Targeting Critical Sediment Source Areas using SWAT and WEPP Roads

Michael J. White
Agricultural Engineer, USDA-ARS Grassland, Soil, and Water Research Laboratory
808 East Blackland Road , Temple, Tx 76502-6712

Daniel E. Storm
Professor, Biosystems and Agricultural Engineering Department
110 Ag Hall, Oklahoma State University, Stillwater, OK 74078-6021

Several state and federal conservation programs provide financial assistance or benefits for landowners who remove cropland from production or implement soil and water conservation measures. Due to limited funding, only a small fraction of a watershed can be included in such programs. The goals of this project were to: (1) Define priority areas in which landowners would be given first access to available funds, or to target specific fields for recruitment into conservation programs and (2) Evaluate the sediment contribution from county roads and target specific road segments for improvement. Two Oklahoma basins were considered, Stillwater Creek and Cobb Creek. Land cover data for both basins were derived from 2001 LandSat TM+ imagery. Both basins were modeled using SWAT and WEPP Roads. SWAT model results for sediment were extrapolated to a 30 meter grid for each basin using the original soils, land cover and Digital Elevation Model themes. This grid was used to target the 5% of the basin with the greatest sediment yield, which accounted for 31% and 75% of the total sediment load for the Fort Cobb and Stillwater Creek Basins, respectively. Visits to fields marked as priority areas visually corroborated that the model was targeting highly erodible fields. Likewise road segments predicted to have high erosion were visually corroborated. Responses from the local conservation personnel and landowners to the targeting maps were positive. The identification of critical source areas at the watershed scale may enable conservation programs to place practices where they are needed most. © *2010 Oklahoma Academy of Science.*

INTRODUCTION

Soil erosion and transport by flowing water is a natural process which influences turbidity, nutrient availability and habitat in aquatic systems. These factors shape riverine and lacustrine biological communities. While sediment is a natural part of all aquatic systems, excessive sediment is a leading cause of water quality impairment. Excessive sediment increases nutrient availability, reduces light penetration and silts in microhabitats needed by many aquatic species (Soulsby et al., 2001). Excessive sediment and turbidity were the fifth and tenth leading causes of impairment for water bodies in the U. S. (EPA, 2010). Areas subject to soil disturbance with little surface vegetation or cover such as construction sites and cultivated agricultural fields are often large contributors. Sediment pollution is particularly insidious because it impairs not only receiving waters, but its loss also degrades the agricultural lands from which it came. Agricultural soil erosion exceeds soil formation by several times to several orders of magnitude (Montgomery, 2007). Sediment carries with it many of our other water quality concerns such as nitrogen, phosphorus, metals and pesticides.

The process of erosion is complex; land cover, topography, soil characteristics, rainfall and management all influence soil erosion (Wischmeier and Smith, 1978). Erosion has a high degree of spatial variability due to the heterogeneity of its influencing factors. The intersection of steep slopes, erosive land covers and susceptible soils may result in dramatically higher erosion rates in some portions of the landscape. Areas which contribute significantly more sediment relative to the surrounding landscape are referred to as critical source areas.

Critical sediment sources can be identified by using simple models like the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). The use of the USLE with Geographic Information Systems (GIS) to map erosion is relatively simple. Most USLE parameters can be derived directly from widely available soils and land cover data. Other parameters such as the length-slope (LS) factor can be estimated from elevation data (Moore and Burch, 1986a; Moore and Burch, 1986b). Sivertun and Prange (2003), used soils, slope, land cover and distance to watercourse within a GIS to predict pollutant loss. They also focused on simple models applicable in commercial GIS products. Although not quantitative, in the sense that actual pollutant loads were predicted, this method is a useful tool to identify critical source areas for planning purposes.

