# ESTIMATING SEDIMENT YIELD IN THE SOUTHERN APPALACHIANS USING WCS-SED

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**Abstract:** We measured and modeled sediment yield over two months on five watersheds in the southern Appalachian Mountains of North Carolina. These watersheds contained first and second-order streams and are primarily forested, but span the development gradient common in this region, with up to 10 percent in suburban and transitional development and up to 27% low-intensity agriculture. Sediment yield was measured using automated pumped samplers, continuous depth measurements, and gravimetric analysis. Sediment yield was predicted using WCS-SED for the coincident period employing fine and medium-resolution elevation, soils, and land use data. Mean sediment yield varied from 0.025 to 0.344 t/ha/yr and was strongly related to the proportion of non-forest area in the watershed. Sediment yield was not related to road density within the watershed or in near-stream areas. Predicted sediment yield was several times higher than observed sediment yield on four of five watersheds, with the most agriculturally developed watershed serving as the exception. Sediment yield was high over the plausible range of USLE land use and cropping factors that underlie the sediment yield predictions.

## INTRODUCTION

Section 303(b) of the Clean Water Act requires that states identify water bodies that are unlikely to meet ambient water quality standards. The states must also identify a Total Maximum Daily Load (TMDL) for each constituent pollutant, and develop a plan to maintain inputs below these values. Sediment from erosion is the most common pollutant in many streams of the southeastern United States. Suspended sediment levels above 20-30 mg/L have been shown to degrade stream biotic integrity (Walters et al., 2001), and impairment may occur at lower concentrations.

Models may be used to estimate sediment generation in uplands and sediment transport to streams. However, model accuracy, appropriate parameters, and sensitivity to input data quality must be determined prior to accepting sediment yield predictions as a monitoring or management tool. When these models are spatially explicit and run in a grid-cell environment, the appropriate cell size, data sources, and model parameters must be identified.

We report on a test of one widely-use sediment model, the Watershed Characterization System – Sediment Tool (WCS-SED), developed by Tetra Tech, Inc., in cooperation with the US Environmental Protection Agency, Region 4. This model is representative of cell-based erosion generation and transport models that use the Universal Soil Loss Equation (USLE) and derivatives (Kinnell and Risse 1998, Hood et al., 2002). We measured suspended sediment transport in five small watersheds in the southern Appalachian Mountains, and compared these to sediment yield predicted with WCS-SED. We evaluated the impact of input data resolution by varying the cell size for elevation data, and the cell size and categorical detail for land use and soils data within each watershed. We estimated the importance of stream network specification, and the sensitivity of predicted sediment yield to variation in the cropping factors for each land use type.

## METHODS

**Study Watersheds:** Analyses were conducted on five study watersheds spanning a range of areas and land use practices in the southern Appalachian Mountains, USA (Figure 1, Table 1). These watersheds represented the current and past land uses typical of many first and second order streams in the southern Appalachian. Watersheds were predominantly forested with varying histories of prior agriculture in near stream portions, and current increases in road and residential development. Two watersheds (Addie Branch and Dryman Fork) were on US Forest Service land and differed primarily in road density, two were forested with light residential development (Reed Mill and Watauga Creek), and one was primarily forested with moderate pasture agriculture and light residential development. Roads were predominantly unpaved gravel, and road density varied within the ranges typical of the region.

