FOREST ROAD EROSION, SEDIMENT TRANSPORT AND MODEL VALIDATION IN THE SOUTHERN APPALACHIANS

Dr. Mark S. Riedel, Research Hydrologist, USDA Forest Service, Otto, NC
Dr. James M. Vose, Project Leader, USDA Forest Service, Otto, NC

USDA Forest Service, Southern Research Station, Coweeta Hydrologic Laboratory, 3160 Coweeta Lab Road, Otto, NC, 28734, tel: (828) 524 – 2128, fax: (828) 369 - 6768

Abstract: The Conasauga River Watershed, located in northern Georgia and southern Tennessee, has one of the most diverse aquatic ecosystems in this region and is currently being considered for designation as a wild and scenic river. The Conasauga River also serves as a major source of drinking water for numerous large cities. Due to the close proximity with the cities of Knoxville, Atlanta, and Chattanooga, intensive public usage, and the high quality of this aquatic resource, the United States Department of Agriculture (USDA) Forest Service has designated the Conasauga River as one of the twelve large-scale watershed restoration projects in the nation. This is warranted as the Conasauga River is experiencing excessive sedimentation from the erosion of private agricultural lands, streambanks, and forest roads. We are working with an erosion model, the Sediment Tool, to facilitate decision-making in the restoration of forest roads. The sediment tool, and its parent model the Watershed Characterization System (WCS), were developed by the US Environmental Protection Agency (EPA). The Sediment Tool is a spatially explicit, GIS based, finite element, lumped parameter model which generates estimates of soil erosion, sediment routing and sediment yield. We applied WCS along segments of thirteen mountain roads in the Conasauga Watershed. The segments provide replication of road types under a variety of usage levels, road base materials and slopes. We sampled overland flow from each segment for total suspended solids (TSS) and surveyed all pertinent road characteristics. While we were able to qualitatively calibrate the model, predicted sediment yields were typically much greater than observed data. Model results improved with digital elevation model (DEM) and computational grid resolution. Error analysis indicated that model sensitivity is limited by the governing equations within the model and the resolution of the input data. The model currently employs the universal soil loss equation (USLE) to estimate soil erosion and empirical sediment yield equations to transport sediment. These empirical equations were not developed for application on aggregate road surfaces. DEM resolution will also present problems in routing the sediment to streams. Streams in the study areas are only one two three meters wide. Floodplains adjacent to these streams are typically four or five meters wide and frequently trap sediment-laden runoff before it reaches the streams. Current efforts to improve upon the model include an adaptation of the process based Water Erosion Prediction Project (WEPP) model and attainment of finer resolution DEM data that will more accurately represent the road surfaces.

INTRODUCTION

The Conasauga River Watershed, Figure 1, encompasses 1,870 square kilometers of the Blue Ridge Ecosystem in northern Georgia and southeastern Tennessee. This watershed hosts the most diverse aquatic ecosystem of any river in this region and hosts over 90 species of fishes and 42 species of mussels (Freeman, et al, 1996). The Conasauga River also serves as a source of drinking water for the cities of Dalton and Atlanta, GA and Cleveland and Chattanooga, TN. Recreational usage of the Conasauga is intensive. Thousands of annual visitors use it for kayaking, canoeing, swimming, fishing, hunting, hiking, mountain climbing, mountain biking, swimming and camping. Currently, water quality and aquatic ecology of the Conasauga River are suffering from excessive sedimentation caused by erosion of streambanks, agricultural lands, development, and gravel roads (Freeman, et al, 1996). Sediment eroded from gravel roads can be a major component of the sediment budget in streams in this region (Van Lear, et al, 1995).

