of the time).

Forest Erosion and Sediment

King (1993) states "roads are the major source of sediment and surface erosion on roads generally declines rapid overly time." Later in the same paper King states, "In forests, human activities (such as timber harvesting, site preparation, and road construction) and natural events (such as large infrequent rainstorms, rain-on-snow events, and wildfires) can result in accelerated erosion and increased levels of stream sedimentation". In undisturbed watersheds, over a 10-year period, annual sediment yields ranged from 10 to 80 kg/ha during low stream flow and from 350 to 500 kg/ha during high stream flow years.

Megahan and Kidd (1972) researched the effects of logging roads on sediment delivery rates in Idaho. Using an average sediment production on undisturbed watersheds of 0.25 kg/ha/day, they found that surface erosion from roads increased 220 times per unit area of road over a six-year period following road construction. It was noted that 84% of the total sediment for the six-year study was produced during the first year after construction and by the end of the second year, 93% of the total sediment was produced.

Bare and graveled roads in the southern Appalachians had an observed range of erosion from 11,209 to 152,436 kg/ha/yr (Elliot et al., 1999). In the Fernow National

Forest, West Virginia, bare and graveled roads had an observed range of erosion rate from 13,450 to 117,689 kg/ha/yr.

Reid and Dunne (1984) studied sediment production from forest road surfaces. They determined sediment yield per kilometer of road for various road types and use levels. The roads were 4 m wide and had an average gradient of 10%. For heavy use, 500,000 kg/yr/km of road was the average sediment yield. Temporary nonuse roads had a yield of 66,000 kg/yr/km of road, while moderate use produced 42,000 kg/yr/km of road. Light use generated only 3,800 kg/yr/km of road, paved roads generated 2,000 kg/yr/km of road and abandoned roads produced 510 kg/yr/km of road. During heavy traffic periods, roads in the study area yielded sediment at 7.5 times the rate of the same roads on days when not being used.

Delivery Ratios

While erosion is a key parameter to understand and determine, the actual sediment that reaches the stream is even more important, especially in terms of stream health and the environment. Accurately predicting sediment delivery from erosion events is important. A delivery ratio (*DR*) is a factor used to determine the fraction of sediment that reaches a stream. There are numerous factors that can influence the *DR* including erosion, land use, cover conditions, slope gradient, slope length, relief-length ratio, rainfall, channel density, watershed shape, and watershed size (area) (Maner, 1958; Ouyang and Bartholic, 1997; Robinson, 1979; Roehl, 1962; Truman, et al., 2001; and USDA, 1983).

There are two ways to develop a delivery ratio. One is based on direct measurements of erosion and sediment yield. The second involves predicting or modeling the *DR*, typically through the factors listed above. Delivery ratios typically are less than one because eroded soil can be deposited on land (Robinson, 1979). However, a *DR* can be more than one if the gross erosion calculation is used, such as USLE, and it does not include gully erosion, channel erosion, or resuspension of sediments in the watershed.

When actual data for erosion and stream sediment is available, calculation of *DR* is relatively simple. To determine the *DR*, one can divide the sediment yield by the gross erosion (Faye et al., 1980; Ouyang and Bartholic, 1997; and USDA, 1983). Using this method for *DR* and the USLE for erosion, Faye et al. (1980) calculated *DR*s for four streams in the Upper Chattahoochee River Basin. These *DR*s were 0.21 (Chattahoochee River), 0.15 (Chestatee River), 0.13 (Big Creek) and 0.89 (Peachtree Creek). The Peachtree Creek station's high DR may show that much of the sediment arises from the stream channel. This data compares well with Roehl's (1962) study in the southeast. Roehl's *DR* values ranged from 0.037 to 0.594. Robinson (1979) determined the effect of watershed size on *DR* and had a range of values for *DR* from 0.049 to 0.53.

If the data is available, one can also develop correlation equations to determine *DR*s from data and parameters of the watershed. Typically, watershed area is thought to be a useful parameter when determining *DR* (Ouyang and Bartholic, 1997; Robinson, 1979). *DR* decreases as area increases. It is one of the most highly correlated factors effecting sediment yield. *DR* is proportional to the drainage area, raised to the power of -0.2 (Ouyang and Bartholic, 1997 and Robinson, 1979).

Other common factors that have been used in *DR* equations include slope, gradient and relief-length. Maner (1958) developed a regression equation to determine *DR* with the relief-length factor:

$$\log DR_e = 2.94259 - 0.82363 \text{ colog } (R/L)$$

where DR_e is the estimated sediment delivery rate in percent of annual gross erosion, colog is the log of the reciprocal, and R/L is the relief-length ratio. This equation had a correlation coefficient (r) of 0.987, explaining 97% of the variation in sediment delivery ratios. The *DR* was based on data from 25 reservoirs in Northern Texas and Oklahoma. Maner (1958) also developed a regression equation to determine *DR* with relief and length as separate variables:

$$\log DR_e = 2.96162 + 0.86868 \log R - 0.85354 \log L$$

where *R* is relief of watershed (in feet) and *L* is the maximum length of watershed (in feet). This equation had a multiple correlation coefficient of 0.979, which explained 96% of the variability in sediment delivery ratios.

Roehl (1962) developed a few *DR* equations with relationships to area, length and relief-length ratio for streams in the Southeastern Piedmont. The *DR*s were developed using sediment basins and sediment yield from these 15 drainage areas. These basins were surveyed to determine the amount of deposition. By knowing the age of the reservoirs, Roehl was able to determine an annual rate of deposition. The *DR*s are as follows:

$\log DR_e = 1.91349 - 0.333852 \log (10\ W)$

where W is the watershed area (square miles). The r-value was –0.721.

$\log DR_e = 1.62792 - 0.64818 \log L$

where L is the average length of the system. The r-value was –0.812.

$\log DR_e = 2.88753 - 0.83291 \text{ colog } (R/L)$ The r-value was –0.867.

The most significant relationship, at an r of 0.961, Roehl (1962) found was when relief-length, area, and bifurcation ratio were combined:

$$\log DR_e = 4.50047 - 0.23943 \log (10\ W) - 0.51022 \text{ colog } (R/L) - 2.78594 \log (BR)$$

where BR is the bifurcation ratio. A bifurcation ration is the ratio of the number of streams of any order to the number of streams of the next highest order.

Models today use GIS and computers to vastly improve their prediction skills. Many models use USLE to determine the erosion rates and then develop a *DR* that is multiplied by the erosion to determine the sediment yield. Others use *DR*s developed from actual data and then apply the *DR* to a new watershed in a similar region. Using GIS, one can determine the various factors, such as slope, area, and soil, and can apply those parameters to grid cells, allowing land use, cover, slope and other factors to be more accurately calculated and allow for natural changes.

Watershed Models - General

Modeling of watersheds is becoming more widely adopted in the TMDL and environmental world. These models widely vary, some being specialized to a specific "environmental phenomena and components of pollution problems" while others are more general (USEPA, 1997). Many of these models use GIS. With GIS, data and attributes can be combined with maps and images, allowing a wide variety of output to be obtained. Models can be applied to a multitude of pollutants in a watershed, such as nutrients, heavy metals, or sediment. In the case of sediment modeling, models can be used to predict nonpoint source components of a TMDL for a stream. These models can also be "used to assist in targeting watersheds, developing goals and objectives, defining solutions, developing plans for management implementation, and tracking progress toward achieving goals" (USEPA, 1997). There are many models available today, such as the BASINS system, Watershed Characterization System (WCS), AGricultural Non-Point Source pollution model (AGNPS), and AQUATOX. Each of these models has a wide variety of uses depending on which pollutant is focused on and the needs of the user.

Watershed Models – BASINS

Better Assessment Science Integrating point and Nonpoint Sources (BASINS) is a software system that allows states and other pollution control agencies to "emphasize watershed and water quality-based assessment and integrated analysis of point and nonpoint sources" (USEPA, 2001). This system uses watershed data, meteorological data, and modeling tools to "(1) facilitate examination of environmental information, (2) provide an integrated watershed and modeling framework, and (3) support analysis of point and nonpoint source management alternatives" (USEPA, 2001). BASINS is a complex tool that incorporates many components, including GIS databases, watershed delineation tools, digital elevation model (DEM) data, land use data, soils data, water quality data, four different models, and various map and report formats. The four models focus on different aspects of watershed water quality. Enhanced Stream Water Quality Model (QUAL2E) is a point source in-stream water quality model (USEPA, 2001). The Hydrologic Simulation Program FORTRAN (HSPF) and Soil Water Assessment Tool (SWAT) models focus on nonpoint source loading and transport in watersheds. Finally, Pollutant Loading Application (PLOAD) works with nonpoint sources and models the annual loading in a watershed. BASINS runs within an ArcView GIS environment and allows for a wide variety of assessment, modeling, and query tools to be utilized in one program.

Watershed Models – Watershed Characterization System (WCS)

Tetra Tech, a private consulting company, developed the Watershed Characterization System (WCS) for EPA Region 4 for use in the development of TMDLs. Like BASINS, WCS is an ArcView-based program that incorporates DEM, land use, soils, climate, and water quality data with GIS databases and assessment tools. Within WCS, there are models for sediment, mercury, and storm water management. The aim for WCS is to "provide a system that will help states meet TMDL deadlines" (Tetra Tech, 2000a).

The Sediment Tool within WCS allows the user to estimate erosion, sediment delivery (delivery ratio), sediment yield, and the impacts of land use, best management practices (BMPs), and roads on the erosion and sediment yield. Erosion is calculated using a basic USLE equation where rainfall, soil erodibility, topography, land use, and soil conservation practices are taken into account (Greenfield et al., 2002).

There are four calculation methods within WCS to determine the sediment delivery ratio in the Sediment Tool. The first method was developed by Sun and McNulty (1998) for a watershed in western North Carolina; the equation is considered distance based. The delivery ratio (*DR*) is represented by

$$DR = Md/M = (1 - 0.97 \bullet D/L)$$

$$L = 5.1 \bullet 1.79 \bullet M$$

Where: *Md* is the mass moved from each cell (tons/acre/year), *M* is seasonal or annual soil loss from USLE (metric tons/year/ha), *D* is the least cost distance to stream, determined using surface roughness, lateral distance and slope (meters), and *L* is the maximum distance (meters) that sediment with Mass *M* (metric tons) may travel (Sun and McNulty, 1998).

The second delivery ratio equation focuses on distance and slope and was developed by Yagow, et al. (1988). Here the delivery ratio is calculated as

$$DR = \exp(-0.4233 \bullet \mathrm{L} \bullet Sf)$$

$$Sf = \exp(-16.1 \bullet (R/L + 0.057)) - 0.6$$

where *L* is the distance (meters) to the stream, *R* is the relief (meters) to the stream, and *Sf* is the slope factor.

The third calculation method is area based and was developed by the Natural Resource Conservation Service (USDA, 1983). In this method, delivery ratio is calculated by

$$DR = 0.417662 \bullet A^{-0.134958} - 0.127097$$

where A is area of the watershed (square miles) (Tetra Tech, 2002b). The final method of calculating sediment delivery is a regression-based equation developed by Swift (2000) and (Dai, 2004). This equation was developed using the Water Erosion Prediction Project (WEPP) model on a forested area and related the sediment output to physical characteristics of the watershed:

$$Z = 0.900 - 0.1341 \bullet X - 0.0465 * X^2 + 0.00749 \bullet X^3 - 0.0399 \bullet Y + 0.0144 \bullet Y^2 + 0.00308 \bullet Y^3$$

where $X > 0$ and $Y > 0$. Here Z represents the percent source sediment passing to the next grid cell, X represents the cumulative distance down slope, and Y represents percent slope in the grid cell.

North Fork Broad River

The North Fork Broad River is located in the North Georgia Piedmont (Fig. 1.1). The headwaters are in Stephens and Banks Counties near Toccoa, GA. This stream has been listed as an impaired stream segment (Broad River being the entire stream) for sediment. This segment of the Broad River runs about 22 miles. There is one USGS gaging station located not far above where the North Fork meets the Middle Fork. Typically, the 47 counties in Georgia Piedmont have been around 71% forested (Burns, 1978). The watershed is about 63% forested and has historically had high amounts of row crop farming (cotton) which might effect the legacy sediment, or historical sediment left in stream. It is unclear at this time how much legacy sediment actually affects the current sediment load in this stream, how much of the upland erosion actually reaches the stream, and how long it takes for this sediment to leave the stream system. The current loads into the North Fork Broad River system thought to be high contributors to the sediment impairment include urban areas, silviculture, and construction (USEPA, 2000).

References

Birkeland, S. 2001. EPA's TMDL Program. Ecol. Law Q. 28:297-327.

Burns, R.G. 1978. An Improved Sediment Delivery Model for Piedmont Forests. Ph.D. diss. Univ. of Georgia, Athens.

Cline, Richard, Gary Cole, Walt Megahan, Rick Patten, John Potyondy. 1981. Guide for Predicting Sediment Yields from Forested Watersheds. U.S. Forest Service Northern Region Intermountain Region.

Conservation Technology Information Center. 2002. TMDL Facts [Online]. Available at http://www.ctic.purdue.edu/KYW/tmdl/tmdlfact.html (verified 23 Sept. 2002).

Dai, Ting. 2004. Personal Communication. Tetra Tech Corporation. 12 March 2004.

Elliot, W.J., D.E. Hall, and S.R. Graves. 1999. Predicting Sedimentation from Forest Roads. J. Forestry. Vol. 97(8): 23-28.

Faye, R.E., W.P. Carey, J.K. Stamer, and R.L. Kleckner. 1980. Erosion, Sediment Discharge, and Channel Morphology in the Upper Chattahoochee River Basin, Georgia. Geological Survey Professional Paper 1107. USEPA.

FitzHugh, T.W. and D.S. Mackay. 2001. Impact of Subwatershed Partitioning on Modeled Source- and Transport-limited Sediment Yields in an Agricultural Nonpoint Source Pollution Model. J. Soil Water Conserv. 56:137-143.

Georgia Department of Natural Resources Environmental Protection Division. 2000. Georgia Rules and Regulations for Water Quality Control: Chapter 391-3-6 [Online]. Available at http://www.state.ga.us/dnr/environ/rules_files/exist_files/391-3-6.pdf (verified 18 Sept. 2002)

Gray, J.R., G.D. Glysson, L.M. Turcios, and G.E. Schwarz. 2000. Comparability of Suspended-Sediment Concentration and Total Suspended Solids Data. Report WRIR 00-4191. U.S. Geol. Surv.

Greenfield, J., M. Lahlou, L. Swift, and H.B. Manguerra. 2002. Watershed Erosion and Sediment Estimation Tool [Online]. Available at http://wcs.tetratech-ffx.com/Documentation/index.htm (verified 19 Nov. 2002).

Haan, C.T., B.J. Barfield, J.C. Hayes. 1994. Design Hydrology and Sedimentology for Small Catchments. Academic Press, Inc. San Diego, California.

King, J.G. 1993. Sediment Production and Transport in Forested Watershed in the Northern Rocky Mountains. In: Proceedings of Technical Workshop on Sediments. USEPA and USDA Forest Service.

Maner, S.B. 1958. Factors Effecting Sediment Delivery Rates in the Red Hills Physiographic Area. Transactions, American Geophysical Union. Vol. 39(4): 669-675.

Megahan, W.F. and W.J. Kidd. 1972. Effect of Logging Roads on Sediment Production Rates in the Idaho Batholith. USDA Forest Service Research Paper INT-123.

NRCS. 2004a. Soil Survey Geographic (SSURGO) Database [Online]. Available at http://www.ncgc.nrcs.usda.gov/branch/ssb/products/ssurgo/fact-sheet.html (verified 15 June 2004).

NRCS. 2004b. State Soil Geographic (STATSGO) Database [Online]. http://www.ncgc.nrcs.usda.gov/branch/ssb/products/statsgo/fact-sheet.html (verified 15 June 2004).