More complex models such as the Hydrological Simulation Program-Fortran (HSPF) (Bicknell et al., 1997) or the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) can also be used to identify critical sediment sources. These models can be calibrated using measured stream flow and sediment concentrations to reduce the uncertainty of their predictions. The SWAT model has been used to target critical source areas within larger watersheds by several researchers. Tripathi et al. (2003) used the SWAT model to identify and prioritize critical sub-watersheds within a larger drainage area. Srinivasan et al. (2005) used SWAT to identify critical source areas for runoff generation. Gitau et al. (2004) used the SWAT model to predict the spatial distribution of phosphorus (P) losses on a 300 ha farm for the purpose of optimizing BMP selection and placement.

The concept of targeting critical source areas has been widely recognized as an important consideration in the placement of soil and water conservation practices within a watershed (Gburek et al., 2002; Pionke et al., 2000; Sivertun et al., 1998). State and federal programs such as the Conservation Reserve Program (CRP), Conservation Reserve Enhancement Program (CREP), Environmental Quality Incentives Program (EQIP) and various state cost-share programs funded by 319(h) and state funds seek to reduce non-point source pollution by implementing conservation practices. These programs have limited funding, thus not every field can be enrolled. To get the most sediment reduction per dollar spent, fields with the highest sediment yields should be considered first.

The Oklahoma Conservation Commission's (OCC) mission is to conserve, protect and restore Oklahoma's natural resources on behalf of the citizens of Oklahoma. The OCC has finite state and 319(h) funding to provide cost-share with landowners who implement soil and water conservation measures. To realize the most benefit per dollar spent, the OCC would like to enroll fields with the highest sediment yield first. In an effort to assist the OCC with this process, SWAT 2000 (Arnold et al., 1998) and LandSat TM+ imagery were used to target fields with high sediment yields in the Cobb Creek and Stillwater Creek Basins for recruitment into cost-share programs. The OCC was also concerned with the contribution of sediment from county roads. Roads are a very visible portion of a watershed, and often perceived by the public to be the largest sediment source. The sediment contribution from roads in each basin was evaluated using the Water Erosion Prediction Project (WEPP) Roads Model.

METHODS AND MATERIALS

Study area

Both Cobb Creek and Stillwater Creek are located in Oklahoma (Figure 1). Both areas were Oklahoma Conservation Commission priority watersheds and heavily involved in agriculture (>50%). Selected basin statistics are given in Table 1. A full description of the basin is given in each project report (Storm et al., 2003a; Storm et al., 2003b). Cultivated crops such as wheat, sorghum, peanuts, cotton and soybeans are the primary agricultural activity in the Cobb Creek basin. These crops are often grown in double cropping rotations, particularly in the 10% of the basin under irrigation. Lack of moisture usually limits dry land double cropping in western Oklahoma. The type of rotations and crop vary from year to year as influenced by market conditions. The primary agricultural activity in the Stillwater Creek Basin is cattle production on pastures. A relatively small (8.0%) of the basin is cultivated, mostly wheat which is typically grazed.

SWAT Background

The SWAT model was used to estimate sediment and nutrient loading from the upland areas of each basin. SWAT is a distributed parameter basin scale model developed by the USDA Agricultural Research Service. SWAT is effective at a variety of spatial scales (Gassman et al., 2007). Distributed parameter hydrologic models allow a watershed to be broken into many smaller subbasins in order to incorporate additional spatial detail. Water yield and pollutant loads are calculated for each subbasin and routed through a stream network to the watershed outlet. The SWAT model takes this

Table 1. Comparison of the Stillwater Creek and Cobb Creek Basins.

	Stillwater Creek Basin	Cobb Creek Basin
Basin Area (km^2)	715	813
Annual Rainfall (mm)	940	853
Fraction Involved in Agriculture	50%	70% [a]
Fraction Cultivated for Crops	8.0%	51%
Fraction Urban Area	3.5%	0.1%
Fraction Forest	22%	6.0%

[a] Approximate, assuming ½ grassland utilization.