The USDA Forest Service has designated the Conasauga River watershed as one of twelve national watersheds targeted by the Large-scale Watershed Restoration Project. This has provided resources to protect and improve the quality of land and water resources within the Conasauga River Watershed. As part of this project, the Forest Service is locating and addressing potential impacts to the mountainous, headwater streams and the Conasauga River in the national forest lands of the Chattahoochee and Cherokee National Forests. Approximately one half of the forest area is designated as a wilderness and provides water of exceptional quality (Ivey and Evans, 2000). However, sediment eroded from the forest roads traversing the remaining forest lands could negatively impact the health and integrity of the aquatic ecosystems (Henley, et al, 2000). The primary means to reduce runoff, erosion, and sedimentation caused by forest roads is through the implementation of road improvement projects, best management practices and, where necessary, closing roads.

RESEARCH DESCRIPTION

Due to limited resources, it is important that road improvement projects be prioritized. The prioritization is based upon the severity of sediment erosion and transport, sediment impacts on water quality, road usage levels and potential effectiveness of restoration. Our goal is to determine the ability of a watershed scale erosion model to assess sediment production, delivery to streams, and predict restoration effectiveness. To satisfy this goal the model must meet the following objectives;

(1) provide an assessment of sediment production and delivery from forest roads,
(2) output must allow users to quantify the effectiveness of road restoration for reducing sediment production and delivery at local and watershed scales and
(3) the model must be a tool that can be used to locate and prioritize high hazard areas and evaluate changes in future sediment production and delivery with the implementation of road improvement projects.

The research presented here is limited to our investigation into the ability of the model to meet objective 1, its ability to assess sediment production and delivery from forest roads.