Ouyang, D., and J. Bartholic. 1997. Predicting Sediment Delivery Ratio in Saginaw Bay Watershed. 22nd National Assoc. of Env. Professionals Conf. Proceedings. Pages 659-671.

Radcliffe, D.E. 2002. A protocol for establishing sediment TMDLs [Online]. Available at http://www.georgiaconservancy.org/WaterQuality/GA_CON QXD.pdf (verified 3 Sept. 2002).

Reid, L.M. and T. Dunne. 1984. Sediment Production from Forest Road Surfaces. Water Resources Res. Vol. 20(11): 1753-1761.

Robinson, A.R. 1979. Sediment Yield as a Function of Upstream Erosion. In: Universal Soil Loss Equation: Past, Present and Future. SSSA Special Publication No. 8. Chapter 2: 7-16.

Roehl, J.W. 1962. Sediment Source Areas, Delivery Ratios, and Influencing Morphological Factors. International Assoc. of Scientific Hydrology. Commission of Land Erosion. Publication 59: 202-213.

Sadar, M. 2002. Turbidity Instrumentation – An Overview of Today's Technology. In: Proceedings of Turbidity and Other Sediment Surrogates Workshop.

Simmons, Clyde E. 1976. Sediment Characteristics of Streams in the Eastern Piedmont and Western Coastal Plain Regions of North Carolina. Geological Survey Water-Supply Paper: 1798-0.

Sun, G. and S.G. McNulty. 1998. Modeling Soil Erosion and Transport on Forest Landscapes. In: Proceedings of Conference 29, International Erosion Control Association. Pages 187-198.

Tetra Tech, Inc. 2000a. Watershed Characterization System (WCS) User's Guide [Online]. Available at http://wcs.tetratech-ffx.com/ (verified 14 Jan. 2002).

Tetra Tech, Inc. 2000b. Watershed Characterization System (WCS) for ArcView GIS 3.1 and 3.2. Release 1.1. Available at http://wcs.tetratech-ffx.com/ (verified 14 Jan. 2002).

Truman, C.C., R.D. Wauchope, H.R. Sumner, J.G. Davis, G.J. Gascho, J.E. Hook, L.D. Chandler, and A.W. Johnson. 2001. Slope Length Effects on Runoff and Sediment Delivery. J. Soil Water Conserv. Vol. 56(3): 249-256.

USDA. 1983. Sediment Sources, Yields, and Delivery Ratios. In: National Engineering Handbook, Section 3, Sedimentation. USDA. SCS. Chapter 6.

USEPA. 1997. Compendium of Tools for Watershed Assessment and TMDL Development [Online]. Available at http://www.epa.gov (verified 29 Nov. 2002)

USEPA. 2000. Proposed Total Maximum Daily Load (TMDL) Development for Sediment North Fork Broad River Georgia [Online]. Available at http://www.epa.gov/Region4/water/tmdl/georgia/savannah/nfbr-sed.pdf (verified 24 August 2002).

USEPA. 2001. BASINS: Better Assessment Science Integrating Point and Nonpoint Sources [Online]. Available at http://www.epa.gov/waterscience/basins/ (verified 6 Nov. 2002).

USEPA. 2002a. Introduction to TMDLs [Online]. Available at http://www.epa.gov/owow/tmdl/intro.html (verified 24 Sept. 2002).

USEPA. 2002b. Overview of Current Total Maximum Daily Load – TMDL – Program and Regulations [Online]. Available at http://www.epa.gov/owow/tmdl/overviewfs.html (verified 24 Sept. 2002).

USEPA. 2002c. Status of the TMDL/Watershed Rule [Online]. Available at http://www.epa.gov/owow/tmdl/watershedrule/watershedrulefs.html (posted 3 June 2002; verified 24 Sept. 2002).

USGS. 2000. Common Water Measurements [Online]. Available at http://dwb.unl.edu/Teacher/NSF/C01/C01Links.ga.water.usgs.gov/edu.characteristics.html (posted 3 Feb. 2000; verified 15 June 2004)

Van Lear, D.H., J.E. Douglass, S.K. Cox, and M.K. Augspurger. 1985. Sediment and Nutrient Export in Runoff from Burned and Harvested Pine Watersheds in the South Carolina Piedmont. J. Environ. Qual. Vol. 14(2): 169-174.

Williams, J.R. and H.D. Berndt. 1976. Determining the Universal Soil Loss Equation's Length-slope Factor for Watersheds. In: Soil Erosion: Prediction and Control. Proceedings of A National Conference on Soil Erosion. Pages 217-225.

Wischmeier, W.H. 1976. Use and Misuse of the Universal Soil Loss Equation. In: Soil Erosion: Prediction and Control. Proceedings of A National Conference on Soil Erosion. Appendix A: 371-381.

Wischmeier, W.H. and D.D. Smith. 1978. Predicting Rainfall Erosion Losses – a Guide to Conservation Planning. U.S. Dept. of Agriculture. Agriculture Handbook No. 537.

Yagow, E.R., V.O. Shanholtz, B.A. Julian, and J.M Flagg. 1988. A Water Quality Module for CAMPS. Paper presented at 1988 International Winter Meeting of ASAE.

Yitayew, M, S.J., Pokrzywka, and K.G. Renard. 1999. Using GIS for Facilitating Erosion Estimation. ASAE. Vol. 15(4): 295-301.

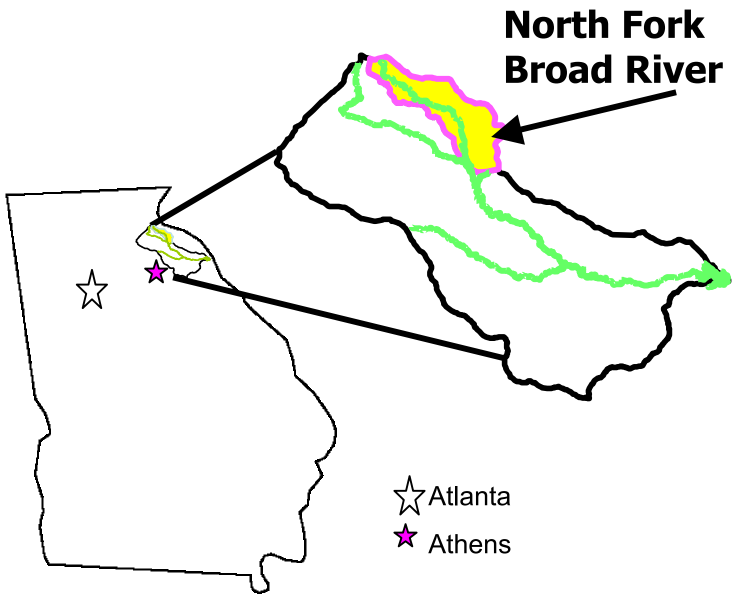

Figure 1.1. North Fork Broad River location in Georgia.

Chapter 3

Watershed Modeling & Uncertainty Analysis for the North Fork Broad River in Georgia, USA

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Abstract

Erosion and the resulting sediment can create serious water quality problems. High sediment loads carry pollutants that create water quality problems, damage biota habitat and can impair recreational use. Georgia's North Fork Broad River has been listed as an impaired stream segment for sediment. This Piedmont stream segment is approximately 63% forested, however historically had large areas of row cropping. Our objective was to use Water Characterization System's (WCS) Sediment Tool to model the sediment in the North Fork. The model uses USLE to determine erosion and four delivery ratios (DR) to determine sediment yield. Another objective was to determine model sensitivity and uncertainty. We have implemented WCS in an Excel spreadsheet coupled with @Risk software, a commercial plug-in to Excel. Our modeling efforts show that the North Fork does have a sediment problem. DR had a great effect on stream sediment loads. Land use changes also affected the sediment yield predictions. Using WCS, there is a large uncertainty in sediment prediction, but much less uncertainty in erosion prediction.

Introduction

The North Fork Broad River is located in the North Georgia Piedmont. The stream is listed as an impaired segment for sediment (USEPA, 2000). The North Fork segment runs about 22 miles (35 km) and the watershed is approximately 88 thousand acres (35,600 hectares). The watershed is 63% forested, however has historically had high amounts of row crop farming. The current sediment contributors to the system are thought to be urban areas, roads, silviculture, and construction (USEPA, 2000). Our objective was to use WCS's Sediment Tool (Tetra Tech, Pasadena, CA) to determine sediment load in the North Fork Broad River. Four delivery ratio methods were used to determine sediment load. Another objective was to compare the model predictions to known suspended sediment data from the Broad River near Bell, GA. A final objective was to determine the sensitivity of the model using @Risk Software (Palisade Corporation, Newfield, NY).

The 1972 Clean Water Act requires states, territories, and authorized tribes to develop impaired water lists. These impaired waters do not meet water quality standards set by the state, territory, or authorized tribe. In order to improve the water quality of the nation, EPA is now enforcing the Clean Water Act provision requiring the creation of Total Maximum Daily Loads (TMDLs) (USEPA, 2002b).

A TMDL can be referred to in two separate but integrated ways. One is a "calculation of the maximum amount of pollutant that a water body can receive and still meet water quality standards" (USEPA, 2002a). This calculation is the sum of all loads of a single pollutant entering the body of water from all point and nonpoint sources. This number must account for seasonal variations and include a margin of safety (MOS). The National Research Council (through National Academy of Science) discusses including uncertainty and MOS in TMDLs as follows: (Reckhow et al., 2001):

> "Uncertainty must be explicitly acknowledged both in the models selected to develop TMDLs and in the results generated by those models. Prediction uncertainty must be estimated in a rigorous way, models must be selected and rejected on the basis of a prediction error criterion, and guidance/software needs

to be developed to support uncertainty analysis. The TMDL program currently accounts for the uncertainty embedded in the modeling exercise by applying a margin of safety (MOS); EPA should end the practice of arbitrary selection of the MOS and instead require uncertainty analysis as the basis for MOS determination. Because reduction of the MOS can potentially lead to a significant reduction in TMDL implementation cost, EPA should place a high priority on selecting and developing TMDL models with minimal forecast error. EPA should selectively target some post-implementation TMDL compliance monitoring for verification data collection so that model prediction error can be assessed."

The second way the term TMDL is commonly used is actually a TMDL Implementation Plan or TMDL program. This program includes identifying impaired waters, establishing a TMDL (calculating a target load), developing ways to reduce the impairment, and assessing all aspects of the implementation (Conservation Technology Information Center, 2002). It is up to the local jurisdictions to create these TMDL programs and to monitor and improve the water quality of their water bodies. However, the EPA must approve each impaired list and TMDL. The TMDL program requires each state, territory, and authorized tribe to create a priority list based on the severity of pollution and develop a TMDL (calculation) within two years.

TMDLs may be based on modeled predictions, instead of data, due to economic and resource constraints of gathering water quality data for every stream. The use of MOS in the TMDL calculation shows that natural variability and prediction error must be accounted for (Borusk et al., 2002). Model uncertainty may come from temporal variability (i.e. precipitation), parameter error (i.e. ranges or distributions), or lumping error (i.e. landuse or topographic) (Hession and Storm, 2000). GIS based models may be especially sensitive to parameter or lumping error due to data precision. One way to look at this uncertainty, as well as parameter correlations and model sensitivity is to use @Risk (Palisade Corporation, Newfield, NY), which uses Monte Carlo simulations (Hession and Storm, 2000). Model sensitivity is based on how each parameter effects the model prediction. For the model prediction, modelers, stakeholder and decision-makers will want to determine the uncertainty of the model in order to gain realistic expectations of the accuracy of the prediction. Blackstock (2003) discusses a court case where it is debated whether mathematical modeling results are admissible or not in court. The Court ruled in a prior case that an error rate should be included in scientific evidence. This proves it is vitally important for model uncertainty and sensitivity to be established.

The North Fork Broad River is listed on the EPA's impaired waters list for sediment. The North Fork TMDL uses "the relationship between natural sediment loads and stream flow…from a reference stream" as the modeling approach (USEPA, 2000). North Fork daily discharge was determined from a downstream Broad River USGS station. A MOS was calculated using the sediment concentration vs. flow regression line and applying a 95% confidence interval to that line. The TMDL modeling produced an annual average sediment load of 18 million kg/yr for 1971-1995. The TMDL recommends, "further analysis be completed on these watersheds".

Materials and Methods

Delivery Ratio Comparison

WCS is a watershed-modeling program, which runs from scripts implemented in ArcView 3.x. WCS was created by Tetra Tech (Tetra Tech, Pasadena, CA) for EPA Region 4. This model is "designed to provide users tools and an initial set of watershed data for characterizing and thereby understanding their watersheds. It can be used to assist users complete the watershed characterization phase required in developing Total Maximum Daily Loads (TMDLs). This may include the following: ·

Characterization of the physical and hydrologic properties of the watershed, such as soil, land use, elevation, climate, and stream flow.

Evaluation of ambient water quality conditions, including inventory of monitoring stations and statistical analysis of observed data.

Assessment of potential sources of impairment, such as permitted dischargers, crop and livestock agriculture, mining, silviculture, and populated places, and preliminary estimation of pollutant loads from these sources" (Tetra Tech, 2001).

A WCS model run begins with a project creation. WCS has data sets available based on Hydrologic Unit Codes (HUC). Utilizing the project builder within WCS, the following themes were added and used for the entire Broad River: soils (STATSGO), roads (Topologically Integrated Geographic Encoding and Referencing (TIGER)), USGS stations (water quality data), land use (MLRC – 1990s), RF3 file (water reaches), and various county and state boundaries. The Digital Elevation Model (DEM) (30 m x 30 m) was also needed in grid format for the Sediment Tool within WCS. To gather these data, 8 separate quads were collected. These quads were in UTM coordinates and were then changed to Albers equal projection coordinates to match the rest of the data. The quads were then merged and, using the map calculation tool, converted from meters to feet.

Once all these data layers were stored within the project, the North Fork of the Broad River had to be delineated. Using the RF3 files and the manual delineation tool, the North Fork Broad River watershed segment was delineated to the point it meets with the Middle Fork Broad River. Once this was done, this polygon was saved for later use with the BMP and construction layers. The land uses and associated areas are shown in Table 2.1.

WCS's Sediment Tool was used to input data and model the erosion and sediment load for the North Fork Broad River. Calculated erosion was the same in each of the sediment delivery calculation methods, using the USLE to determine erosion. Sediment Tool determines each of the 5 parameters of USLE (*R*, *K*, *LS*, *C* and *P*) on a grid cell basis (Tetra Tech, 2000b). These USLE parameters, calculated automatically within the model, are determined using the soils, climate, elevation (DEM), and landuse (MLRC) layers. Each grid cell is 30 m x 30 m. WCS also uses the road layer to calculate a separate erosion rate based on the road impact (Dai, 2004). For each regular cell, a source erosion and sediment yield is determined. Then for each cell that contains a road, the road elevation is clipped from the cell and the slope of the road is determined. New road *LS*, *C* and *P* values are determined for the USLE and a road erosion rate is calculated using the original *R* and *K* values. The road erosion rate is then applied to 25% of that cell, leaving 75% of the total cell erosion determined from the source erosion originally calculated with the regular USLE parameters.