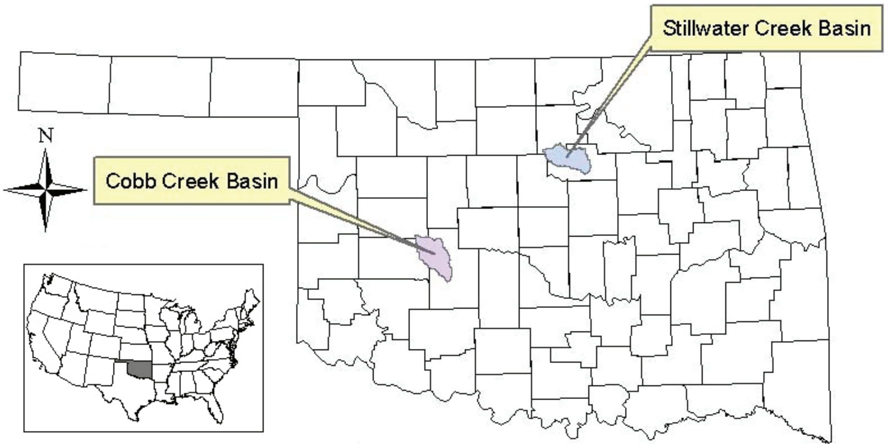

Figure 1. Location of the Stillwater Creek and Cobb Creek Basins.

approach a step further, by incorporating the concept of Hydrologic Response Units (HRUs). An HRU is a unique combination of soil and land cover within a subbasin which is simulated as a single unit. Processes within each HRU are calculated independently and the total nutrient load or water yield for a subbasin is the sum of all the HRUs it contains. HRUs allow more spatial detail to be included by allowing more land cover and soil combinations to be represented in a computationally efficient manner.

Input Data

The data requirements of a distributed model require the use of a GIS interface which generates model inputs from commonly available GIS data. These GIS data are summarized by the interface and converted to a form usable by the model. The following is a list of data that were utilized in the simulations of Stillwater and Cobb creeks.

- 10 m or 30m United States Geologic Survey (USGS) Digital Elevation Model (DEM)
- 200 m Natural Resources and Conservation Service (NRCS) soils data
- 30 m Landsat ETM+ derived land cover
- EPA Reach3 Streams
- NOAA Cooperative Observation Network daily rainfall and temperature

Land cover was derived from 30 meter Landsat 7 ETM+ imagery, digital aerial photos and ground truth data provided by Oklahoma State University (OSU) and OCC personnel. Imagery for June 10, 2001, classified using an unsupervised Iterative Self-Organizing DATA (ISODATA) clustering algorithm. After several iterations these clusters were combined into individual land cover categories.

Identification of Critical Sediment Sources

The identification of critical source areas requires subdividing a basin into individual units followed by evaluating the sediment yield from each unit. Critical sediment source identification using SWAT is generally done at the subbasin level, but HRU level predictions can be used to identify smaller critical sediment sources. By ranking subbasins, or HRUs in terms of predicted sediment yield, critical sources can be identified.

SWAT model HRU level predictions were mapped using the original GIS soils, land use and slopes to create a map of sediment yield for each basin. A database of sediment yield from each soil, land use and slope combination represented as an HRU in SWAT was included. This database was used to predict sediment yield for each grid cell in each basin. Because slope is a continuous variable, sediment yield was adjusted based on the grid cell slope and the HRU slope reported the database for that particular soils and land cover combination. This adjustment was derived from the Universal Soil Loss Equation LS factor using the following equation:

$$E_g = E_o \frac{0.065 + 0.456 S_o + 0.00654 S_o^{\;2}}{0.065 + 0.456 S_g + 0.00654 S_g^{\;2}}$$

where S_0 is HRU slope in percent, S_g is gridcell slope percent, E_0 is HRU erosion rate (Mg/ha), and E_g is the gridcell erosion rate (Mg/ha).