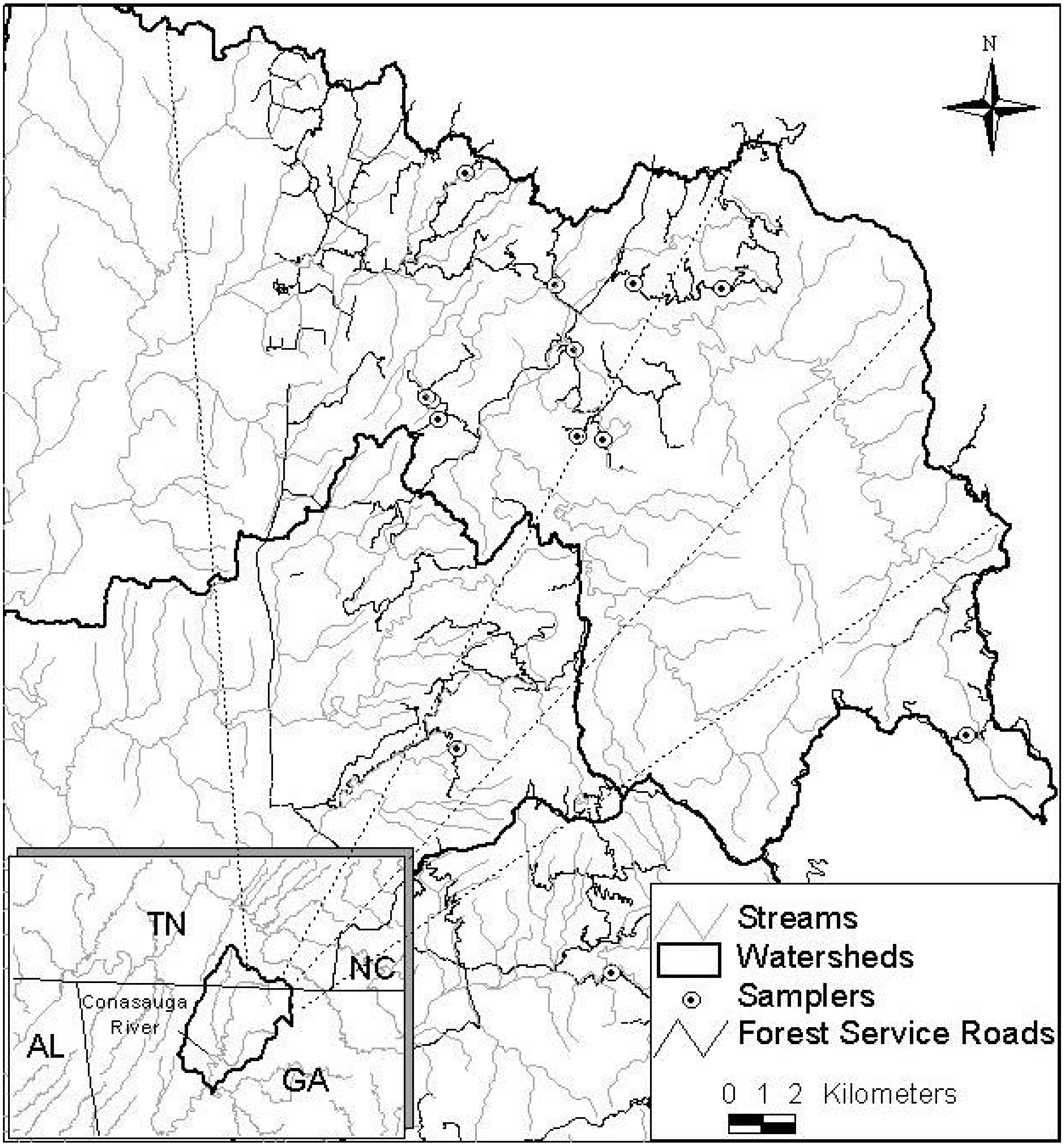

Figure 1: Location of Conasauga watershed and study sites in the southern Appalachians.

Model Description: The modeling environment we employed is the Watershed Characterization System (WCS). WCS is an adaptation of the Environmental Protection Agency (EPA) ARCVIEW™ based watershed data management system known as BASINS (EPA, 2001a). WCS was developed by Region 4 of the EPA to facilitate the development of total maximum daily loads (TMDLs) in the southeastern United States. Sediment is the primary pollutant for which TMDLs are established consequently, the EPA developed a soil erosion and transport module for WCS called the Sediment Tool (Tetratech, Inc. and EPA, 2000). The Sediment Tool is an Avenue™ extension that is called by ARCVIEW from within WCS. It is spatially explicit, finite element, lumped parameter model that estimates soil erosion, sediment transport and sediment yield. Soil erosion is simulated on a grid cell basis with the USLE while one of four user specified transport equations is used to tansport sediment from cell to cell. The development, scientific basis, and background research leading to the creation of the Sediment Tool have been reported by previous authors (Greenfield, et al, 199?; McNulty and Sun, 1998; McNulty, et al, 1994).

Site Description: The entire study site is located in the Blue Ridge Mountains. Bedrock in the Blue Ridge belt is primarily sedimentary and metamorphic. Soils in the study area are largely of metamorphic crystalline bedrock origin. The loamy mountain soils from gneiss, mica-shist, quartz and granitic bedrock are highly erodible when exposed (Van Lear, et al, 1995).

Climate and Hydrology: Elevation and terrain strongly influence climate, precipitation patterns, soil depth, soil moisture, solar insolation and the natural distribution of vegetation. High precipitation and mild temperatures place this region in the marine, humid temperature classification of Koppen's climate system (Swift, et al, 1988). Average annual rainfall at upper elevations is 230 cm per year while lower elevations receive approximately 180 cm of rainfall per year. Ridgelines and upper elevation south facing slopes tend to be drier while slopes with northern aspects are moist and cool (Van Lear, et al, 1995). Due to higher rainfall, shallower soils and steeper hydraulic gradients, water yields and stream flow response in this region increase with watershed elevation (Swift, et al, 1988).