Following the erosion calculations, a delivery ratio must be calculated to determine the sediment reaching the stream. This delivery ratio is a number between 0 and 1 that is multiplied by the erosion in each grid cell to give a sediment yield for each cell. There are four methods in Sediment Tool to calculate the sediment delivery ratio. The first was developed by Sun and McNulty (1998) and is considered distance based. The delivery ratio (DR_1) is calculated as following:

$$DR_1 = Md/M = (1 - 0.97 \bullet D/L);\ L = 5.1 \bullet 1.79 \bullet M$$

where *Md* is the mass moved from each cell (tons/acre/year), *D* is the least cost distance to stream, determined using surface roughness lateral distance and slope (meters), *L* is the maximum distance (meters) that sediment with mass *M* (metric tons) may travel, and *M* is the seasonal or annual soil loss determined by USLE (metric tons/year/ha) (Tetra Tech, 2002b). *D* was calculated using a PATHDISTANCE function within the ArcInfo GIS system (Sun and McNulty, 1998)

The second delivery ratio equation uses distance and slope as parameters and was developed by Yagow (1998). Here the delivery ratio is calculated as

$$DR_2 = \exp(-0.4233 \bullet L \bullet Sf)$$

$$Sf = \exp(-16.1 \bullet (r/L + 0.057)) - 0.6$$

where *L* is the distance (meters) to the stream, *r* is the relief (meters) to the stream and *Sf* is the slope factor (Yagow, et al, 1988).

The third calculation method is area based and was developed by the Natural Resource Conservation Service (USDA, 1983). The area-based calculation was created for reservoir sedimentation data in the Southeast US (Greenfield et al., 2002). However, it does not apply topography, land use, or flow direction to the evaluation. Consequently, it is not applicable to evaluating the effects of Best Management Practices (BMPs) for roads (Greenfield et al., 2002). In this method, delivery ratio is calculated by

$$DR_3 = 0.417662 \bullet A^{-0.134958} - 0.127097$$

where A is area of the watershed (square miles) (Tetra Tech, 2002b).

The final method of calculating sediment delivery (DR_4) is a regression-based equation developed by Swift (2000) (Dai, 2003). This calculation is as follows:

$$Z = 0.900 - 0.1341 \bullet X - 0.0465 \bullet X^2 + 0.00749 \bullet X^3 - 0.0399 \bullet Y + 0.0144 \bullet Y^2 + 0.00308 \bullet Y^3$$

where $X > 0$ and $Y > 0$. Here Z represents the percent source sediment passing to the next grid cell, X represents the cumulative distance down slope, and the Y represents percent slope in the grid cell.

The WCS model was run, using each of the four methods, on the North Fork Broad River. Total erosion and sediment yield were calculated for each method and compared.

Next, a best management practice (BMP) layer was applied. Using the saved polygon from delineating the North Fork segment, the chosen BMPs could be applied to the entire watershed. With WCS's BMP tool, land use was selected as the basis for applying the BMPs. The BMP tool allows the user to change the P-value for certain land uses. This P-value is part of the USLE equation, and represents the conservation practice. For this project, the transitional, pasture/hay, and row crop landuses were selected for BMP application. Values were already provided for a multitude of currently used BMPs. For the pasture/hay (19137 acres or 7744 hectares) (Table 2.1) land-use, we applied a filter strip BMP, changing the *P*-value from 1.0 to 0.65. For the row crop (9018 acres or 3650 hectares) land-use, we applied reduced tillage practices, changing the *P*-value from 1.0 to 0.75. Normally, tillage practices are incorporated into *C*-values; however, in WCS Sediment Tool *P*-values are used to simulate the effect of reduced tillage. Finally, we applied a user-defined BMP value to the transitional (169 acres or 68 hectares) land-use, changing the *P*-value from 1.0 to 0.60. These three areas represent 32.1% of the watershed.

We also applied a construction layer, using the same North Fork Broad River watershed polygon. The construction layer was applied to the entire watershed. The construction layer allows the user to change the *C*-value (cropping factor in USLE) and apply the new *C*-value to a percentage of each land use category. For this project, normal *C*-values ranged from 0.003 to 0.75, depending on landuse. When applying the construction layer, a *C*-value of 0.50 was applied to the four land use categories chosen. Three percent of low intensity residential, 5% of high intensity residential, 10% high intensity commercial/industrial/transportation, and 40% transitional areas were chosen to have a construction layer applied. In total, these categories only represent 3.5% of the entire watershed. The four delivery ratio methods were compared for the control, BMP, and construction models.

Broad River versus North Fork Broad River Sediment Load

To access the accuracy of the Sediment Tool's predictions, we wanted to be able to compare actual measured data against our North Fork Broad River predictions. Because there were no sediment data collected on the North Fork Broad River, we decided to utilize the sediment and flow data from the USGS water quality station located at Bell, GA, near the outlet of the Broad River (Perlman, 1985). Suspended Sediment Concentration (SSC) data were periodically available from 14 January 1958 through 29 October 1979. Using the flow (cfs/s) and SSC (mg/L) from the Bell water quality station, we applied a log scale and fit a regression line to the data (Fig. 2.2).

Using the regression equation and more extensive flow data downloaded from the USGS NWISWeb for the same station at Bell SSC values were predicted for the time period from November 1, 1926 to September 30, 2002 (USGS, 2004). For each date, a flow value from the USGS data set was plugged into the regression equation and a SSC value was predicted. Using these predicted SSC values, we could then develop a long-term sediment load for the Broad River.

For comparison purposes, the same process was used for the Chattahoochee River near Cornelia, GA, the Chestatee River at Dahlonega, GA, Falling creek near Juliette, GA, and the Middle Oconee River near Athens, GA. Flow and SSC data were downloaded from the USGS NWISWeb and a linear regression was fit to the data for each stream. The linear regression equation was then used with more extensive flow data, downloaded from USGS NWISWeb for the four rivers, to predict SSC value for various periods of time. The predicted SSC values were then used to determine a long-term sediment load for the Chattahoochee River, Chestatee River, Falling Creek and Middle Oconee River.

Finally, the predicted sediment load from the Broad River near Bell, GA was used to estimate a sediment load for the North Fork Broad River. The Soil Conservation Service (SCS), now Natural Resource Conservation Service (NRCS), has a procedure for estimating a sediment yield for a small watershed, using measured sediment yield data on a larger watershed (Holeman, 1975). This method may be used on watersheds between one-half and one-tenth as large as the watershed with measured sediment yield.

The relationship is as follows:

$$S_e = S_m \bullet (A_e/A_m)^{0.8}$$

where S_e is the predicted sediment yield.

S_m is the measured sediment yield.

A_e is the drainage area of the watershed to be predicted.

A_m is the drainage area of the measured watershed.

Using this method, we predicted a sediment load for the North Fork Broad River based on measured SSC values from the Broad River station near Bell. Ultimately, the sediment loads from all models were compared, including the Broad River near Bell, Chattahoochee River near Cornelia, the Chestatee River at Dahlonega, Falling creek near Juliette, and the Middle Oconee River near Athens, North Fork Broad River – SCS Method, and North Fork Broad River Sediment Tool.

Lastly for the North Fork Broad River, there are 17 sedimentation reservoirs located within the watershed. These reservoirs were built between 1954 and 1878 as sediment control structures. We wanted to look at a possible way to determine how much sediment was taken out by these reservoirs. A delineation was made at the base of each reservoir. Then the sediment model was run, determining a possible sediment yield caught by the sedimentation reservoirs. After all 17 reservoirs were delineated, the sediment contributed from the watershed upstream of these reservoirs was subtracted from the total sediment for the North Fork Broad River.

Tom's Creek Erosion and Sediment Predictions and Uncertainty Analysis

In order to look at model uncertainty, WCS's Sediment Tool was used to model erosion and sediment on a smaller sub-watershed of the North Fork Broad River. This smaller watershed, Tom's Creek, was approximately 10% of the North Fork Broad River, at 8,715 acres (3527 hectares). We used a smaller watershed to enable the use of an uncertainty analysis tool known as @Risk (Palisade Corporation, Newfield, NY), which runs as an Excel spreadsheet plug-in. This meant that we had to implement the Sediment Tool calculations in Excel. Each GIS grid cell in the Sediment Tool corresponded to an Excel spreadsheet cell. The entire North Fork Broad River would have required more than the 65,536 Excel cells allowed in each column. Therefore, we used Tom's Creek to implement the Sediment Tool calculations with @Risk.

Tom's Creek watershed was manually delineated in the Sediment Tool in the same process as the North Fork Broad River. All GIS data layers were applied, including the DEM grid, soils (STATSGO), roads, USGS stations (water quality data), land use (MLRC – 1990s), RF3 file (water reaches), and various county and state boundaries. We chose the Area based *DR* method (DR_3) for our Tom's Creek model. The Sediment Tool was run for the Tom's Creek watershed; sediment and erosion predictions were calculated.

Next, the Excel spreadsheet was created to enable @Risk simulations to be run. This required data analysis in WCS, Java, and Excel. First, we wanted to verify that the erosion rates we calculated for each grid point in Excel (with the USLE) were the same as those calculated by the Sediment Tool. This required each of the GIS USLE parameter layers (i.e. *R*, *K*, *C*, *LS*, & *P*) to be exported as an ASCII file (text). Once each of these grid files was exported as text, we used a Java program to put the data in column format, making the importation into Excel much easier. As with the delivery ratio comparison experiment, Sediment Tool calculated source erosion, road erosion and then derived composite erosion from those two. The basic USLE parameters were exported as well as road *C*, *P*, and *LS*. Also, delivery ratio, source erosion and sediment, road erosion and sediment, and composite erosion and sediment were exported as ASCII files.

The Java program, created by Dr. Feng Chen, enabled columns to be created and also removed all cells with no value. ArcInfo was used to match up the road USLE, road erosion and road sediment with the corresponding cell containing source

USLE, source erosion and source sediment. This matching enabled the 25% road and 75% source erosion calculation to be completed.

Once the original GIS layers were properly imported into Excel, erosion and sediment were calculated and verified with the Sediment Tool predictions. During the process of calculating and verifying erosion and sediment calculations, mistakes within the Sediment Tool programming were found. It was determined that the composite values were not correct because the road/source calculation was not completed correctly in the programming of the model. Through correspondence with Sediment Tool programmers, the problem was found and corrected. After the model corrections, Tom's Creek was re-modeled, grids were exported and compiled, and all source, road and composite erosion and sediment calculations matched with the Sediment Tool values.

Once all erosion and sediment data were in Excel, we could begin to use @Risk, a risk analysis program, to determine model uncertainty and sensitivity. @Risk allows uncertain cell values in Excel to be defined as one of 37 probability distributions (Palisade, 2002). In @Risk's simulation analysis, Monte Carlo and Latin Hypercube simulations are used to determine model outputs. In an @Risk model, input variables varied to determine the variability of the model. This variability can then be looked at as model uncertainty with simple statistical approaches (i.e. standard deviation) or a distribution graph (Fig. 2.8). Also, the variables can be viewed on a "tornado" graph, showing the sensitivity of the model to the variables (Fig. 2.9).

In order to determine our model uncertainty and sensitivity, we began determining the parameters we could vary within our @Risk Monte Carlo Simulation. In USLE, *R* and *P* were the same for the watershed and therefore could not be varied. The *R* is taken from national *R*-value maps that have very coarse resolution, therefore for our watershed was the same. The P deals with cropping management practices and the landuse data used in the Sediment Tool is coarse and only denotes row crop or pasture/hay, not the type of management factor being employed. We also decided that it was beyond the scope of this project to try and vary the *LS* factor, even though it is one of the most variable inputs to the USLE (Williams and Berndt, 1976). This was due to the difficulty in determining the slope length with grid (raster) based elevation data. The remaining USLE parameters, *C* and *K*, could be varied. However, a range of values within which we could vary *C* and *K* needed to be determined, as well as the type of probability distribution. Also, we needed to determine a range and type of distribution for the delivery ratio.

The *K* factor range was determined using the STATSGO GIS layer. There is one STATSGO mapping unit in the Tom's Creek watershed. This mapping unit had three soils with three different *K* factors of 0.24, 0.28 and 0.32, based on more detailed soil information. Once these values were determined, a percentage of the area occupied by each soil and *K* factor was calculated using soils data from NRCS. Using the *K* factor values and associated percent areas in @Risk, a probability density curve was used to fit the distribution. The triangular distribution was the best-fit using @Risk. This fit utilizes a minimum, most likely and maximum value.

Next, the *C* factor range was determined. The *C* value for each grid cell in the Sediment Tool is based on the MLRC land use. This means there are at least 15 different possible land uses for each grid cell. Each of these land uses has an individual *C* value within the model. We decided to vary the row crop, pasture/hay, and forest landuses since these three land uses provide much of the erosion and sediment contribution in the watershed. Each of these three landuses then had a minimum and maximum value.

Using NRCS and Georgia Soil and Water Conservation Commission data, *C* values for each of the three land uses were determined (NRCS, 1998) (GSWCC, 2000). The undisturbed forest values were 0.001 to 0.004 for 70% to 45% canopy and undergrowth (middle category) (GSWCC, 2000). In the absence of any information on the areal distribution of forest cover, we used a uniform distribution for the forest *C* values. The pasture/hay range was from 0.02 to 0.005 and a uniform distribution (since we had no information on areal distribution of pasture/hay cover) was applied for @Risk (NRCS, 1998). Finally, the row crop *C* value was based on county agricultural census data from 1990 for Stephens and Franklin counties. The crops included were corn, wheat, cotton, oats, rye, sorghum, and soybeans. The most appropriate management system was chosen for each value, based on discussions with conservationists and extension specialists in the area. The overall crop C-value range was from 0.030 to 0.38. Using the values and percentages of total area in @Risk, a probability density curve was used to fit the distribution. The best-fit distribution was the Weilbull distribution.

Finally, the delivery ratio range and distribution was determined. We wanted to use actual measured delivery ratio data from the Piedmont. Erosion and sediment data from various sediment control structures in the Southeast of the US was reported by Roehl (1962). This data included 15 delivery ratios for the Piedmont. Roehl developed the *DR*s using sediment yield from these 15 sediment basins. Each basin was surveyed to determine the amount of deposition. By knowing the age of the reservoirs, the annual rate of deposition was able to be determined. We plotted the log of each *DR* as a function of log of drainage area (Fig. 2.3). A linear regression line was fitted to the data in Excel. Using the linear regression equation, a 95% confidence interval (CI) was developed. This CI was calculated using a F-statistic, alpha, mean square error, and sum of squares. Once the 95% CI was completed, a *DR* range for Tom's Creek was calculated, based on the watershed size of 8,715 acres. In @Risk, a normal distribution (an assumption in linear regression is that the residuals are normally distributed) was used for the *DR* range of 0.05 to 0.48.

Once the *K* factor, *C* factor, and *DR* ranges and distributions were determined, @Risk could be run. Using the *K* factor range, 3 *C* factor ranges, and *DR* ranges and distributions as inputs, an @Risk Monte Carlo simulation was run with Composite Sediment (total sediment yield for Tom's Creek watershed) as the output. This simulation used the Monte Carlo method to vary each of the 5 inputs randomly within their range according to their distribution and compute the composite sediment variance. One thousand iterations were used to run the simulation and analysis. Two thousand and three thousand iterations were run and no significant difference was found in the simulation results. Once the @Risk simulation was run, a distribution and sensitivity analysis was determined.

As a second @Risk simulation, the *K* factor range and 3 *C* factor ranges were used as input and Composite Erosion (total erosion for Tom's Creek watershed) was used as an output. One thousand iterations option was used again. A distribution of composite erosion values and sensitivity analysis were determined as well.

Results

Delivery Ratio Comparison

The North Fork Broad River Sediment Tool prediction shows that erosion is at a rate of 136,509 us ton/year (123,839 metric tons/year) (Fig. 2.4). When the total erosion is viewed by landuse, row crops play the highest role in the North Fork Broad River (Table 2.2). Roads, a quarry, and pasture/hay round out the top 4 erosion producing landuses (Table 2.2). It is also interesting to note that forest (deciduous, evergreen and mixed), which make up the biggest area of the watershed, produce much less of the erosion in the watershed. Roads do greatly effect the watershed in terms of erosion and sediment (Fig. 2.5)

The total erosion estimated using the USLE was the same for all four methods of *DR* calculation. The model predicted 3,090 lb/acre/year (3,463 kg/hectare/year) of erosion for the current (control) land-use (Fig. 2.6), while the BMP model produced a 30.8% decrease in the amount of erosion at 2,138 lb/acre/year (2,396 kg/hectare/year). In comparison, the construction model resulted in a 7.7% increase of erosion, as expected, with 3,328 lb/acre/year (3,730 kg/hectare/year). The BMP layers were applied to 28.4% of the watershed allowing for the larger decrease in sediment. However, the construction layer was only applied to 3.5% of the watershed, but still had a significant increase in total erosion for the amount of land involved. These erosion totals were then transformed into changes in the total sediment yield for each of the four *DR* methods.