Table 1: Characteristics of Study Watersheds

| Name | Area (ha) | Road density (m/ha) | Forest (%) | Agric. (%) |
|---|---|---|---|---|
| Addie Branch | 574 | 6.54 | 100.0 | 0 |
| Dryman Fork | 153 | 42.57 | 100.0 | 0 |
| Sutton Branch | 132 | 14.97 | 72.6 | 26.2 |
| Reed Mill | 440 | 11.12 | 95.8 | 0 |
| Watauga Creek | 1,675 | 40.64 | 87.3 | 4.9 |

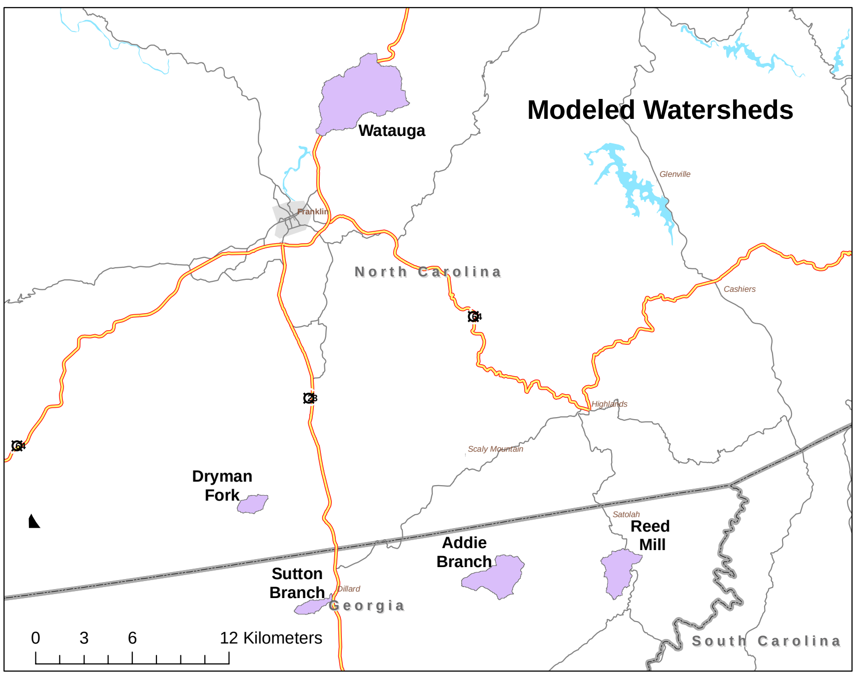


Figure 1 Watersheds in this study

**Spatial Data Collection:** Watershed boundaries were delineated from US Geological Survey (USGS) National Elevation Datasets (NED), 10 meter resolution, using a flowpath analysis (Bolstad, 2005). These boundaries were used to extract elevation, slope, roads, soils, stream, and land use data from developed and new sources.

Elevation data were derived from three sources. Ten meter (NED) and 30 meter (1:24,000 scale quad-based) resolution raster data were extracted from USGS sources, and slope derived using a third-order finite difference algorithm (Bolstad, 2005) for all study watersheds. A three-meter resolution DEM was created from digitized contours of a 1:7,200 paper map produced by the US Forest Service for the Dryman Fork basin. Roads were extracted from 1:24,000 scale USGS digital line graph data, and updated based on interpretation of May 2003

SPOT 2.5 meter satellite images. Soils data were digitized from US Natural Resource Conservation Service soil survey data, both county-level (SSURGO) and statewide (STATSGO).

Land use data were derived from two sources. Moderate resolution data were extracted from the 1990s National Land Cover Dataset (NLCD, Vogelman et al., 1998). Landcover was resolved into one of 21 potential classes for 30 meter cells for the entire United States based primarily on early 1990s Landsat satellite images, 30 meter DEMs, and US Census data. Data were extracted for each study watershed. From four to 10 categories were present in the watersheds. Classification accuracies were above 60% for all watersheds, and above 86% when aggregating mature forest classes.

High resolution land use (UMN) data were manually interpreted from resolution-merged SPOT satellite images collected in May 2003. Panchromatic 2.5 meter data were merged with 10 meter multispectral data using a principal component transform (Pohl and Van Generen, 1998). Land use was assigned to NLCD categories. Withheld points indicate the classification accuracy above 96% when aggregating mature forest classes.