Land Use: While forest harvesting in this region began in the late 1800's, much of the Conasauga Watershed was still forested at the turn of the century. An inventory of land use in 1900 and 1901 indicated that the mountainous areas in the southern Appalachians were typically forested with merchantable timber densities of 1,000 to 10,000 board feet per acre (Ayres and Ashe, 1904). Forest harvesting increased greatly in the early 1900's and spread throughout the entire region. With the clearing of land, the conversion of valley bottoms and riparian areas to farming and grazing became widespread. Beginning in the 1920's, the mountainous headwaters regions of the Conasauga River were purchased by the federal government and incorporated into National Forests. These lands were reforested and have been continuously managed by the Forest Service to the present day (Ivey and Evans, 2000).

METHODS

Field Work: During late summer, 2001, we instrumented 13 forest roads in the Conasauga watershed with overland flow samplers. The road sites were selected to be representative of road usage levels, surface types, slopes, types and severity of erosion, maintenance practices and proximity to streams. At each site we surveyed roadbed slope, contributing surface area, distance between samplers, the slope along transects between samplers and roadbed characteristics. These are summarized in Table 1. The usage intensity for each road is based upon national forest road management and usage data. We categorized usage intensity as; closed - official traffic only, horse trail; gated - seasonal public access; slight - open, few vehicles per day, no outlet; moderate - multiple vehicles, recreation area access; intensive - numerous vehicles, thoroughfare access; ORV - off road vehicle recreation trail. The third column in Table 1 presents the typical maintenance schedule for each road. The number of samplers installed at each site is listed in column 4. The roadbed materials specified in the fifth column are; native –

native soil; improved – native soil amended with aggregate; aggregate – full aggregate base. The next two columns present the slope of the road that contributes runoff to each sampler and the total contributing area above each sampler. The last column is the estimated runoff curve number (RCN) for each road, as described in the data analysis section.

Site Name	Usage intensity	Maint. per Year	Samplers	Roadbed	Road Slope (%)	Road Area (m^2)	RCN
Horsetrail	Closed	0	5	Native	3	441	87
Double culverts	Closed	0	4	Native	8	391	87
Doc Howell	Gated	0 - 1	4	Native	2	502	89
Jigger Creek	Gated	0 - 1	4	Native	13	90	89
Doogan Mtn	Slight	2	3	Improved	11	334	91
Beach Bottom	Slight	2	5	Improved	12	403	91
Cowpen Mtn	Moderate	2	5	Aggregate	15	254	91
Three Forks	Moderate	2	4	Aggregate	18	168	91
Sina Branch	Moderate	2	4	Aggregate	15	316	91
Alaculsy Branch	Moderate	2	5	Aggregate	14	512	91
Double Branch	Intensive	2 - 3	5	Aggregate	13	485	94
Taylor Branch	Intensive	2 - 3	5	Aggregate	10	513	94
Rocky Flats	ORV	0	5	Variable	13	217	94

Table 1: Study site and road characteristics.

Overland Flow Sampler Installation and Operation: The overland flow samplers employed in this study are of custom design developed at the USDA Forest Service Coweeta Hydrologic Laboratory. Each sampler consists of three pieces, an intake, a hose, and a storage vessel. The intake is a stainless steel trough with a 30cm x 10cm rectangular inlet orifice and a 10cm diameter exit orifice. Each intake has a two-stage approach apron on the upstream side of the inlet orifice. The first stage of the apron is installed below grade and the second stage is installed at grade to direct flow into inlet orifice. Flanges that prevent flow from circumventing the sampler border the sides of the inlet orifice. Water and sediment that enter the orifice flow by gravity, through the outlet, through a flexible connecting hose and into an 18-liter storage vessel. Each storage vessel has an exhaust to allow air to be freely displaced by entering water.

We installed samplers during the first week of August, 2001. At each site, samplers were installed along a transect that began where overland flow left the road surface and ended where flow terminated at a stream channel or infiltrated into the forest floor. Each transect consisted of a serial array of three to five individual flow samplers. We operated the samplers from mid August, 2001 through early January, 2002 and checked them on a weekly basis to insure that they were operating properly. The samplers were also serviced immediately following each significant rainfall event. This consisted of thoroughly mixing the collected water in the 18L containers and extracting a one-liter sub sample of the sediment and water mixture. The samplers were then cleaned and prepared to collect samples from the next rain event. The sub samples were analyzed for total suspended solids to 1.5 μm in accordance with the American Public Health Association standard methods for wastewater analyses (Franson, 1981).