The BMP model had a great reduction in the overall sediment load reaching streams, using all four methods of calculating *DR*, with a average of a 28% decrease in total compared to the control. When the construction model and control sediment totals were compared, the construction model showed an average increase of 6.4%.

Finally, the different *DR* methods were compared. The sediment yield varies greatly when comparing the 4 *DR* methods. It was found that the *DR* methods greatly affect the predicted sediment load (Fig. 2.6). The distance-relief method produced the highest sediment load. This distance-relief based equation is mostly used for cropland and pasture areas (Greenfield et al., 2002). The North Fork Broad River, according to MRLC land use layer we used, is 31% (28,156 acres or 11,394 hectares), cropland and pasture (Table 2.1). Slope (topography) highly affects the rate at which erosion will reach the stream, and that may explain why the distance-relief-based equation predicted much higher sediment loads than the distance-based equation. The distance method resulted in the least sediment load. This equation is best applied to forested watersheds (Greenfield et al., 2002). The watershed is 63% (55,770 acres or 22,569 hectares) deciduous, evergreen and mixed forested.

The ranking of different land uses in terms of their contribution to total sediment load is shown in Table 2.3 using the Distance-Relief and Distance methods for calculation *DR*. Row crop areas play the largest role in producing sediment for the North Fork Broad River watershed. The second highest percentage of sediment was generated from the Pasture/Hay land use and the filter strips worked well in reducing the total sediment. Row crop areas play the largest role in producing sediment for the North Fork Broad River watershed. Therefore, the BMPs applied during this project represent the most obvious way to try to reduce sediment. There is a quarry located near Toccoa, GA, which is the third highest sediment producer for the watershed with the Distance-Relief Delivery Ratio Method. There is silviculture activity within the watershed in terms of building roads and stream crossings and harvesting timber. However, with land use categories as defined, it is not possible to know the extent of such activities. Overall, BMPs applied to agricultural areas (which usually constitute a large percentage of the total land area), can reduce erosion and therefore sediment load within a watershed as this project shows.

In summary, the top 4 erosion producers for the North Fork Broad River are row crops, roads, a quarry and pasture/hay landuses. However, roads, row crops, and pasture/hay produce the most sediment for the watershed. How the model delivers sediment greatly effects which landuses have the most influence on sediment yield and each of the 4 *DR* methods used within the Sediment tool vary greatly. The North Fork Broad River, a highly forested watershed, the model showed that BMPs have a significant impact in reducing sediment load. This was due to the high percentage of area that is agricultural. Construction areas slightly increased the sediment load. Given the limited urban land-use this was expected. The modeling methods for sediment delivery ratio vary highly in their predicted sediment load. More data needs to be collected to verify which method is best, and how much error is contributed by each of these models.

Broad River versus North Fork Broad River Sediment Load

All three segments of the Broad River (North, Middle and South) are listed as impaired by sediment (USEPA, 2000). The regression equation for the Broad River was as follows:

$$y = 0.2196 \bullet x^{0.7723}$$

where y is the predicted SSC and x is the flow (in cubic feet per second, cfs). A plot of SSC vs. flow is shown in Figure 2.2. Similar regression equations were determined for the Chattahoochee River near Cornelia, GA, the Chestatee River at Dahlonega, GA, Falling creek near Juliette, GA, and the Middle Oconee River near Athens, GA. It is apparent, when comparing the rating curve sediment loads of the Broad River with other rivers, that the Broad River has a sediment problem (Table 2.4). The Broad River ranks intermediate for sediment load, however when comparing SSC (mg/L) it ranks highest. The sediment load is highly affected by the watershed size, as load is based on watershed size while SSC does not take into account the watershed size. Comparing other rivers in the same region enables one to see a bigger picture on how much the river is truly impacted.

Using the SCS method to convert the load at Bell to the smaller watershed, the North Fork Broad River is estimated to have an even higher sediment load. The WCS's Sediment Tool, however, predicts a much lower sediment yield. Removing the reservoir data predicts an even lower sediment yield, at 214 lb/acre/year (240 kg/hectare/year). One possible reason for the Sediment Tool having predicted less sediment load is that the USLE only takes in to account sheet erosion. Gully or channel erosion may play a big part in the North Fork Broad River and can be estimated at up to 34% of the Southern Piedmont's erosion (Roehl, 1962). Another possibility is that there is large uncertainty in the predicted sediment load, as we discuss below.

Tom's Creek Erosion and Sediment Predictions and Uncertainty Analysis

The composite sediment @Risk simulation produced a mean value of 2,223 tons/yr (2,017 metric tons/yr) (Fig. 2.8). In comparison, Sediment Tool predicted composite sediment to be 2,157 tons/yr (1,957 metric tons/yr) so the mean of the distribution produced from a Monte Carlo simulation was close to the model prediction. There was a great deal of uncertainty in the predicted sediment yield with an upper confidence limit at 95% of 4,744 tons/yr (4,304 metric tons/yr) and a lower confidence limit at 5% less than zero (-208 tons/yr). The distribution appeared to be normally distributed and the standard deviation of sediment yield was 1,514. The coefficient of variation (standard deviation divided by the mean) was 65%.

The sediment prediction was most sensitive to variation in *DR* in Tom's Creek (Fig. 2.9). This comes as no surprise as the range for *DR* was much wider than the ranges for each of the USLE parameters and the calculation is a simple multiplication of all factors. Also *C* and *K* factors do not usually provide as much control over erosion, and therefore sediment, as does the *LS* factor. For sediment, the second highest sensitivity was to the *K* factor. For this watershed model with only C and K varied within the USLE, none of the *C* factors had any regression sensitivity for sediment according to @Risk. It is probable that because only 3 landuses were varied, the *C* factor did not have a high of an impact on the final sediment prediction.

An @Risk Monte Carlo simulation was also run for composite erosion. This model produced a mean erosion of 13,292 tons/yr (12,058 metric tons/yr) (Fig. 2.10). Using the area *DR* method, the Sediment Tool produced an erosion rate of 12,946 tons/yr (11,744 metric tons/yr), close to the mean of the Monte Carlo distribution. The Monte Carlo simulations produced a distribution of erosion rates that appeared to be normal with a lower (5%) confidence limit of 12,952 tons/yr (11,750 metric tons/yr) and an upper (95%) confidence limit of 13,627 tons/yr (12,362 metric tons/yr). The standard deviation was 199 and the coefficient of variation was 1.5%. It is interesting to note how widely the sediment load varied, while the distribution for erosion was much smaller. This again shows how great a role delivery ratio plays in stream sediment and sediment pollution as a whole. Erosion was most sensitive to the *K* factor (Fig 2.11). The *C* factors also contributed to the variance of erosion.

Conclusion

Our results support the contention that the North Fork Broad River has a sediment pollution problem. An estimate of the suspended sediment load for the entire Broad River watershed, using long-term data from a USGS gauging station, showed that the average annual sediment yield was greater in the Broad River than in other rivers in the area. Using the SCS method to convert this sediment yield to the small watershed of the North Fork Broad River produced an even greater load. Modeling provided a valuable way to determine if applying BMP layers would actually result in a reduction of sediment load and how much of an effect construction within a watershed plays on the sediment load. This information could be used for making sound economical decisions for watershed management and TMDL development.

Many different factors affect predicted sediment loads using models or stream sediment analysis. When modeling, the method for calculating the delivery ratio has a great effect on the predicted sediment load. This shows a need for more research to determine the best type of delivery ratio calculation. Also, it is important to factor in possible land use changes, such as construction or BMPs. These changes can have an impact on the erosion within a watershed such as the North Fork Broad River. Landuse has a great effect on erosion yield for this model in the North Fork Broad River.

When looking at the sensitivity of sediment load predictions in the Tom's Creek watershed, delivery ratio played the largest role in the variance. There is a very large uncertainty in the sediment load predicted by the Sediment Tool with confidence limits that range from less than zero on the lower end to nearly twice the predicted value on the high end. Erosion predictions varied somewhat, but much less than sediment load for this watershed. Accurately quantifying the delivery of sediment to a stream provides the key to sediment modeling and certainty of predictions.

Through watershed modeling, we can learn how to plan better for our future growth and find ways to make our streams healthier. However, it is essential in modeling to base our models on past data, enabling the predictions to be more certain, and therefore more valuable. Watershed modeling can be a valuable tool in planning and managing a watershed and its pollution, past, present and future.

References

Blackstock, R.B. 2003. Using Computer Models in Court: Challenges for Expert Witnesses. In: Total Maximum Daily Load (TMDL) Environmental Regulations II, Conference Proceedings. Pages 8-12.

Borsuk, Mark E., Craig A. Stow, and Kenneth H. Reckhow. 2002. Predicting the Frequency of Water Quality Standard Violations: A Probalistic Approach for TMDL Development. Environmental Science and Technology. Vol. 36(10): 2109-2115.

Conservation Technology Information Center. 2002. TMDL Facts [Online]. Available at http://www.ctic.purdue.edu/KYW/tmdl/tmdlfact.html (verified 23 Sept. 2002).

Dai, Ting. 2004. Personal communication. Tetra Tech Corporation. 12 March 2004.

Georgia Soil and Water Conservation Commission (GSWCC). 2000. Manual for Erosion and Sediment Control. Athens, GA.

Greenfield, J., M. Lahlou, L. Swift, and H.B. Manguerra. 2002. Watershed Erosion and Sediment Estimation Tool [Online]. Available at http://wcs.tetratech-ffx.com/Documentation/index.htm (verified 19 Nov. 2002).

Hession, W.C. and D.E. Storm. 2000. Watershed-Level Uncertainties: Implications for Phosphorus Management and Eutrophication. J. Environ. Qual. Vol. 29: 1172-1179.

Holeman, John N. 1975. Procedures Used in the Soil Conservation Service to Estimate Sediment Yield. In: Present and Prospective Technology for Predicting Sediment Yields and Sources. Proceedings of the Sediment-Yield Workshop. Pages 5-9.

Natural Resources Conservation Service (NRCS). 1998. Revised Universal Soil Loss Equation (RUSLE) Handbook. USDA. Georgia.

Palisade Corporation. 2002. A Guide to Using @Risk. Version 4.5. Newfield, NY.

Perlman, Howard A. 1985. Sediment Data for Georgia Streams, Water Years 1958-82. USGS Open-File Report 84-722. USGS Doraville, Georgia.

Reckhow, Kenneth H., et al. 2001. Assessing the TMDL Approach to Water Quality Management [Online]. Available at http:www.nap.edu/catalog/10146.html (verified 20 June 2004).

Roehl, John W. 1962. Sediment Source Areas, Delivery Ratios, and Influencing Morphological Factors. Presented at Symposium on Land Erosion.

Sun, G. and S.G. McNulty. 1998. Modeling Soil Erosion and Transport on Forest Landscapes. In: Proceedings of Conference 29, International Erosion Control Association. Pages 187-198.

Tetra Tech, Inc. 2000a. Watershed Characterization System (WCS) User's Guide [Online]. Available at http://wcs.tetratech-ffx.com/ (verified 14 Jan. 2002).

Tetra Tech, Inc. 2000b. Watershed Characterization System (WCS) for ArcView GIS 3.1 and 3.2. Release 1.1. Available at http://wcs.tetratech-ffx.com/ (verified 14 Jan. 2002).

Tetra Tech, Inc. 2001. Watershed Characterization System [Online]. Available at http://wcs.tetratech-ffx.com/ (verified 10 July 2004).

USEPA. 2000. Proposed Total Maximum Daily Load (TMDL) Development for Sediment North Fork Broad River Georgia [Online]. Available at http://www.epa.gov/Region4/water/tmdl/georgia/savannah/nfbr-sed.pdf (verified 24 August 2002).

USEPA. 2002a. Introduction to TMDLs [Online]. Available at http://www.epa.gov/owow/tmdl/intro.html (verified 24 Sept. 2002).

USEPA. 2002b. Overview of Current Total Maximum Daily Load – TMDL – Program and Regulations [Online]. Available at http://www.epa.gov/owow/tmdl/overviewfs.html (verified 24 Sept. 2002).

USGS. 2004. NWISWeb Water Data [Online]. Available at http://waterdata.usgs.gov/nwis/ (verified 13 June 2004).

Williams, J.R. and H.D. Berndt. 1976. Determining the Universal Soil Loss Equation's Length-slope Factor for Watersheds. In: Soil Erosion: Prediction and Control. Proceedings of a National Conference on Soil Erosion. Pages 217-225.

Yagow, E.R., V.O. Shanholtz, B.A. Julian, and J.M Flagg. 1988. A Water Quality Module for CAMPS. Paper presented at 1988 International Winter Meeting of ASAE.

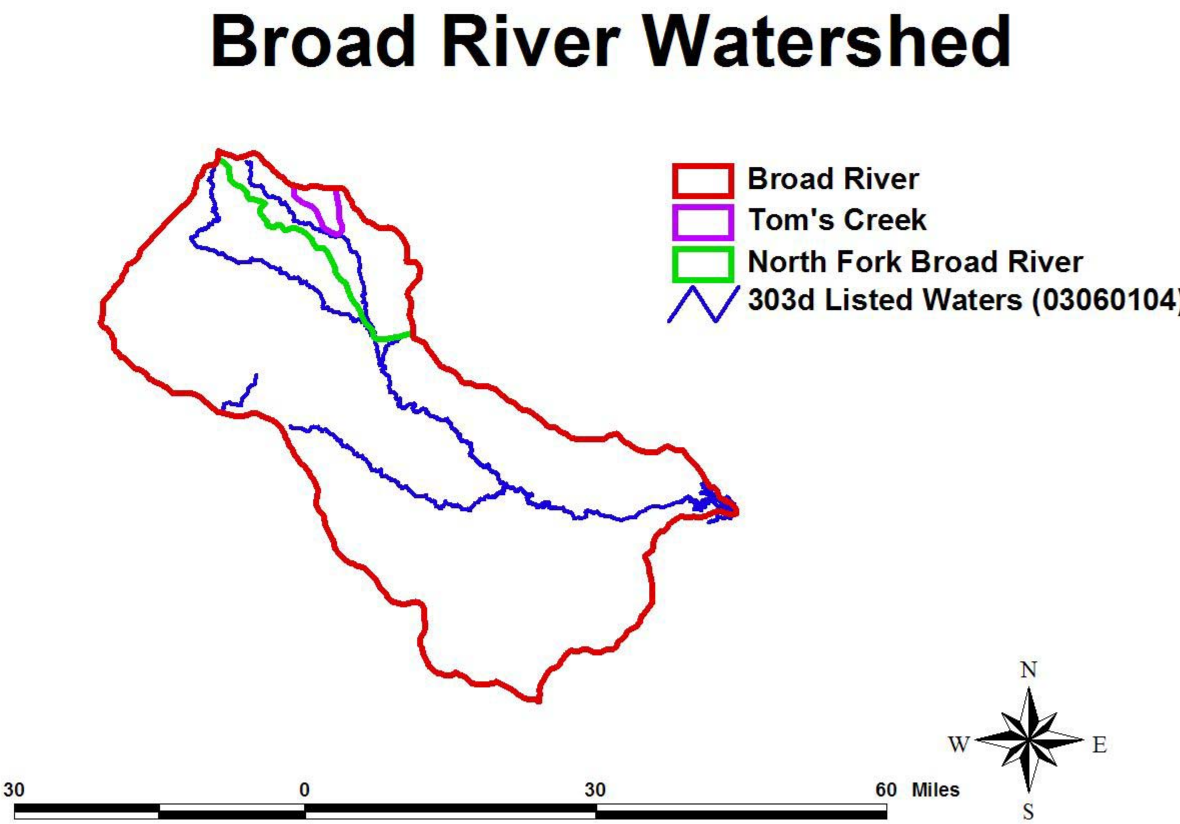

Figure 2.1. Broad River Watershed.