Only one of the models was calibrated to measured data. Calibration is the process by which a model is adjusted to make its predictions more closely match some observed data. SWAT is designed for use on large ungaged basins and can be used without calibration. However, calibration generally improves the reliability of the model predictions. The model for the Cobb Creek Basin was calibrated using two USGS stream gages and 60 water quality samples. Details of the calibration are given in Storm et al. (2003). Insufficient flow and water quality data were available to calibrate the Stillwater Creek Basin model.

Road Erosion Estimation

The Water Erosion Prediction Project (WEPP) Roads model (Elliot et al., 1999) was used to estimate road and bar ditch erosion. Thirty years of weather data were simulated for use in WEPP based on statistics collected at a Weatherford, Oklahoma, weather station. Data on road surfaces, soil textures and bar ditch conditions were collected by OCC personnel for each 0.4 km (1/4 mile) and attributed onto US Census Bureau Topologically Integrated Geographic Encoding and Referencing System (TIGER) road location data. Slope was estimated from USGS 10 or 30 meter DEMs depending on availability.

The WEPP model is particularly sensitive to roads segment length. Segment length is the distance that runoff travels down the bar ditch until it is diverted into a natural drainage such as a stream or a artificial turnout. Increasing segment lengths result in more concentrated bar ditch flow and increased sediment transport capacity. Road segments were defined at every intersection and significant change in the aspect or slope of the road surface. Aspect was derived from a simplified Triangular Irregular Network (TIN) developed from available DEMs using an elevation tolerance of 3 meters. The use of a simplified TIN eliminates small undulations in topography which were likely removed during road construction and maintenance. Despite the importance of segment length no data were available to evaluate this methodology. Each basin contained approximately 11,000 road segments.

The Web Based WEPP Roads model was applied to these data to generate erosion predictions for each section. Roads were assumed to be 10 meters wide including the bar ditches. Bar ditches were assumed to drain the road surface exclusively, no additional contributing area was specified. It is likely that many ditches also drain cut slopes but no data were available to make reasonable estimates.

RESULTS AND DISCUSSION

Field Erosion

The Cobb Creek Basin high-resolution erosion map was visually validated in the field and appeared reasonable; however, a few anomalies were found. In the northwestern portion of the basin several targeted areas were discovered to be gypsum outcroppings that were miss-classified as cropland in the land cover data (Figure 2). These outcrops are common in Cornick soil series which is characterized by its very shallow soil, with only 5-20 inches to gypsum bedrock. This soil is rocky and seldom suitable for tillage. Areas listed in the MIADs soils data as Rough Broken Land were also considered unsuitable for tillage. When the land cover data listed one of these areas as cropland, it was likely miss-classified. Exposed rock and bare soil are similar in color, making it difficult to differentiate them from a satellite image. These areas were tagged as non-typical in the final product (Figure 3). Cropland areas with slopes greater than 15% were also tagged as non-typical. It is unlikely that tillage would be performed in these steep areas. The final product was generated by dividing the basin into four categories:

- High Priority is 5% of the basin with the highest predicted erosion.
- Medium Priority includes the next highest eroding 5%.
- Low Priority covers the remainder.
- Non-typical areas are suspected miss-classifications in land cover including cultivated fields with slopes greater than 15%, gypsum outcroppings, or rough broken land.