Data Analyses: The TSS data obtained with the overland flow samplers and the annual erosion estimates generated by WCS are not quantitatively similar. To make these data comparable, we adjusted their spatial and temporal scales to uniform dimensions. We multiplied TSS ($g*m^{-3}$) by runoff depth (m) and contributing surface area (m^2) to get loading in kg for each storm at each sampler and summed these to obtain total yield for the sampling period. We used the RCN method and the depth of rainfall from each storm to compute depth of runoff and as given in USDA (1986).

We reduced the temporal scale of the soil erosion estimates from an annual soil loss to that of the four months corresponding to our overland flow-sampling period, August 15 – January 15, 2001. We did this by using the bi-weekly erosivity factors (USDA, 1997) to partition out the fraction of the annual erosivity corresponding to our sampling period (EPA, 2001b).

Modeling: WCS is distributed on an 8 digit Hydrologic Unit basis by Region 4 of the EPA for the states of Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee. These data are very similar to the 8 digit hydrologic unit code (HUC) data distributed with the EPA model, BASINS. Consequently, their resolution is fairly coarse. The data relevant to this study include the USGS one degree DEMs (90m resolution), USGS 8 digit HUCs, USGS level 3 streams (1:24,000 scale), NRCS STATSGO soils data, Tiger roads data, and climate station network. We augmented these with additional data to improve data quality and resolution. We obtained 30m and 10m DEMs for the study site, replaced the Tiger roads data with roads data from the USDA, Forest Service. These data are part of the national forest database and have full attributes including length, usage, maintenance, road base type, vehicle type and jurisdiction. While SSURGO data for the study area were not available, we updated the STATSGO data to reflect the existence of the forest roads. We did this by buffering the forest roads coverage to the road widths and intersecting the road buffers with the STATSGO soils database. Within the soils attribute table, we created new soil types for the improved and aggregate road bases. We determined the erodibility values for these types using RUSLE to compute the K factor for the observed road surface characteristics (USDA, 1997).

Calibration: In the beginning of this study, we qualitatively calibrated WCS to each road site. For the initial runs of WCS, we employed USLE C factors for gravel roads published by the USDA (1976, p. 70). During sampler installation, we rated each site on a scale of 0 to 4 based upon the severity and types of road erosion, Table 2. We then adjusted the C factor for each site so that the predicted categories best matched those observed.

Erosion Scale	Standard deviations from the observed or predicted mean erosion rate	Description
0	Less than -1	Below average
1	1 to -1	Average
2	1 to 2	Slightly above average
3	2 to 4	High
4	Greater than 5	Extreme

Table 2: Qualitative road erosion categories for calibration of WCS.

RESULTS

In Table 3, we present the observed and predicted sediment yield data for each road segment in our study. These values are totals the period of sampler operation, August 15th – January 15th. Observed sediment yield data are presented in the second column. The remaining columns present the predicted sediment yield data for each study road as a function of DEM resolution and computational resolution. The last rows present the results of regressing the predicted sediment yields on the observed yield. All of the regressions are significant ($p < 0.01$).