Land use Category	Area (acres)	% Of Total Watershed
Deciduous Forest	30463.45	34.47
Pasture/Hay	19137.29	21.66
Evergreen Forest	15279.32	17.29
Mixed Forest	10026.98	11.35
Row Crops	9018.46	10.21
Low Intensity Residential	1518.24	1.72
High Intensity Commercial/Industrial/Transportation	1341.22	1.52
Other Grasses (Urban/Recreational)	481.69	0.55
Open Water	334.91	0.38
Woody Wetlands	207.71	0.24
Transitional	169.90	0.19
Unclassified – Other	130.50	0.15
High Intensity Residential	88.07	0.10
Bare Rock/Sand/Clay	75.83	0.09
Quarries/Strip Mines/Gravel Pits	71.39	0.08
Emergent Herbaceous Wetlands	19.57	0.02

Land use

Table 2.1. Landuse area and percentage of entire North Fork Broad watershed.

Erosion

Land use Category	Erosion (tons)
Row Crops	75,379.35
Roads	27,212.76
Quarries/Strip Mines/Gravel Pits	20,842.50
Pasture/Hay	11,209.40
Deciduous Forest	593.04
Low Intensity Residential	274.48
Evergreen Forest	265.66
High Intensity Commercial/Industrial/Transportation	264.55
Mixed Forest	199.52
Woody Wetlands	127.87
Other Grasses (Urban/Recreational)	66.14
Transitional	49.60
High Intensity Residential	20.94
Emergent Herbaceous Wetlands	3.31
Open Water	0.00
Bare Rock/Sand/Clay	0.00

Table 2.2. Erosion in tons by landuse for North Fork Broad River.

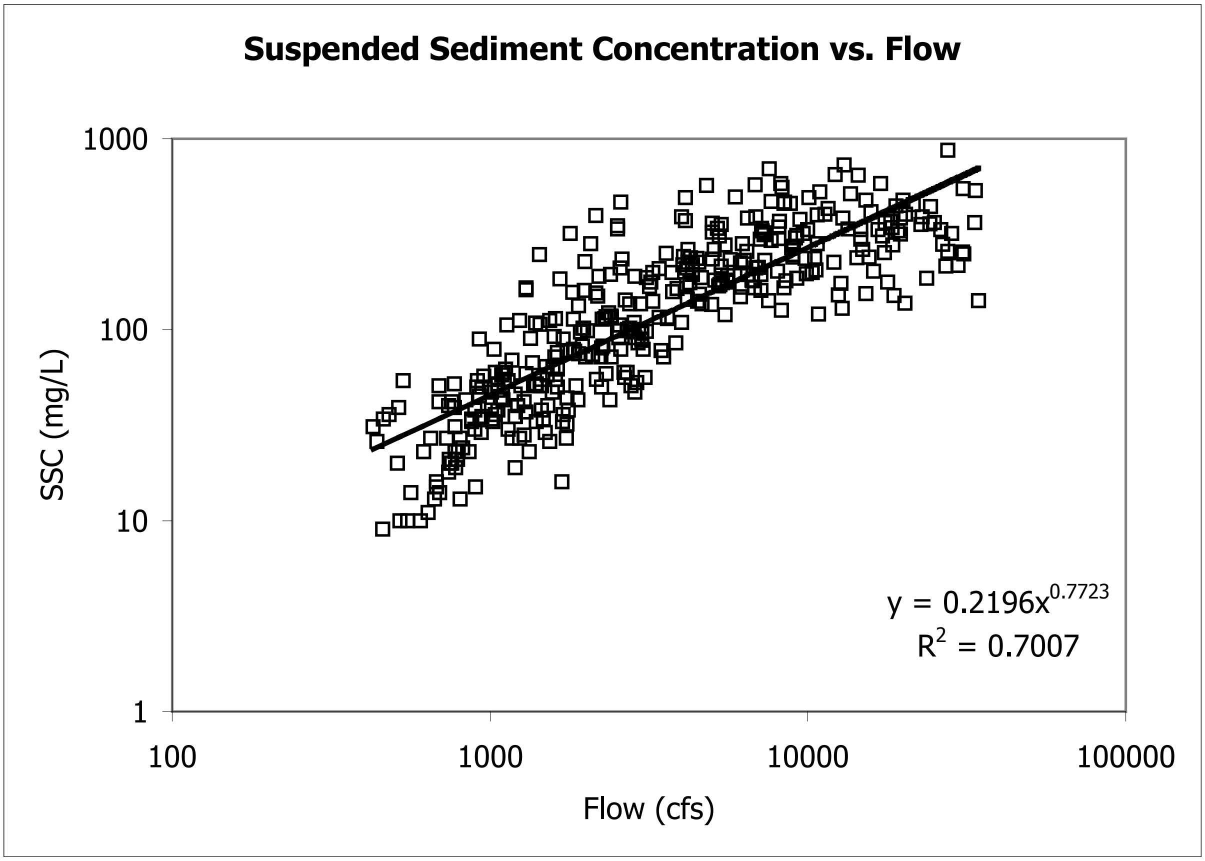

Figure 2.2. Log-log plot of Bell, GA Suspended Sediment Concentration vs. Flow (sample data and regression line).

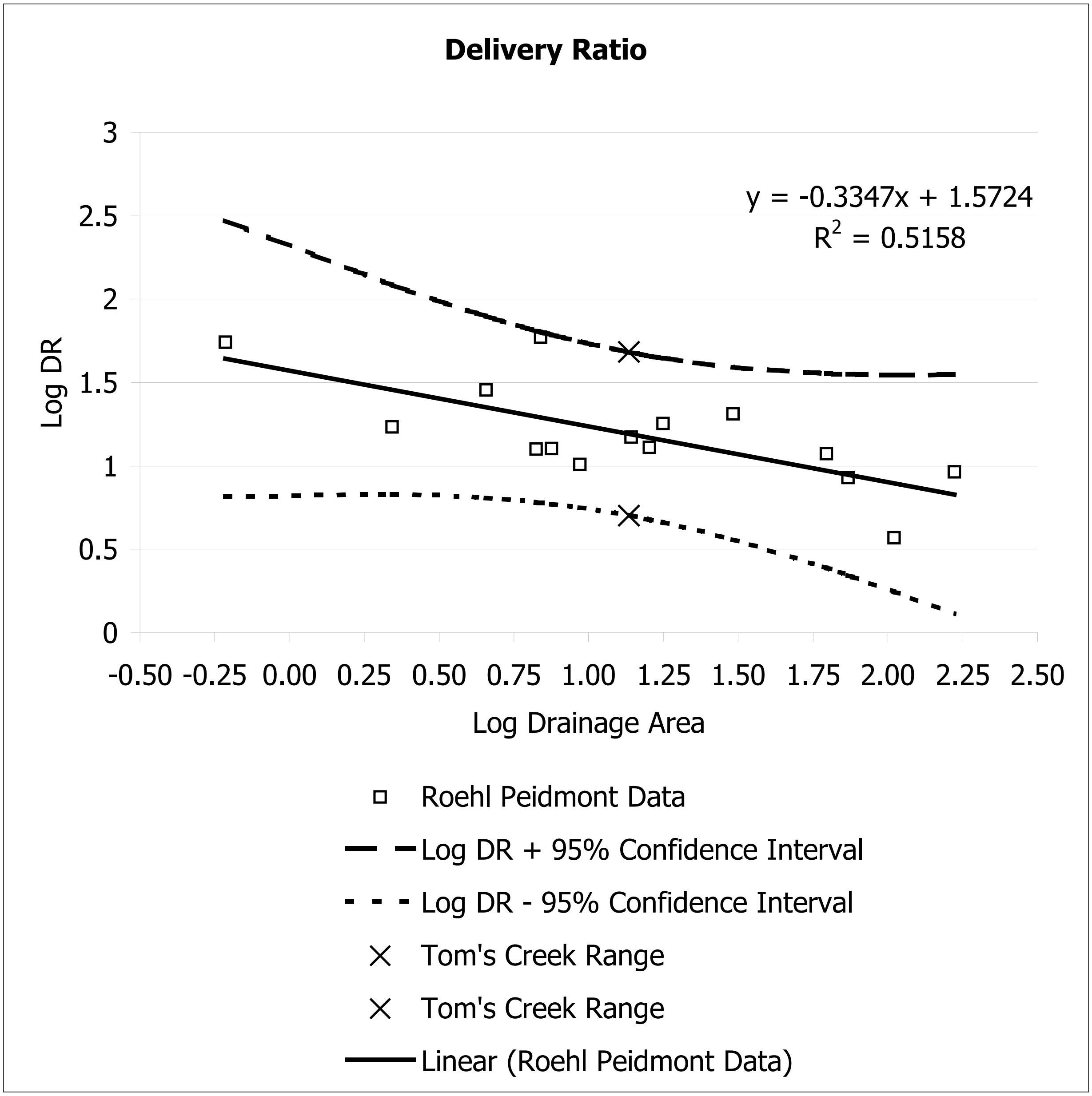

Figure 2.3. Roehl Piedmont Delivery Ratios with linear regression line and 95% confidence intervals applied. The x's mark the upper and lower confidence intervals for a watershed with the drainage area of Tom's Creek.

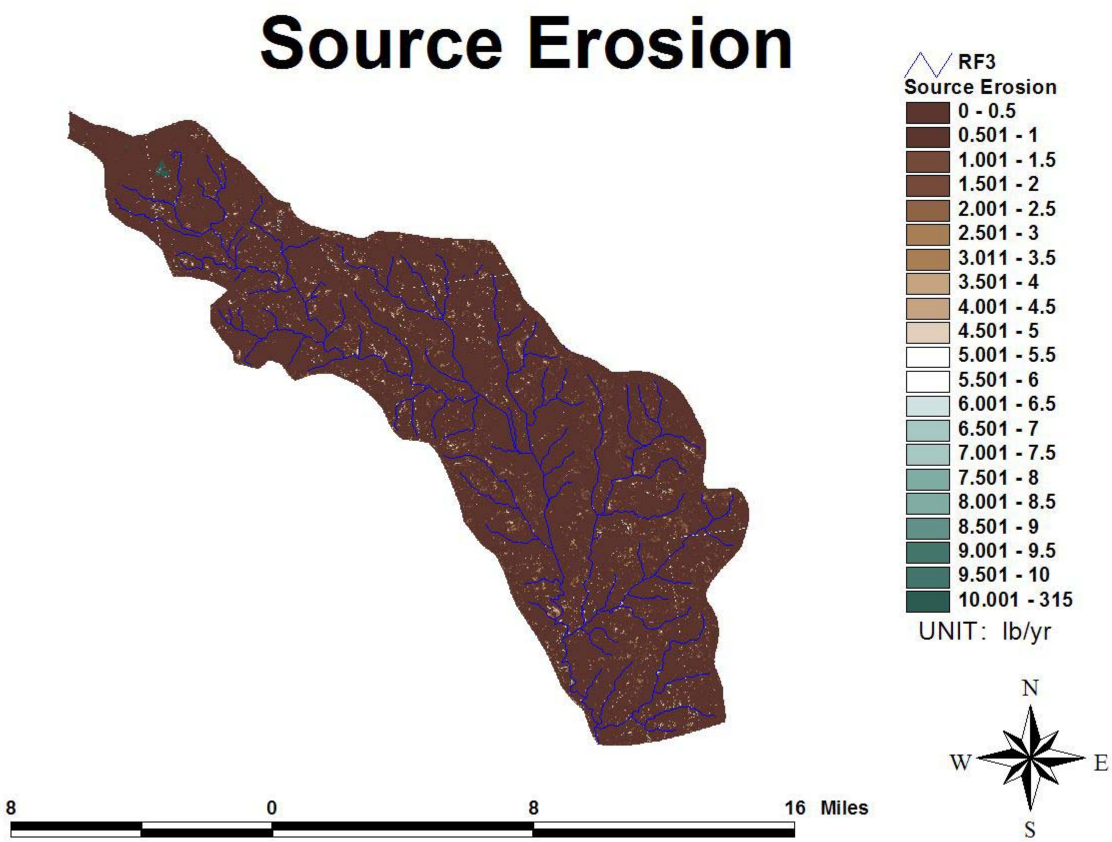

Figure 2.4. Source Erosion for North Fork Broad River.

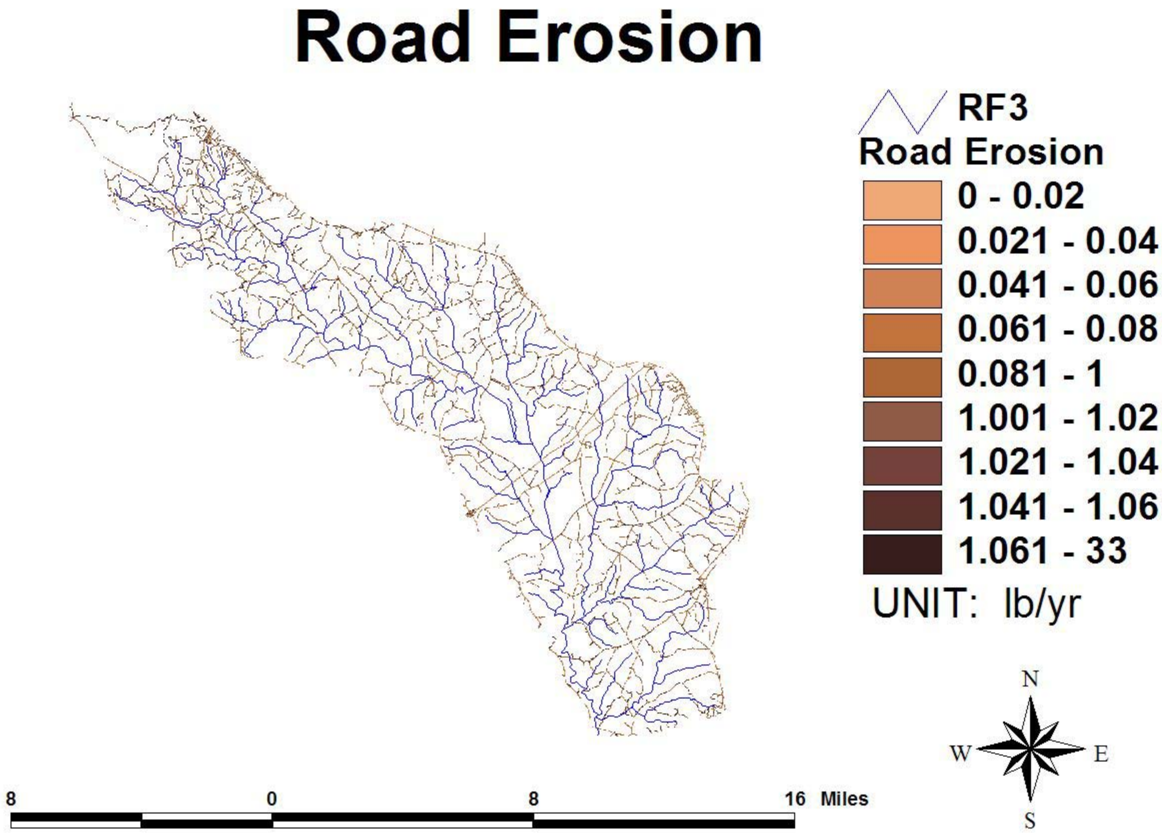

Figure 2.5. Road Erosion for North Fork Broad River.