**Water Sampling:** Flow data and water quality samples were gathered with automated pumping samplers, as described in Riedel et al., (2004). Stream stage was logged on 15 minute intervals with submerged pressure transducers. Data were checked via manual gauging on a weekly basis. Samplers collected water samples, calibrated via manual depth integrated sampling, under baseline conditions and storm flow conditions. Samples were analyzed gravimetrically to determine total suspended solids (TSS) to 1.5 μm and combusted to determine ash-free dry weight (USGS, 1978).

**Field Data Analysis:** Sediment concentration data were paired with discharge data based upon sediment/discharge rating curves to calculate sediment transport during the calibration period. Due to a hysteretic relationship between sediment and discharge on Addie Branch and Dryman Fork, separate rating curves were generated for rising and falling limbs of stormflow hydrographs. The curves were generated using filtered data. Filtering was based on hydrograph regime, dQ/dt, computed as the percent difference in stream flow over three consecutive intervals; a one percent threshold for dQ/dt most consistently differentiated hydrograph regime. The reader is directed to Riedel, et al., (2004) for a complete discussion of the methods. A summary of filtering is shown in Table 2. Cumulative sediment transport was estimated for an approximate two-month period spanning June and July, 2003.

Table 2 Filtering limits for defining hydrographs and sediment regimes

| Percent change in slope | Hydrograph regime | Sediment regime |
|---|---|---|
| $dQ/dt > 1$ | Rising Limb | Proportional increase with flow. |
| $-1 < dQ/dt < 1$ | Baseflow | Low (<10 ppm) |
| $dQ/dt < -1$ | Recession Limb | Disproportional decrease with flow, then low (<10ppm). |

**Model Runs:** Sediment yield was estimated through application of the WCS model, sediment tool module (Tetra Tech, 2000). WCS-SED uses the USLE to calculate surface erosion and variable transport equations to estimate delivery to water courses (Yagow 1988, Sun and McNulty 1998). Sediment yield is assumed equal to delivery, thereby assuming no bank erosion or net in-stream source or sink. All model runs were conducted for the two-month sampling period, adjusting period rainfall from annual sums based on observed relative rainfall intensity.

Multiple model runs were performed, varying the source of elevation (and hence slope), soils, and land use data. Precipitation amount and characteristics derived from the nearby Coweeta Hydrologic Lab weather station were used to specify the USLE R factor, held constant across all runs. Soil erodibility factors (K) were derived from NRCS source materials for digital soils data, slope factors (LS) from digital elevation models, and cropping management factors (C) from NRCS entries that matched the land use categories.

Models were run across a coarse and fine-resolution elevation (30 m and 10 m), soils (STATSGO and SSURGO), and land use data (NLCD from Landsat 30 m, and UMN from SPOT 2.5 m).

Stream network was held constant across a primary set of runs at a threshold. The stream network is defined in WCS-SED by a contributing area threshold. First order streams are initiated when an upstream, contributing area exceeds a specific area. Streams accrue downstream, joining to form higher order streams in a network. We varied the threshold to best match the stream network observed in the field, arriving at a value of 1600 for a 10 meter resolution DEM to match the observed stream density. All the initial runs over the combinations of soils, DEM resolution, and land use data were conducted at this threshold. A second set of runs were performed to estimate the impact of inferred stream density on estimated sediment yield, using the highest resolution data (SSURGO soils, 10 m DEM, and UMN-SPOT based 2.5 meter land use data). Stream thresholds were varied at 50, 450, 1600, and 2500 10 m cells, all other data constant.

## RESULTS

**Land Use:** Forest land use dominated the study watersheds, with between approximately 73 to 100% forest extent (Table 2). Estimates of forest area varied only slightly between the NLCD and UMN-SPOT high resolution data sources, although there were substantial differences when resolving forest types. Differences among forest types are minor when estimating erosion in this region of the southern Appalachians, as rates are effectively zero in most closed-canopy forest types.

There were substantial differences in the amount of urban and transitional urban land uses when comparing the NLCD and higher resolution UMN-SPOT data (Table 2).