Road Name	Observed Yield	90m DEM		30m DEM			10m DEM	
		30m	10m	30m	10m	5m	10m	5m
Horse Trail	0.75	4.5	2.7	64	95	100	21	18
Double Culverts	1.07	11	68	77	160	300	45	24
Doc Howell	0.07	4.1	23	53	110	170	5.1	2.2
Jigger Creek	0.08	5.6	3.0	27	1.2	2.5	7.6	2.5
Doogan Mtn	0.93	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Beach Bottom	0.24	18	13	0.0	0.0	0.0	0.0	0.0
Cowpen Mtn	1.75	5.0	8.1	49	93	54	15	9.3
Three Forks	2.94	22	62	260	780	1050	X	X
Sina Branch	0.09	1.1	6.0	37	0.0	0.0	0.0	0.0
Alaculsy	0.37	5.1	2.0	59	61	190	2.3	0.3
Double Branch	1.22	0.0	0.0	530	0.0	0.0	X	X
Taylor Branch	0.36	3.9	9.9	12	22	45	1.9	2.0
Rocky Flats	3.13	9.8	19	41	110	270	30	67.3
Mean	1.00	6.95	16.65	92.74	109.52	167.02	11.67	11.43
Intercept		4.03	7.06	47.6	-17.2	-13.7	3.89	-3.97
Slope		2.92	9.59	45	127	181	9.69	19.2
Deg. of Freedom		11	11	11	11	11	9	9
r^2		0.20	0.19	0.10	0.40	0.43	0.37	0.78
Se		6.3	21	140	170	220	12	10

Table 3: Observed sediment yield (kg/ha) from overland flow samplers and predicted sediment yield (kg/ha) for each road plot. Predicted data are grouped by digital elevation model (DEM) resolution and computational resolution. Cells with an "X" correspond to sites where 10m DEM data were not available at the time of this study. All regressions are significant ($p < 0.01$).

The intercepts indicate that the WCS Sediment Tool generally overestimates sediment yield with the coarser DEM data. As resolution increases, the intercepts approach zero. The slopes of the regressions indicate that WCS over predicts sediment yield and this error increases with observed rates of sediment yield. The estimates of sediment yield obtained with the combination of 10m DEM data and a 5m computational grid best fit the observed data (Figure 2). In this figure, the regression line is much steeper than the predicted = observed line. The Rocky Flats ORV trail site, labeled as "Influential Point", is significantly influencing the regression ($p = 0.00035$). However, this point does not appear to be an outlier in this or the other regressions. Also, numerous sediment yield estimates for the Doogan Mountain, Beach Bottom, Sina Branch and Double Branch sites are zero while the erosion estimates were not zero. This indicates that while WCS predicted that erosion would occur on these sites, it predicted that the eroded sediment would be deposited before reaching the samplers. Sediment yield was observed at these sites indicating that the sediment transport functions underestimated sediment transport in these areas.

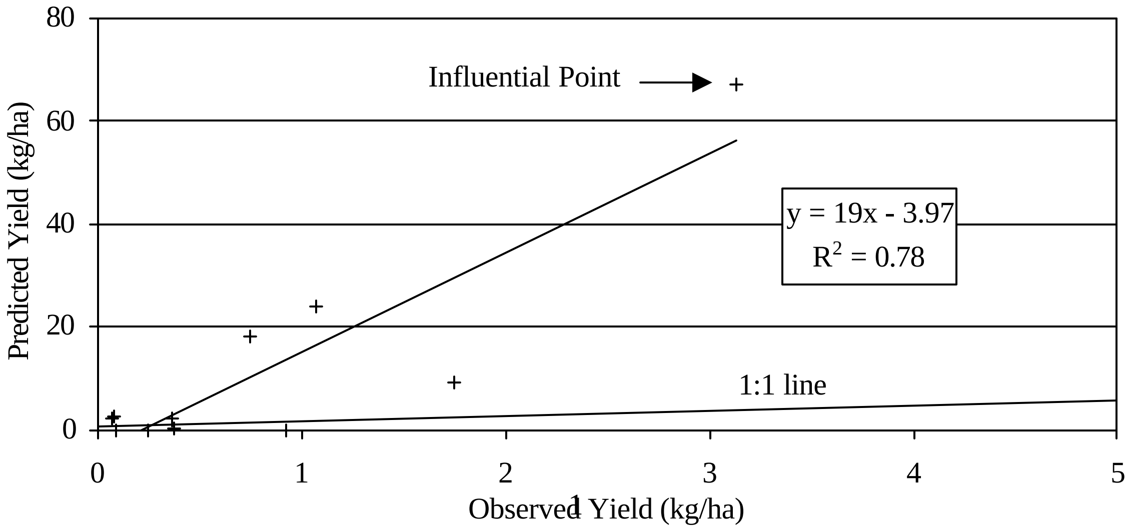

Figure 2: Linear regression of sediment yield predicted from 10m DEM data and a 5m computational grid against observed sediment yield.