High erosion fields in the Stillwater Creek Basin were generally cultivated (Figure 2). Erosion priority areas for Stillwater Creek were visually validated and were reasonable in most areas visited, however a number of land cover misclassifications were identified. The extent of these misclassifications was not sufficient to warrant the

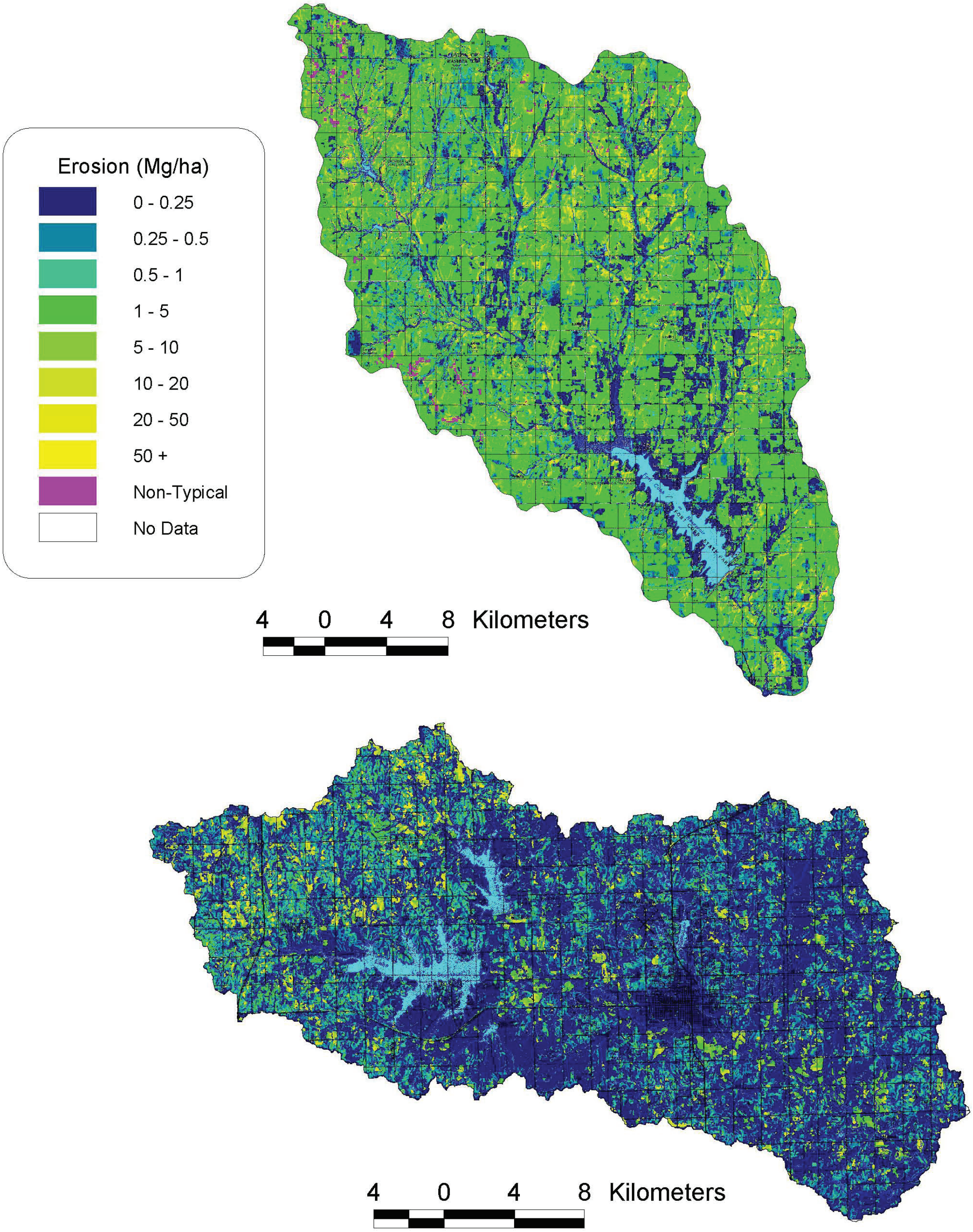

Figure 2. Gridcell Erosion predictions derived from Soil and Water Assessment Tool 2000.