Table 2 Land use data for the five study watersheds, based on an interpretation of 2003 SPOT high-resolution satellite images (UMN) or 1990s NLCD data (NLCD). Land use classes are reported in percent.

| | UMN | NLCD | UMN | NLCD | UMN | NLCD | UMN | NLCD | UMN | NLCD |
|---|---|---|---|---|---|---|---|---|---|---|
| Low Dense Urban | 0.00 | 0.00 | 0.00 | 0.00 | 4.22 | 0.00 | 1.16 | 0.00 | 2.54 | 0.13 |
| High Dense Urban | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.89 |
| Transitional Urban | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.40 | 0.00 | 0.00 | 2.36 | 0.06 |
| Deciduous Forest | 0.00 | 0.00 | 0.00 | 93.64 | 0.00 | 16.02 | 72.64 | 42.06 | 0.00 | 69.49 |
| Evergreen Forest | 0.00 | 0.00 | 0.00 | 0.37 | 0.00 | 36.18 | 0.00 | 4.59 | 0.00 | 7.84 |
| Mixed Forest | 100.0 | 100.0 | 100.0 | 5.93 | 95.78 | 45.36 | 0.00 | 28.33 | 87.35 | 14.64 |
| Pasture/Hay | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 | 0.82 | 26.18 | 24.34 | 7.18 | 4.52 |
| Row Crops | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.22 | 0.00 | 0.68 | 0.51 | 0.88 |
| Other Grasses | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.55 |
| Woody Wetlands | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.06 | 0.01 |

**Observed Sediment Yield:** Sediment yields for the two-month monitoring period were generally within limits observed in previous studies in the region, with mean baseflow sediment concentrations typically varying between 1 and 7 ppm, and maximum stormflow concentrations ranging from approximately 15 to 40 ppm. Two-month observed yields vary between 4.2 and 57.3 kg/ha (Figure 2), equivalent to approximate annualized yields of 0.025 to 0.344 t/ha/year. These fall within the ranges observed for eastern forests.

Sediment yield was strongly influenced by percent non-forest, primarily agricultural and low density residential development. Sutton Branch is the only watershed with substantial areas in agriculture, primarily pasture and hayfields in near-stream areas. Despite nearly 100% perennial vegetation in this watershed, substantially higher sediment yield values were observed than in predominantly forested watersheds and in watersheds with lower levels of development. Two watersheds, Reed Mill and Watauga Creek, were characterized by low density and transitional suburban/rural land uses in less 2 to 5% of their surface area, and pasture and hay in 1 to 7% of their surface, and these watersheds exhibited commensurately lower sediment yields than Sutton Branch. Road density was not well correlated with sediment yield, with Watauga Creek and Dryman Fork exhibiting the highest values (4.0 and 4.2 $km/km^2$, respectively), Sutton Branch and Reed Mill intermediate (0.11 and 0.14 $km/km^2$), and Addie Branch the lowest density (0.065 $km/km^2$).

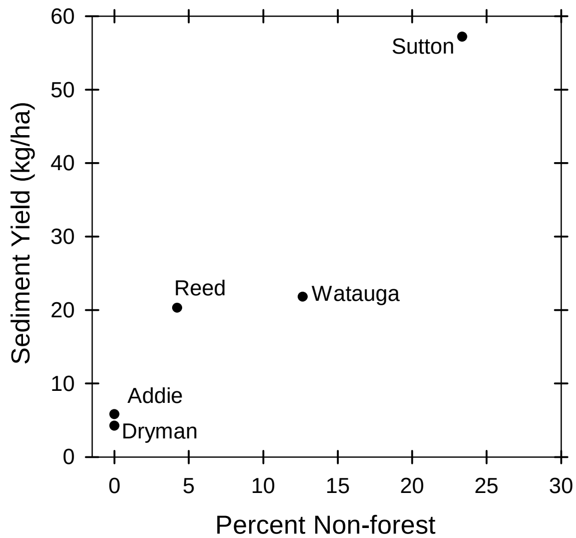


Figure 2  Observed sediment yield during June and July, 2003, plotted vs. percent non-forest in each study watershed