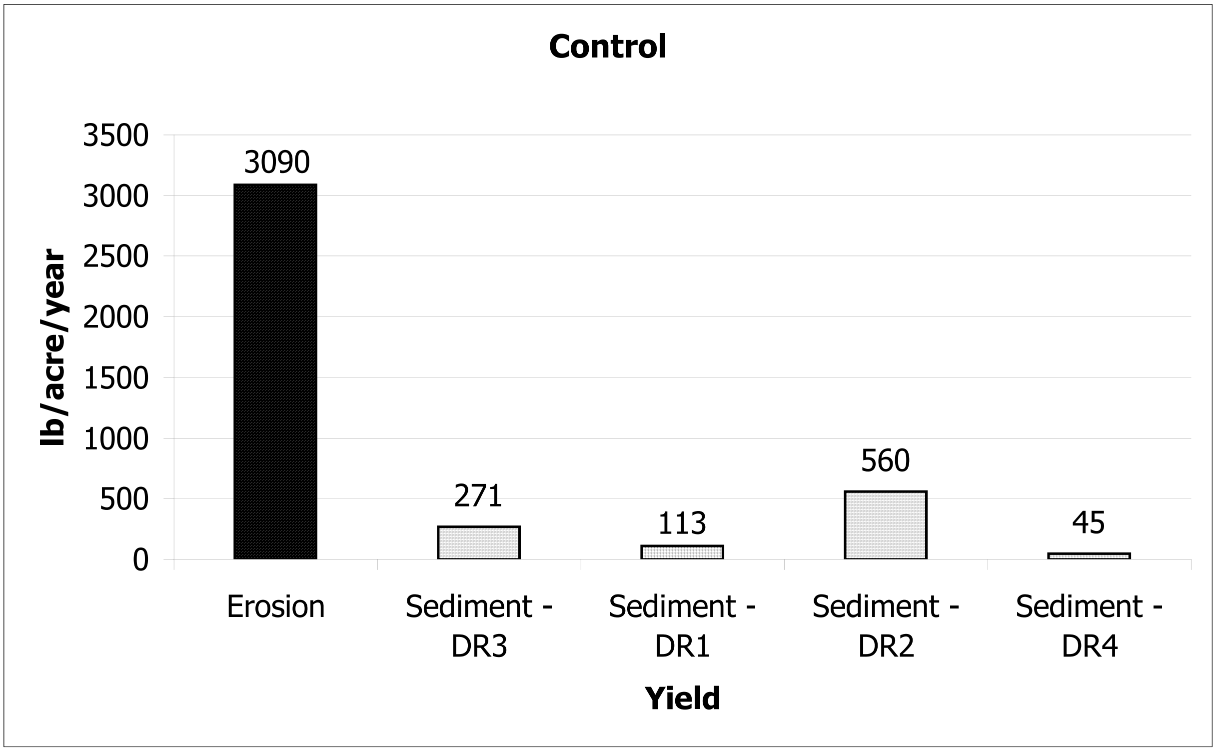

Figure 2.6. Erosion and sediment totals for the NF Broad watershed using four methods of calculating DR.

Sediment Ranking according to Land use (by US ton)				
Rank: DR2	**Sediment: DR2 (US ton)**	**Rank: DR1**	**Sediment: DR1 (US ton)**	**Land use**
1	15732.59	2	1871.19	Row Crops
2	6056.17	1	2900.49	Roads
3	2360.60	3	185.74	Pasture/Hay
4	198.04	NA	0.00	Quarries/Strip Mines/ Gravel Pits
5	132.54	4	25.86	Deciduous Forest
6	64.33	7	8.65	Low Intensity Residential
7	60.78	6	9.95	High Intensity Commercial/Industrial/ Transportation
8	54.33	5	20.27	Woody Wetlands
9	49.00	9	3.90	Evergreen Forest
10	35.77	8	4.47	Mixed Forest
11	16.16	10	0.83	Other Grasses (Urban/Recreational)
12	2.32	11	0.44	Transitional
13	1.16	12	0.32	Emergent Herbaceous Wetlands
14	0.11	13	0.68	High Intensity Residential

Table 2.3. Sediment total rankings for Distance-Relief and Distance DR methods.

River	Model Method	Sediment Load lb/a/yr	Sediment lb/yr	Suspended Sediment Concentration mg/L
Chattahoochee River near Cornelia, GA	Flow Rating Curve	812	1.64E+08	45
Chestatee River at Dahlonega	Flow Rating Curve	876	8.59E+07	22
Falling Creek near Juliette	Flow Rating Curve	117	5.41E+06	15
Middle Oconee River near Athens	Flow Rating Curve	263	9.35E+07	48
Broad River at Bell, GA	Flow Rating Curve	575	5.26E+08	64
North Fork Broad River	SCS Calculation	956	8.54E+07	---
North Fork Broad River	WCS Sediment Tool – Area Delivery Ratio	271	2.39E+07	---
North Fork Broad River	WCS Sediment Tool – Area Delivery Ratio (reservoirs removed)	214	1.89E+07	---

Table 2.4. Predicted sediment load for six Georgia Rivers.

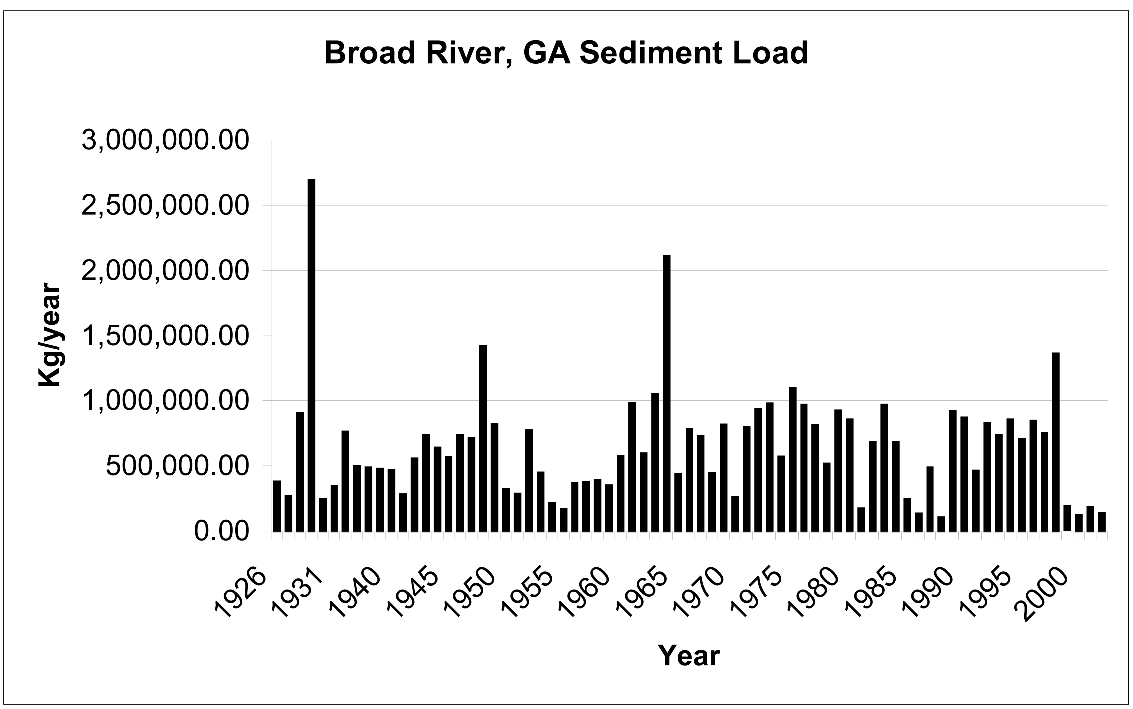

Figure 2.7. Broad River predicted sediment load.

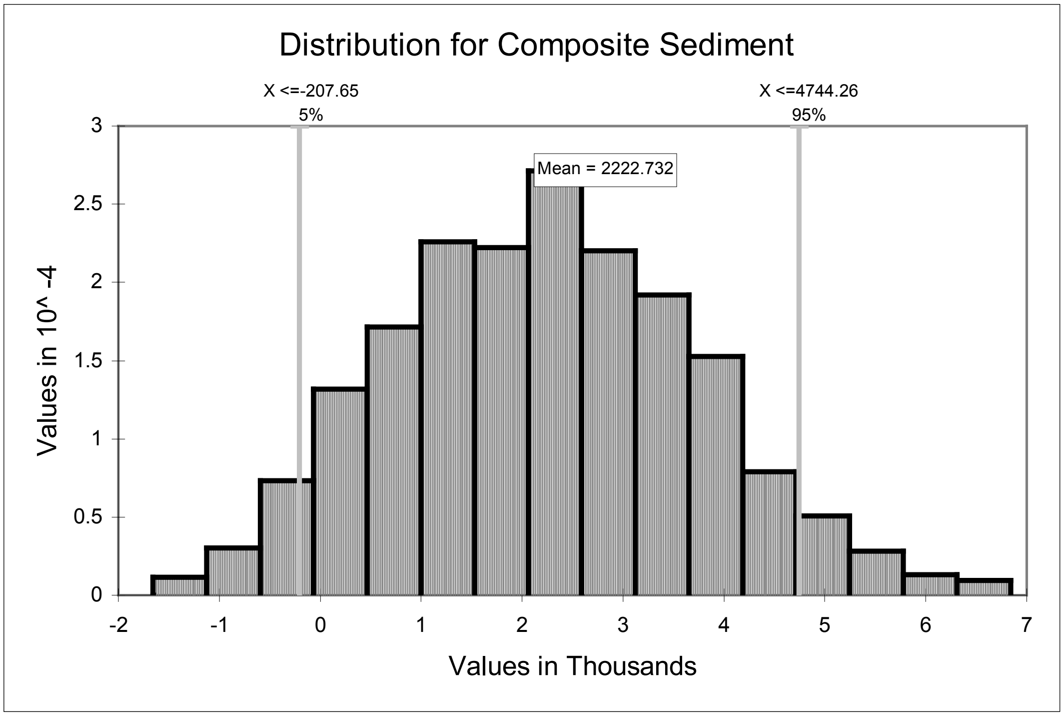

Figure 2.8. @Risk Monte Carlo Simulation Distribution for Composite Sediment.

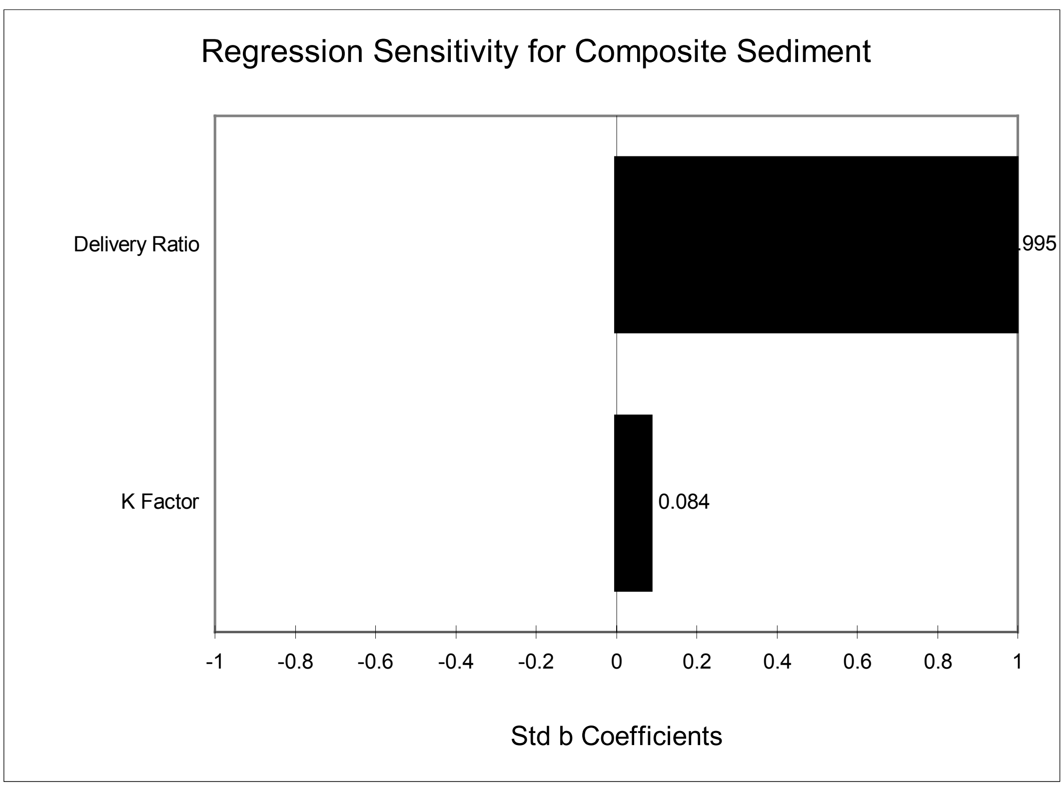

Figure 2.9. @Risk Monte Carlo Simulation Regression Sensitivity for Composite Sediment.

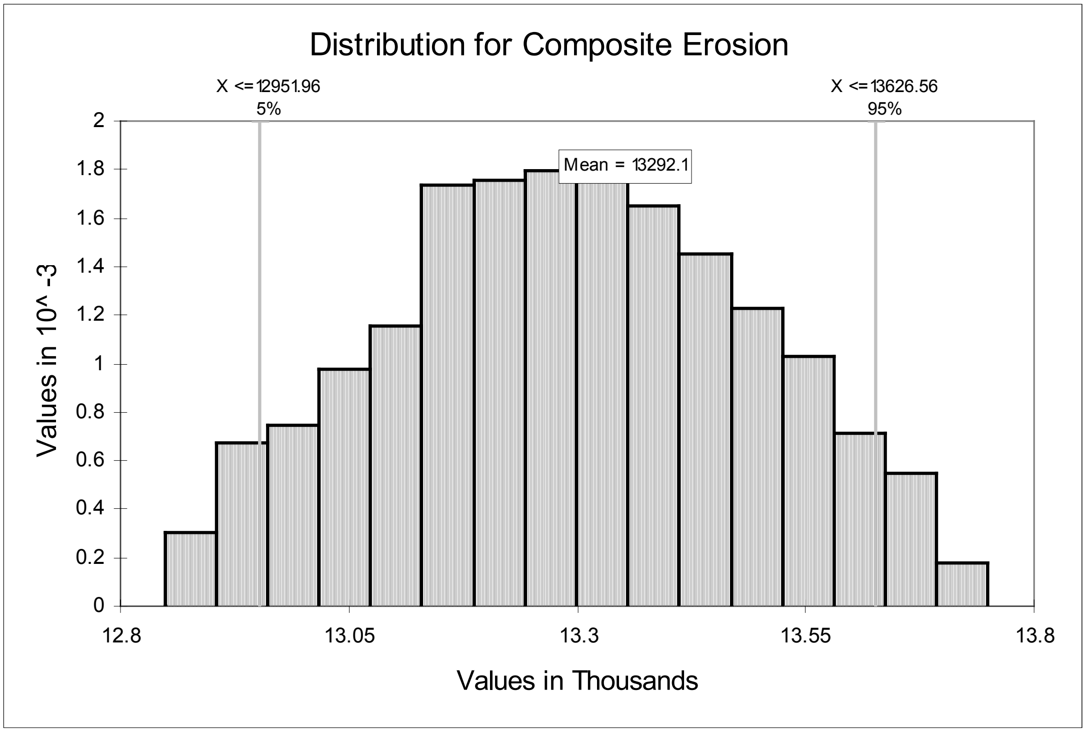

Figure 2.10. @Risk Monte Carlo Model Distribution for Composite Erosion.