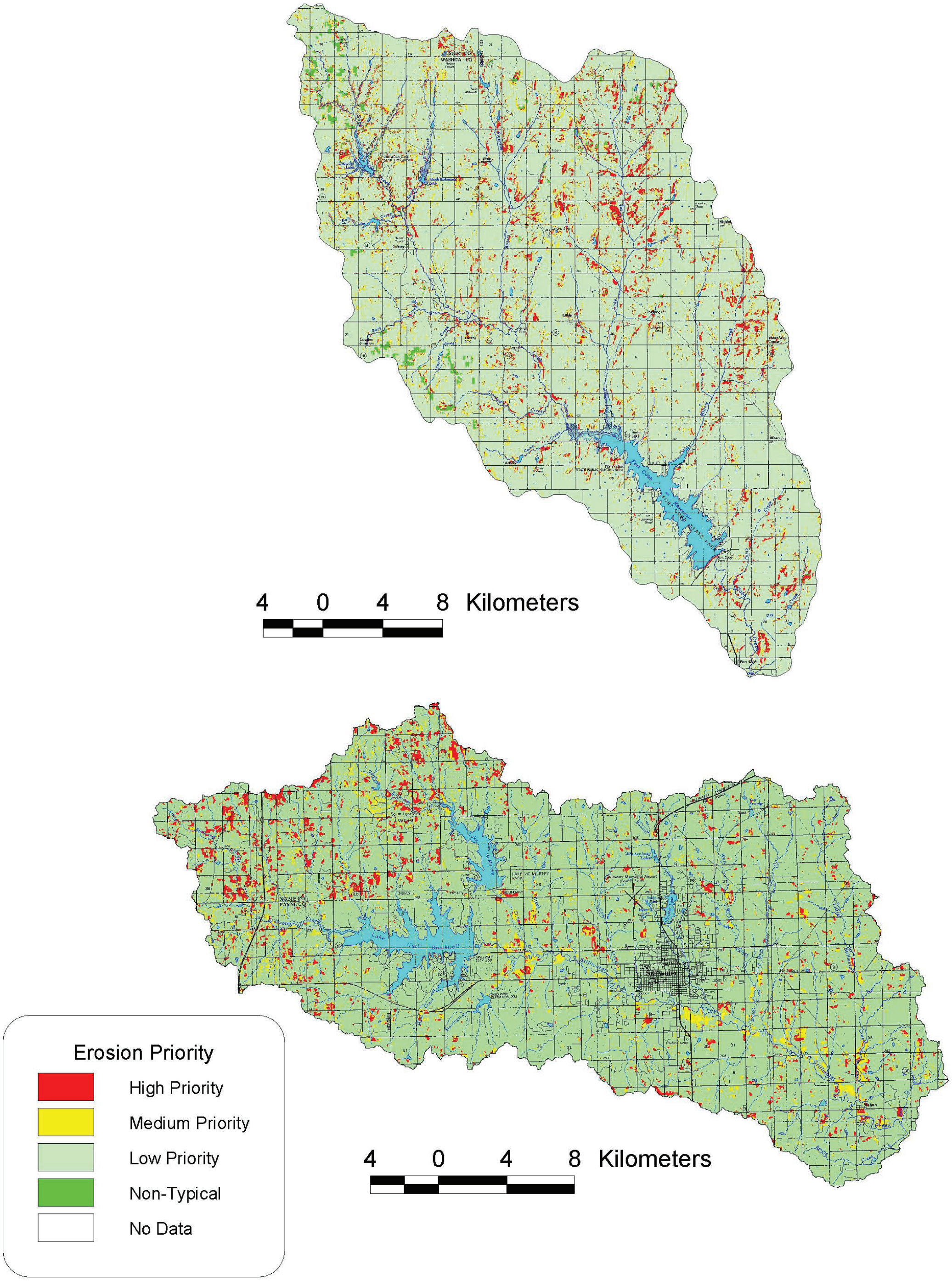

Figure 3. **Erosion Targeting Map. High Priority is 5% of the basin with the highest predicted erosion. Medium Priority includes the next highest eroding 5%. Low Priority covers the remainder. Non-typical areas are suspected miss-classifications in land cover including agricultural fields with slopes greater than 15%, gypsum outcroppings, or rough broken land. Derived from Soil and Water Assessment Tool 2000.**

addition of a non-typical category for the Stillwater Creek Basin (Figure 3).