**<u>Modeled Sediment Yield:</u>** Predicted WCS-SED sediment yield was higher than observed yield for four of the five measured watersheds, typically by a factor of three to four (Figure 3). Modeled sediment yield for Sutton Branch was approximately one-third lower than observe sediment yield. Modeled sediment yield followed these patterns irrespective of the combination of digital elevation model resolution, land use data source, and soils data used. Previous work has found that modeled sediment yield is often higher than observed yield when using the USLE and related functions, both within the framework of WCS-SED, and within other systems (Ward and Trimble 2003, Wu et al., 2004, Riedel et al. 2005).

There may be many sources for this over prediction, including overestimation of erosion via the constituent USLE factors and erroneous estimation of transport. USLE factors have been developed and validated over a large range of conditions, and assume a field length 72.6 ft, or approximately 22 m. This dimension is spanned by the range of DEM cell sizes used in these calculations. However, slopes may not be accurately represented at this resolution, with elevation errors on the order of a few meters common. Previous work has shown more accurate estimates of yield when finer-grained DEMs are used (Riedel et al., 2004); however, it is not clear whether this increased accuracy is due to improved estimates of erosion or improved estimates of sediment transport.

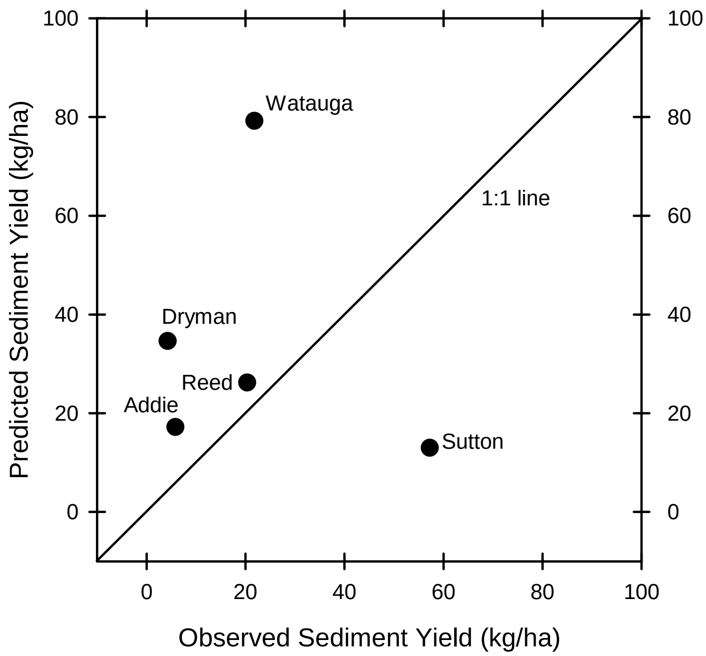


Figure 3 Predicted and observed sediment yield for five study watersheds for the period encompassing June and July, 2003. Predicted values were based on USGS 10 meter DEMs, NRCS SSURGO data, and 2003 land use data derived from a manual interpretation of SPOT 2.5-10m pan sharpened image data.