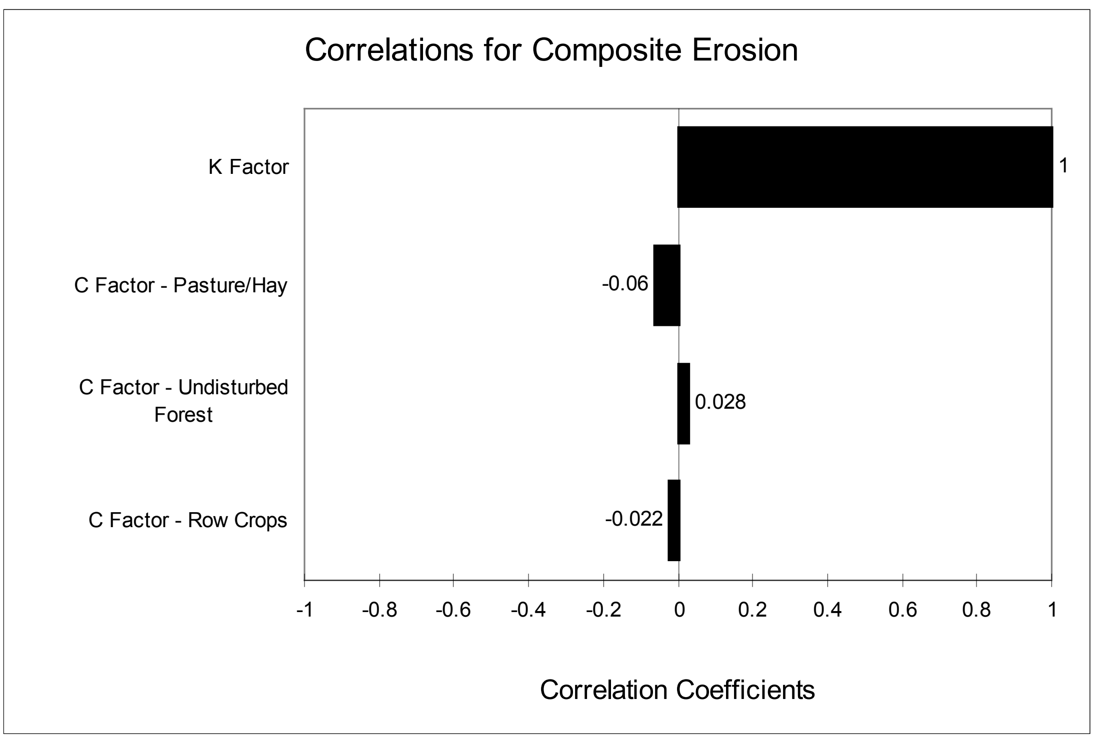

Figure 2.11. @Risk Monte Carlo Simulation Correlations for Composite Erosion.

Appendix A - Erosion and Sediment Yield

Model	Delivery Ratio Method	Erosion us ton/yr	Sediment us ton/yr	Erosion lb/a/yr	Sediment lb/a/yr
Control	DR3	136509.00	11977.10	3089.68	271.08
Control	DR1	136509.00	4977.99	3089.68	112.67
Control	DR2	136509.00	24763.90	3089.68	560.49
Control	DR4	136509.00	1997.87	3089.68	45.22
BMP	DR3	94458.70	8287.65	2137.93	187.58
BMP	DR1	94458.70	4389.48	2137.93	99.35
BMP	DR2	94458.70	19532.80	2137.93	442.10
BMP	DR4	94458.70	1476.31	2137.93	33.41
Construction	DR3	147056.00	12902.50	3328.39	292.03
Construction	DR1	147056.00	5221.08	3328.39	118.17
Construction	DR2	147056.00	26287.20	3328.39	594.97
Construction	DR4	147056.00	2259.18	3328.39	51.13

Table A.1. Erosion and Sediment Yield by Delivery Ratio Method and Model type.

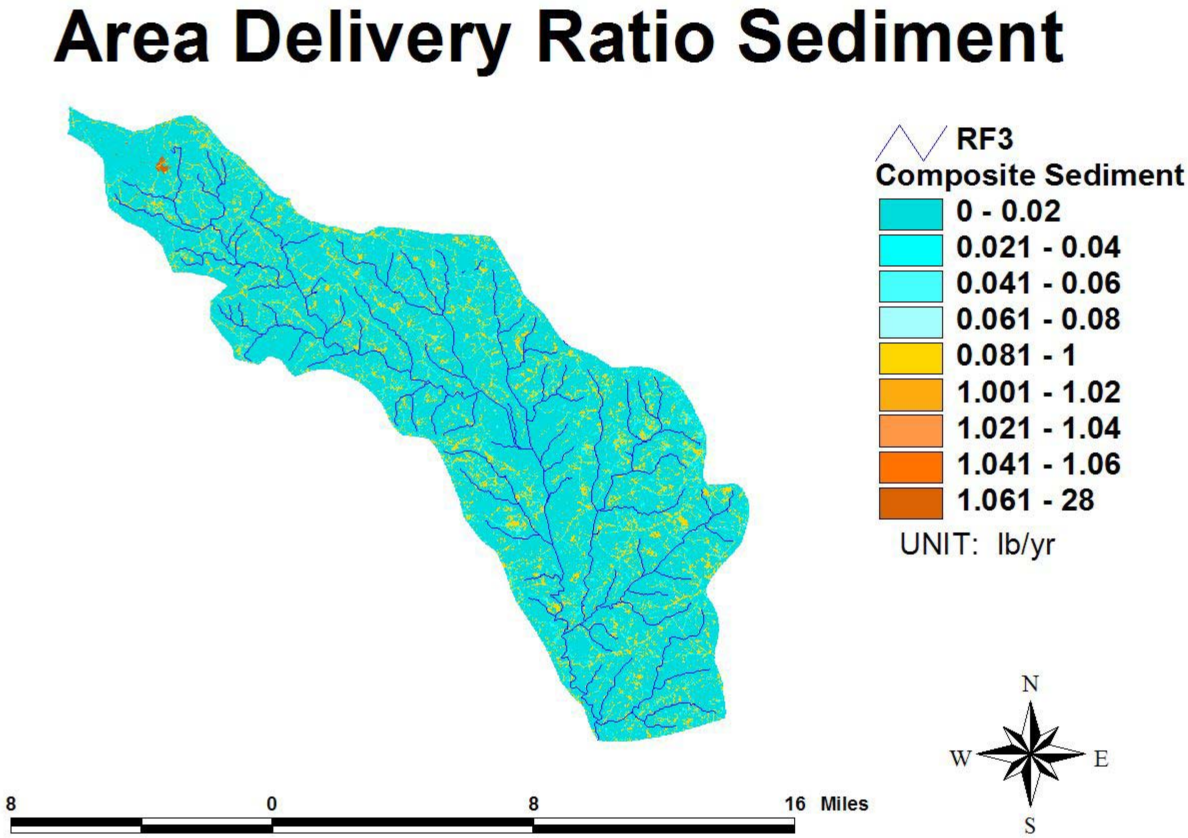

Figure A.1. Area Delivery Ratio Sediment Yield map.

BMP Layer

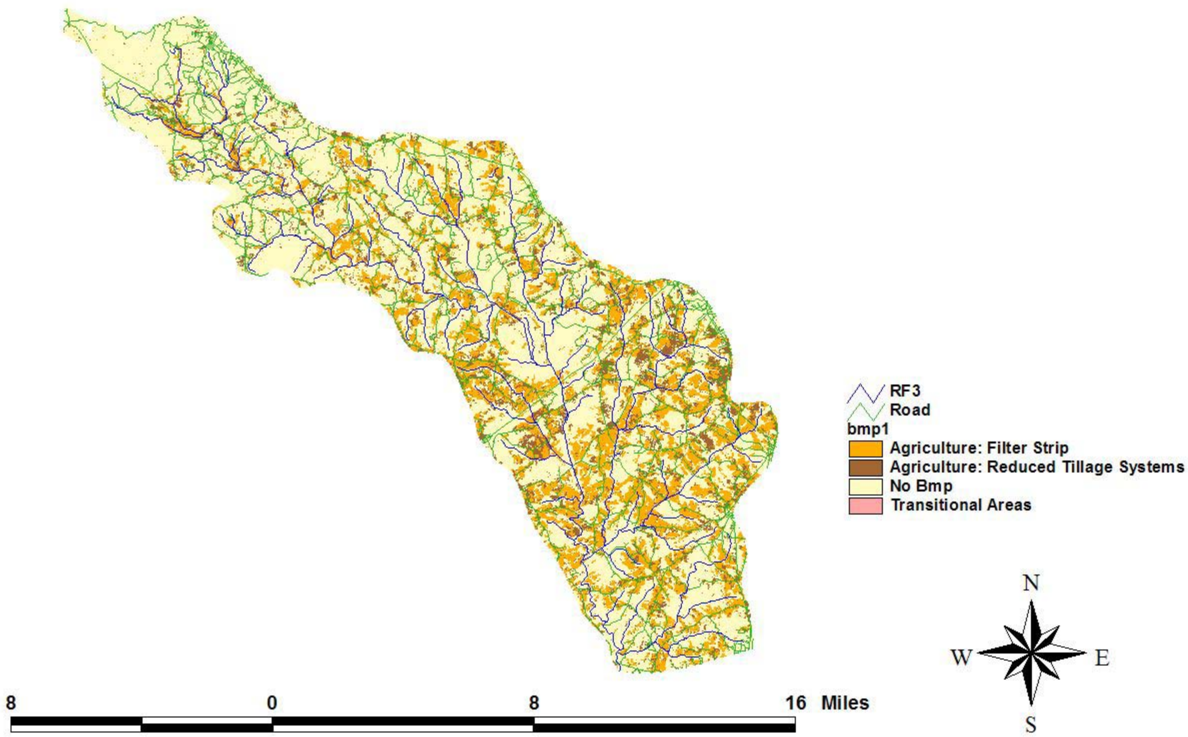

Figure A.2. BMP Layer Map

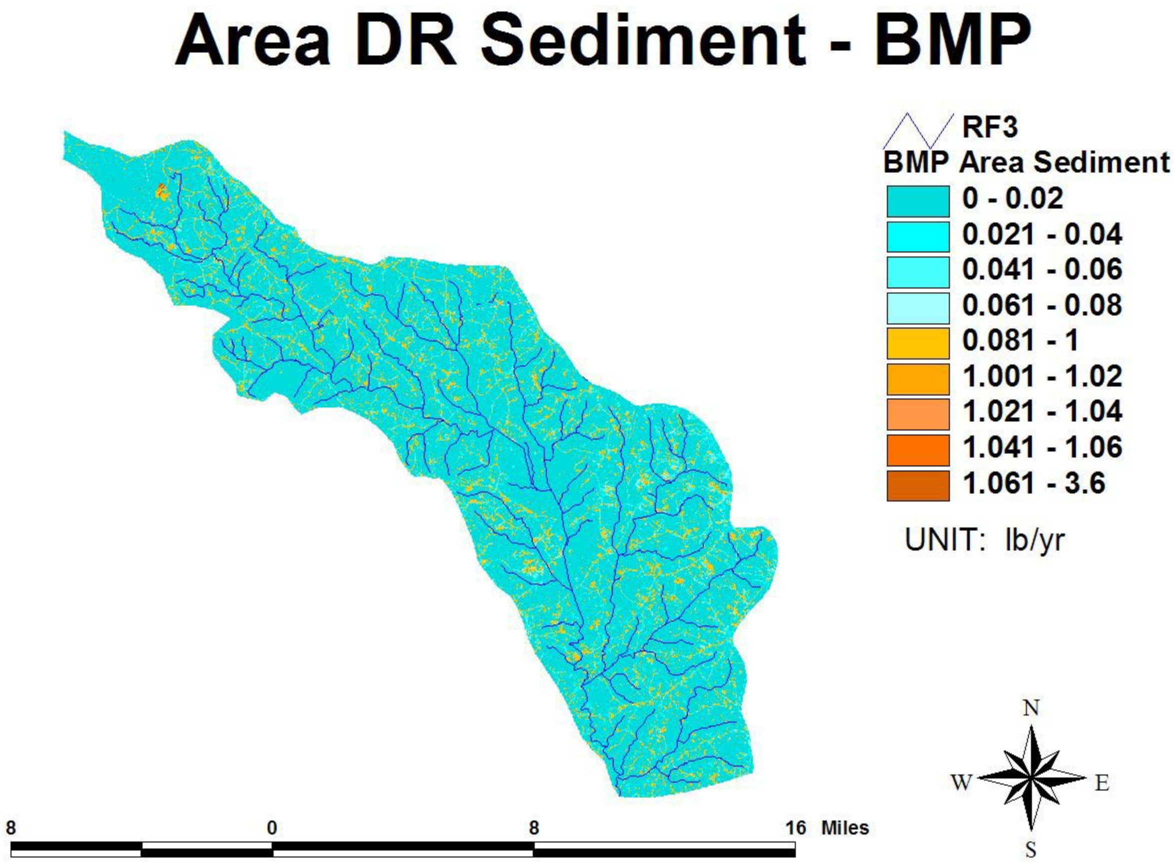

Figure A.3. Area Delivery Ratio Sediment for BMP model.

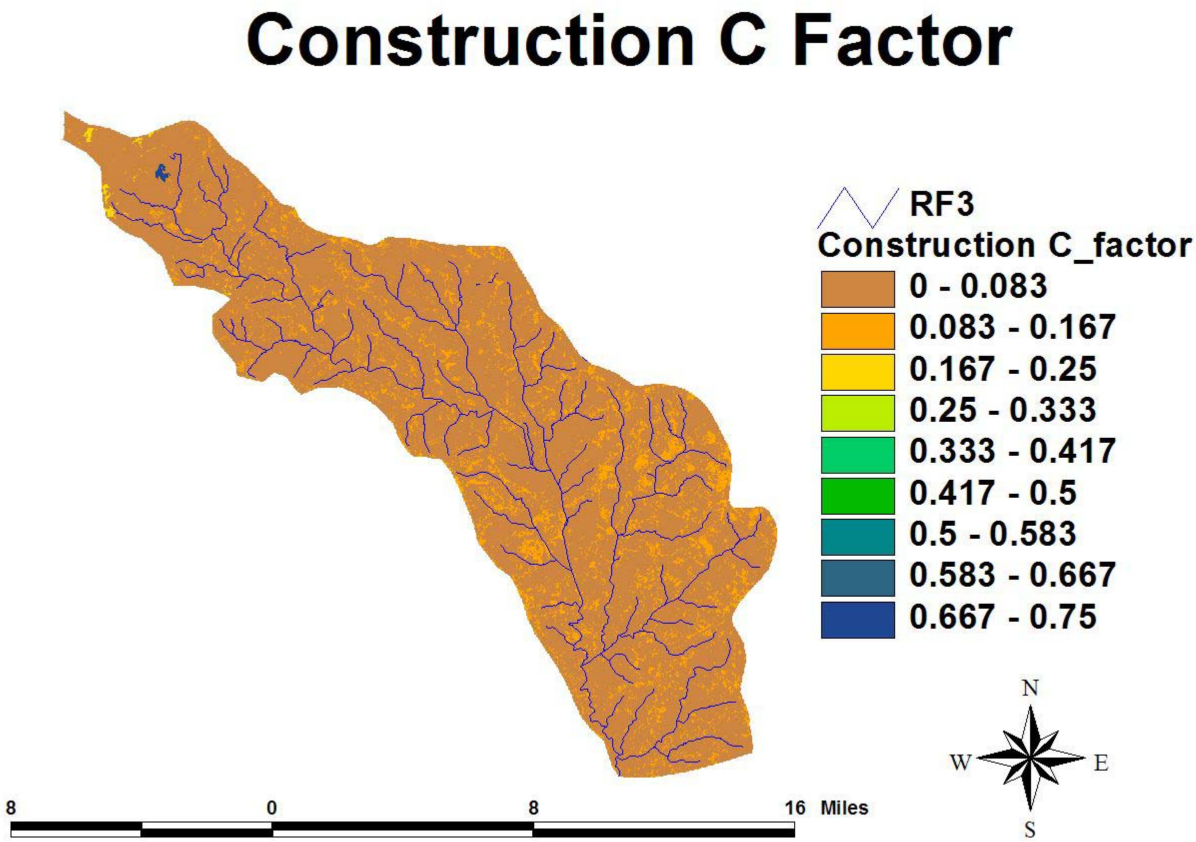

Figure A.4. *C*-values for Construction Layer.