Road Erosion

Although roads are among the most visible portion of rural watershed, they cover only a small fraction of the total land area. Assuming a 10 m road width, roads covered 1.1% and 1.3% of the Cobb creek and Stillwater Creek Basins. These roads and bar ditches were predicted to generate annual sediment loads of 6,000 and 12,700 Mg respectively. Roads categorized by road surface and bar ditch condition and their average lengths are given in Table 2. The sediment contributions of each category are given in Table 3. Sediment loads from paved roads were disproportionally high as compared to dirt roads, but the paved roads have longer segment lengths on average for some bar ditch conditions. Paved roads also have no infiltration, thus producing higher surface runoff. In addition, bar ditch erosion is very sensitive to segment length and runoff volume.

The predictions of road erosion in the Stillwater Creek basin differ from estimates by other researchers. Peranich et al. (2005) estimated annual sediment yields of 82,000 Mg in the basin by extrapolating measured data collected on 4 unpaved road sections in the basin. This prediction was considerably higher than the 12,700 Mg predicted by WEPP. The extrapolation of data collected at 4 sites to an entire basin generates considerable uncertainty, and the sites were deliberately selected to contain design flaws common to unpaved low traffic volume roads in the basin. Peranich et al. (2005), found the WEPP model to systematically underpredict sediment yields from the same four road segments. Given the uncertainty in the estimation of road segment length and drainage areas it is reasonable to assume that WEPP may have under predicted sediment losses from roads.

Table 2. Road surface and bar ditch categories as a percentage of all roads in Cobb Creek and Stillwater Creek Basin. Data collected by Oklahoma Conservation Commission (OCC) personnel.

	Barditch Type			
Road Surface	Stable	Eroding	Flume	All
Stillwater Creek Basin				
Paved	38	13	0.0	50
Gravel	2.4	46	0.6	49
Gravel and Dirt	0.0	0.1	0.0	0.1
Dirt	0.0	0.8	0.1	0.9
All Surfaces	40	59	0.7	100
Cobb Creek Basin				
Paved	46	7.3	0.6	54
Gravel	11	4.8	0.1	16
Gravel and Dirt	5.7	9.3	0.2	15
Dirt	4.0	11	0.0	15
All Surfaces	67	32	0.9	100

Table 3. Average sediment yield (Mg/km/yr) from roads in Cobb Creek and Stillwater Creek Basin as predicted by the Water Erosion Prediction Project (WEPP): Roads Model.

	Barditch Type			
Road Surface	Stable	Eroding	Flume	All
Stillwater Creek Basin				
Paved	2.9	15	0.0	6.0
Gravel	9.4	21	18	20
Gravel and Dirt	0.0	26	0.0	26
Dirt	0.0	48	19	43
All Surfaces	3.3	20	17	13
Cobb Creek Basin				
Paved	2.1	10	0.0	3.2
Gravel	7.7	15	13	10
Gravel and Dirt	6.5	18	24	14
Dirt	4.9	9.0	11	7.9
All Surfaces	3.6	13	6.2	6.7

ACKNOWLEDGMENT

We would like to acknowledge the Oklahoma Conservation Commission, the US Environmental Protection Agency Region VI and the Oklahoma Agricultural Experiment Station for funding this research.

REFERENCES

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large Area Hydrologic Model Development and Assessment Part 1: Model Development. Journal of the American Water Resources Association, 34(1):73-89.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, A.S. Donigian, and R.C. Johanson. 1997. Hydrological Simulation Program—FORTRAN User's Manual for Version 11. EPA - National Exposure Research Laboratory, Triangle Park, NC.