Estimated sediment yield was only inconsistently sensitive to cell resolution, with higher, lower, and similar yield predictions among 10 and 30 meter DEMs. Yield was sensitive to soil source with SSURGO-based predictions consistently 10 to 30% lower than STATSGO-based predictions. Yield was most sensitive to the C factors used in the USLE, and plausible C values resulted in substantially improved predictions for the agriculturally-dominated watershed, Sutton Branch (Figure 4). Initial model runs employed the best estimated C values for the predominant land uses given the site conditions and published tables (0.005 and 0.003 for pasture and forest, respectively). USLE C values span a wide range of values to reflect the density and stature of vegetation. Forest areas in this study were characterized by greater than 85% crown cover, and pasture by greater than 95% vegetation cover, and standard model runs employed the appropriate C values. Our initial runs may have used inappropriately high C values on forested sites and low C values on pasture sites, which might lead to the observed errors. However, sediment yield was overpredicted by a factor of more than two at extremely low C values (0.0005/0.0003) on predominantly forested sites, and as expected, sediment yields for higher than indicated C values increased overprediction on Dryman, Addie, Watauga, and Reed watersheds accordingly. We conclude that no plausible range of C values in forested sites are likely to improve estimation of sediment yield. However, an increase in C values for agricultural lands improved agreement between predicted and observed sediment yield on Sutton Branch (Figure 4), the lone watershed with substantial agricultural lands.

Predicted sediment yields were also strongly dependent on the threshold that established stream network density. Increasing the threshold substantially reduced the stream network, with a substantial reduction in estimated sediment. Sediment yield varied from 10 to 37 kg/ha as the stream threshold varied from 2500 to 50 10-meter cells. The lowest threshold generated approximately one-half the known reaches in the study watersheds, and still predicted more than twice the observed sediment yield for our study period.

We suspect sediment transport equations or poor estimates of road-generated sediment are primarily responsible for the large errors observed in estimated sediment yield, particularly on the four watersheds with little agriculture. Transport equations used in WCS-SED rest on a narrow empirical base, and need be tested over a wider range of conditions. The equations have been developed in one to a few studies, with a limited range of soils, land uses, terrain, and soil conditions.  In addition, the study areas have high road densities for predominantly rural areas, a legacy of dispersed small holdings and active forest management. A majority of the roads are unpaved and are significant sources of sediment to streams (Riedel et al., 2005).

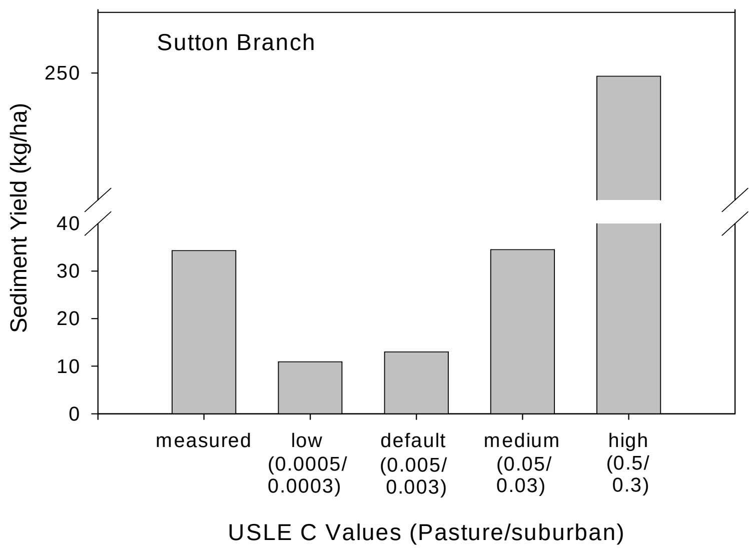


Figure 4  Sediment yield by USLE C values used in estimating sediment deliver to streams. Implausibly low C values did not substantially improve estimated yield, while plausibly high values substantially degraded model performance.

## CONCLUSIONS

Sediment yields predicted by WCS-SED were substantially higher than observed values over a summer study period on four of five study watersheds in the southern Appalachian Mountains. The general trends in observed sediment yield were replicated in predictions, but predicted values were generally three to four times higher than observed sediment yields. This increase was consistent across completely forested watersheds, and across watersheds with significant near-stream development. Predicted values were lower than observed values for Sutton Branch, the study watershed with the highest proportion of non-forest land use.