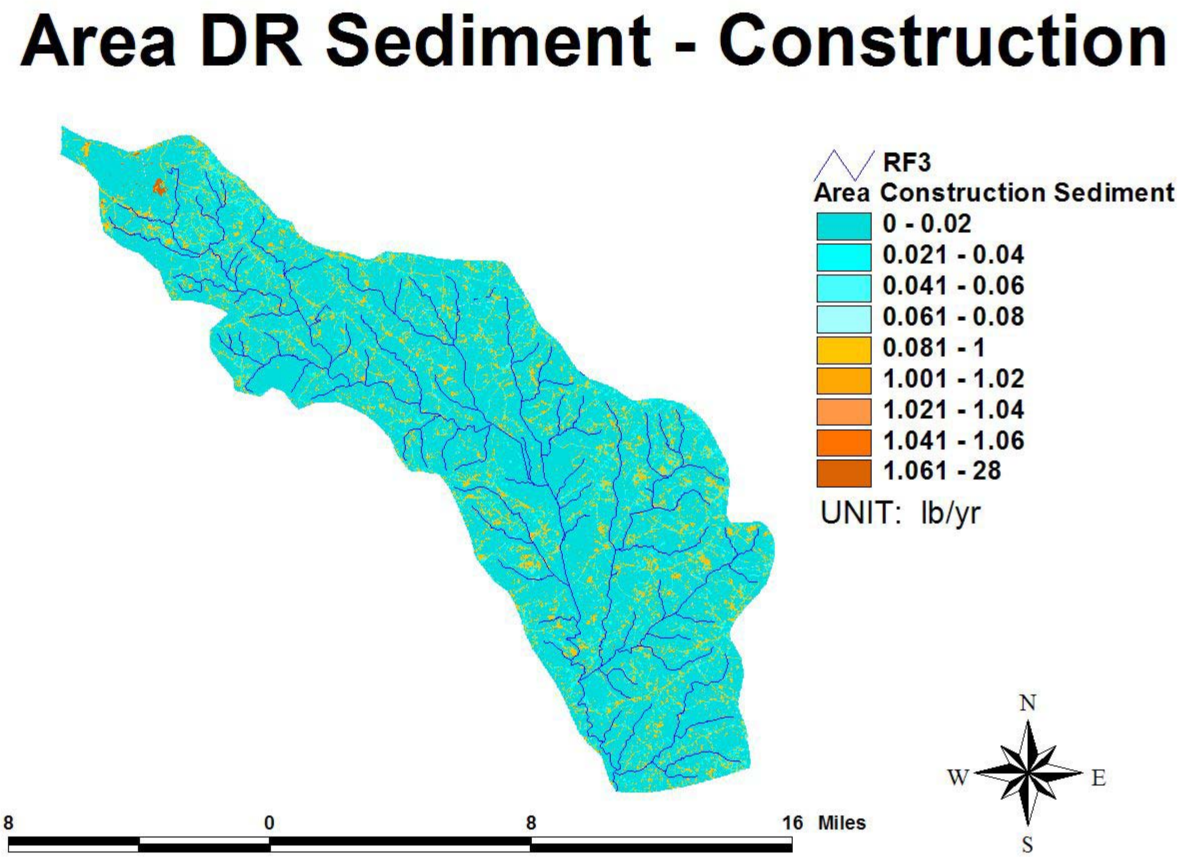

Figure A.5. Area Delivery Ratio Sediment for Construction Model.

Appendix B – Delivery Ratio Comparison BMP and Construction Graphs

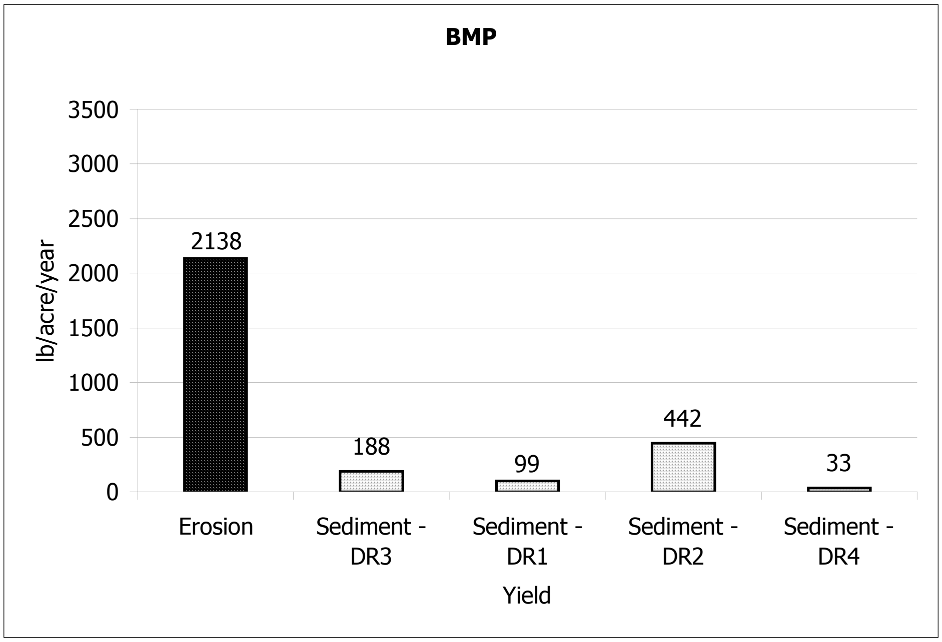

Figure B.1. Erosion and sediment totals for the BMP model of all four DR methods.

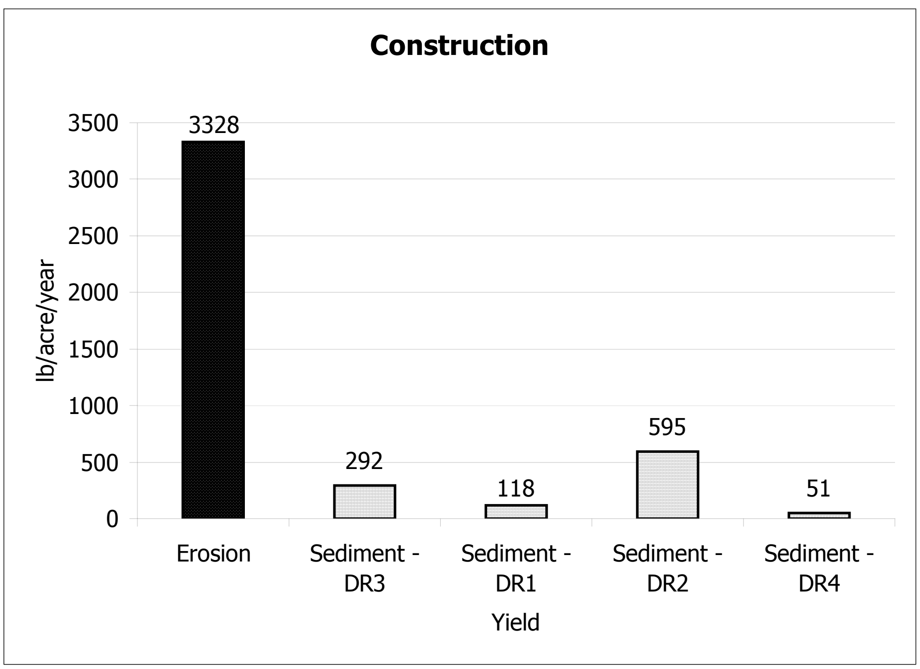

Figure B.2. Erosion and sediment totals for the construction model of all four DR methods.

Appendix C - Example Bell, GA Flow and Suspended Sediment Concentration Data.

Date	Water Discharge cfs	Suspended sediment concentration mg/L
1/14/1958	1750	44
1/21/1958	1200	19
1/29/1958	2000	72
2/11/1958	1950	82
2/27/1958	8400	460
3/6/1958	1700	36
3/12/1958	2650	56
3/25/1958	5500	120
4/15/1958	2800	97
4/23/1958	3000	89
6/25/1958	760	42
8/27/1958	940	29
9/21/1958	440	26
10/31/1958	460	9
11/17/1958	564	14
12/13/1958	605	10
12/16/1958	680	15
12/19/1958	640	11
12/21/1958	520	10
12/26/1958	670	13
12/29/1958	1980	160
12/29/1958	1990	227
12/30/1958	1240	112
12/31/1958	955	57
1/1/1959	925	45
1/6/1959	795	23
1/11/1959	780	19
1/18/1959	930	34
1/21/1959	760	20
1/22/1959	1300	165
1/22/1959	1660	185
1/23/1959	2520	336
1/23/1959	2150	397
1/24/1959	1300	162
1/26/1959	1040	60
2/1/1959	910	50
2/4/1959	1820	157
2/4/1959	2600	234

Appendix D - Example Chattahoochee River near Cornelia, GA Flow and Suspended Sediment Concentration

Date	Water Discharge cfs	Suspended Sediment Concentration mg/L
10/22/1975	801	6
12/5/1975	724	4
1/14/1976	1270	45
3/10/1976	976	21
4/7/1976	1210	11
5/19/1976	1330	21
11/3/1976	572	12
12/15/1976	2570	155
3/9/1977	753	21
2/8/1978	1150	7
3/23/1978	902	15
5/4/1978	777	26
7/26/1978	418	26
9/7/1978	472	21
10/20/1978	298	7
3/5/1979	3460	161
5/15/1979	1220	17
9/18/1979	557	10
10/30/1979	1220	38
12/4/1979	792	19
1/24/1980	1150	19
3/4/1980	669	3
5/27/1980	1200	11
7/8/1980	655	18
8/19/1980	378	9
10/3/1980	586	20
11/18/1980	511	6
12/16/1980	354	5
2/5/1981	310	5
3/17/1981	446	5
4/28/1981	349	7
6/12/1981	792	38
7/21/1981	188	6
10/13/1981	236	7
12/1/1981	1350	131
2/18/1982	1320	24
3/29/1982	725	4
5/10/1982	676	9

Appendix E - @Risk Output

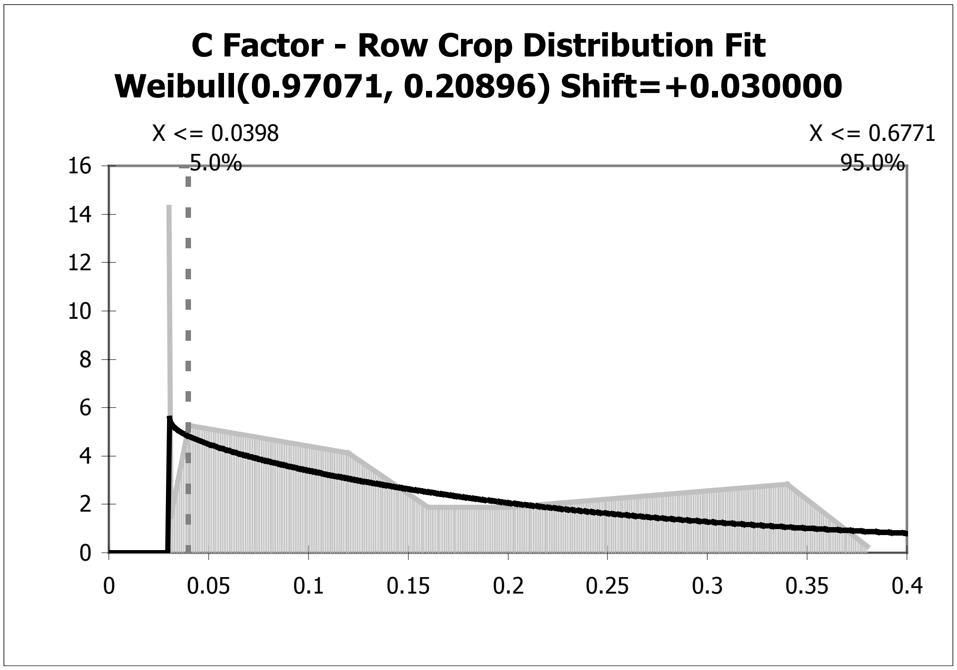

Figure E.1. C Factor - Row Crop @Risk Distribution Fit. Weibull distribution with alpha of 0.97071, beta of 0.20896, and a shift of 0.03.

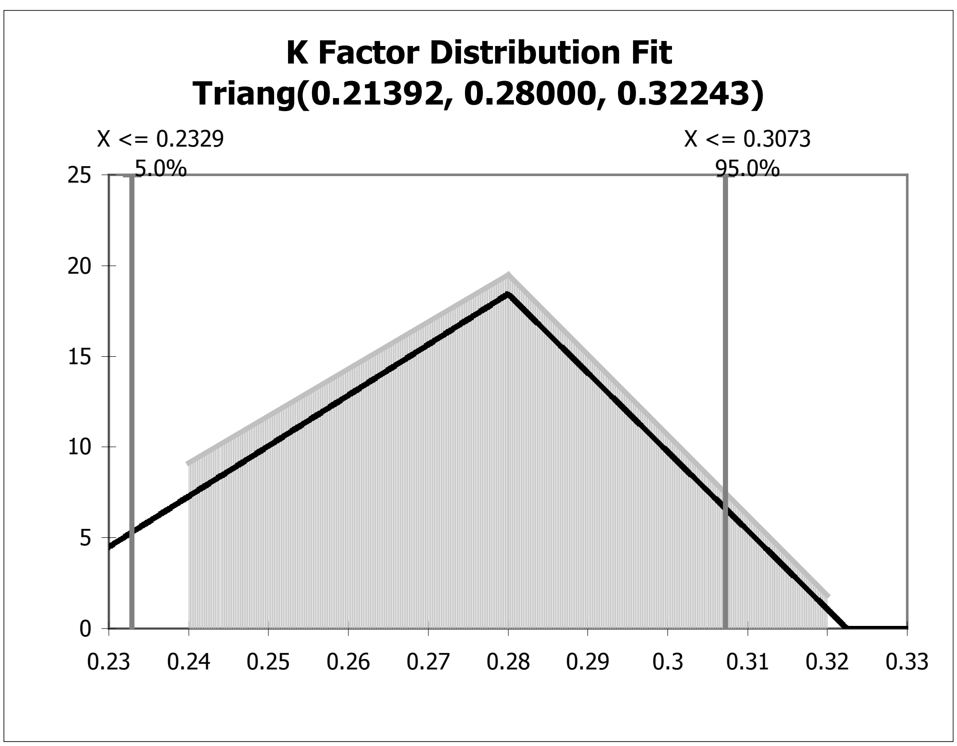

Figure E.2. K Factor @Risk Distribution Fit. Triangular distribution with a minimum of 0.21392, maximum of 0.32243, and a most likely value of 0.28.

	Composite Erosion
Iterations	**Monte Carlo Output**
1	13481.82422
2	13039.9209
3	13090.10352
4	13295.92285
5	13199.83496
6	13461.19824
7	13166.43262
8	13116.85059
9	13257.16113
10	13257.55664
11	13298.33691
12	13066.41895
13	13063.95508
14	13072.66309
15	13430.38086
16	13686.68457
17	13475.18945
18	13655.1416
19	13176.71191
20	13354.57129
21	13267.04297
22	13205.46484
23	13105.54199
24	13626.56445
25	13228.70605
26	13211.26172
27	13307.17285
28	13182.88184
29	13418.82129
30	13269.67285
31	13588.26855
32	13565.49316
33	13651.48926
34	13520.20117
35	13446.26465

Table E.1. Example @Risk Monte Carlo Output (first 35 iterations) for Composite Erosion.