Elliot, W.J., D.E. Hall, and D.L. Scheele. 1999. WEPP Interface for Predicting Forest Road Runoff, Erosion and Sediment Delivery Technical Documentation. USDA Forest Service, Rocky Mountain Research Station, Moscow, ID.

EPA. 2010. Fact Sheet: Introduction to Clean Water Act (CWA) Section 303(d) Impaired Waters Lists. Online: http://www.epa.gov/owow/TMDL/results/pdf/aug_7_introduction_to_clean.pdf (verified 2-15-10).

Gassman, P.W., M.R. Reyes, C.H. Green, and J.G. Arnold. 2007. The Soil and Water Assessment Tool: Historical Development, Applications and Future Research Directions. Transactions of the ASABE, 50:1211-1250.

Gburek, W.J., C.C. Drungil, M.S. Srinivasan, B.A. Needelman, and D.E. Woodward. 2002. Variable-source-area controls on phosphorus transport: Bridging the gap between research and design. Journal of Soil and Water Conservation 57:534-543.

Gitau, M.W., T.L. Veith, and W.J. Gburek. 2004. Farm-level optimization of BMP placement for cost-effective pollution reduction Transactions of the ASAE 47:1923-1931.

Montgomery, D.R. 2007. Is agriculture eroding civilization's foundation? GSA Today 17(10):4-9.

Moore, I., and G. Burch. 1986a. Modeling erosion and deposition: topographic effects. Transactions of the ASABE, 29(6):1624-1630.

Moore, I.D., and G.J. Burch. 1986b. Physical Basis of the Length-slope Factor in the Universal Soil Loss Equation. Soil Science Society of America, 50(5):1294-1298.

Peranich, C.M. 2005. Measurement and modeling of erosion from four rural unpaved road segments in the Stillwater Creek watershed. Masters thesis, Oklahoma State University, Stillwater, Ok.

Pionke, H.B., W.J. Gburek, and A.N. Sharpley. 2000. Critical source area controls on water quality in an agricultural watershed located in the Chesapeake Basin. Ecological Engineering, 14(4):325-335.

Sivertun, A., and L. Prange. 2003. Non-point source critical area analysis in the Gisselo watershed using GIS. Environmental Modelling & Software 18(10):887-898.

Sivertun, A., L.E. Reinelt, and R. Castensson. 1998. A GIS method to aid in non-point source critical area analysis. International Journal of Geographical Information Science 2(4):365-378.

Soulsby, C., A.F. Youngson, H.J. Moir, and I.A. Malcolm. 2001. Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment. The Science of the Total Environment, 265:295-307.

Srinivasan, M.S., P. Gerard-Marchant, T.L. Veith, W.J. Gburek, and T.S. Steenhuis. 2005. Watershed scale modeling of critical source-areas of runoff generation and phosphorus transport. Journal of the American Water Resources Association 41(2):361-377.

Storm, D.E., M. White, and S. Stoodley. 2003a. Stillwater Creek Modeling and Land Cover Classification.

Storm, D.E., M.J. White, and S. Stoodley. 2003b. Fort Cobb Basin - Modeling and Land Cover Classification.

Tripathi, M.P., R.K. Panda, and N.S. Raghuwanshi. 2003. Identification and Prioritization of Critical Sub-watersheds for Soil Conservation Management using the SWAT Model. Biosystems Engineering 85(3):365-379.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting Rainfall Erosion Losses Agricultural Handbook 537. US Department of Agriculture, Washington, DC.

White, M.J., D.E. Storm, P.R Busteed, S.H. Stoodley, S.J. Phillips, 2009. Evaluating nonpoint source critical source area contributions at the watershed scale. Journal of Environmental Quality. 38(4): 1654-1663.

Received: August 12, 2010; Accepted December 3, 2010.