Predicted sediment yield was only slightly dependent on source data resolution. While predictions were generally better when using finer resolution SSURGO soils, SPOT-based land use and 10 m DEMs, improvements were slight relative to the observed error.

**Acknowledgements:** This work was supported by NSF via the Coweeta Long-Term Ecological Research Project, and by the University of Minnesota Agricultural Experiment Station. We thank Charles Marshall and Ryan Kirk for primary data collection.

## REFERENCES


Bolstad, P.V. (2005). GIS Fundamentals: A first text on geographic information systems. Eider Press, White Bear Lake, 543 p.

Hood, S. M., Zedaker, S.M., Aust, W. M., and Smith, D.W. (2002). “Universal Soil Loss Equation (USLE)-Predicted Soil Loss for Harvesting Regimes in Appalachian Hardwoods,” Northern Journal of Applied Forestry, Society of American Foresters, v. 19, no. 2, p. 53-58.

Kinnell, P.I.A., and Risse, L.M. (1998). :USLE-M: Empirical Modeling Rainfall Erosion Through Runoff and Sediment Concentration.” Soil Science Society of America Journal, v. 62, no. 6, p. 1667-1672.

Pohl, C., Van Genderen J.L. (1998. “Multisensor image fusion in remote sensing: concepts, methods and applications,” International Journal of Remote Sensing 19:832-854.

Riedel, M.S.,Vose, J.M., and Bolstad P.V. (2004). “Characterizing Hysteretic Water Quality in southern Appalachian Stream,” in Proc. 2004 National Water Quality Monitoring Conference, United States Advisory Committee on Water Information – National Water Quality Monitoring Council, Chattanooga, TN, May 17th – 20th.

Riedel, M.S., Jenks, A.C., Bolstad, P.V., and Vose, J. M. (2005). “Application and Validation of a Sediment Yield Model in Developing Regions of the Southern Appalachians,” in Watershed Management to Meet Water Quality Standards and Emerging TMDL (Total Maximum Daily Load), Third Conference, Atlanta, GA.

Sun, G., McNulty, S. (1998). “Modeling soil erosion and transport on forest landscapes,” in Proceedings of Conference 29, International Erosion Control Association, February 16-20, Reno, Nevada, 187-198.

Tetra Tech. (2000). Watershed Characterization System, Sediment Tool User’s Guide. Fairfax, VA.

U.S.G.S. (1978). Laboratory Analysis – Suspended-Sediment Concentration. Section 3.F.2.a. in Chapter 3 – Sediment of the National Handbook of Recommended Methods for Water Data Acquisition. United Stages Geological Survey, Office of Water Data Coordination, Reston, VA.

Vogelmann, J.E., Sohl,T., Campbell, P.V., and Shaw D.M. (1998). “Regional land cover characterization using Landsat Thematic Mapper data and ancillary data sources,” Environmental Monitoring and Assessment 51: 415-428.

Walters, D.M., Freeman, M.C., Leigh, D.S., Freeman, B.J., Paul, M.J., and Pringle, C.M. (2001). “Bed texture and turbidity as indicators of fish biotic integrity in the Etowah River System,” in K.J. Hatcher (ed.) Proceedings of the 2001 Georgia Water Resources Conference. March 26-27, 2001. Athens, Georgia. p. 233-236.

Ward, A.D., and Trimble, S.W. (2003). Chapter 9, Soil Conservation and Sediment Budgets, Environmenat Hydrology: Boca Raton, FL, CRC Press LLC, p. 448.

Wu, S., Li, J., and Huang, G. (2004). “Effect of Digital Elevation Model Resolution on Empirical Estimation of Soil Loss and Sediment Transport with GIS,” International Journal of Sediment Research, v. 19, no. 1, p. 28-36.

Yagow, E.R., Shanholtz, V.O., Julian, B.A., and Flagg, J.M. (1988). “A water quality module for CAMPS,” International Winter Meeting of ASAE, December 13-16, 1988, Chicago, Il.