In Figure 3, we have regressed the absolute value of the residuals$^{1/2}$ against observed yield. The residuals are dependent upon observed sediment yield ($p<0.01$), increasing with sediment yield from the study roads.

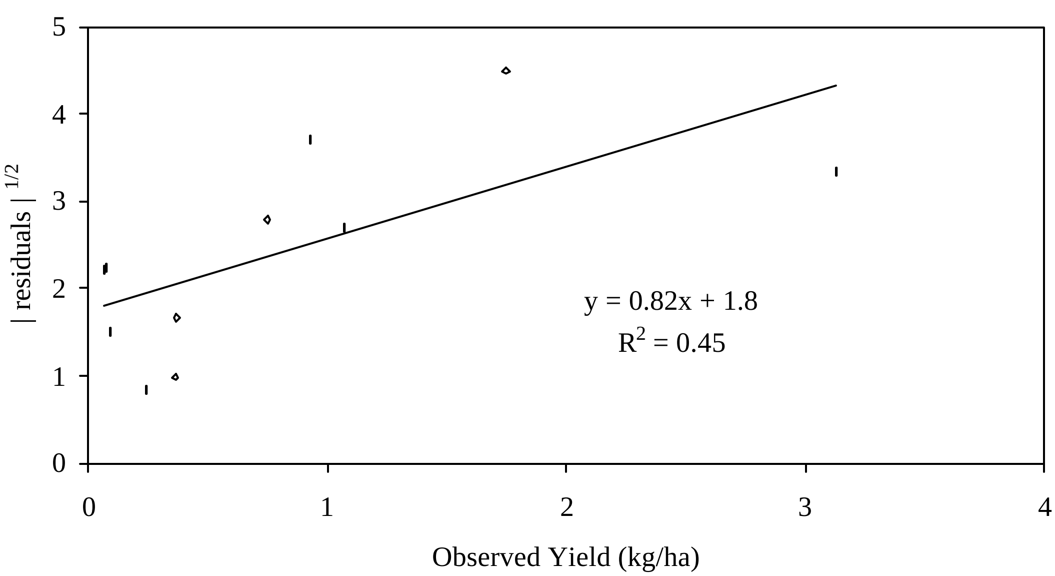

Figure 3: |Residuals|$^{1/2}$ regressed on observed yield. Transformation of residuals to the ½ power was necessary to remove non-linearity in the residuals. The residuals are dependent upon observed yield ($p < 0.01$).

As this dependence is based upon a transformation of the residuals to the ½ power (2 dimensional to 1 dimensional transformation), we suspect that the error might be a propagation of spatial scale and data resolution influences through the model. We repeated this regression, replacing observed yield with road area (Table 1) as the independent variable. The residuals are independent of road area indicating that the error is not a function of the contributing area upstream of each sampler.

The influences of DEM resolution and computational grid resolution on spatial accuracy of the model are illustrated in Figure 4. In this figure, we have plotted road and stream data for a variety of DEM and computational grid resolution combinations. Existing roads and streams are superimposed with the road erosion and stream grids created by the WCS Sediment Tool. The road grid generally matches the road coverage well because it was created from the road coverage. The accuracy of the stream grid is dependent upon the DEM and computational grid resolution. While none of the resolution combinations perfectly match the mapped streams and roads, accuracy increases with resolution. The spatial extent and severity of road erosion generally decrease with increasing DEM and computational grid resolution. In Table 3, the standard error of the estimate (Se) is lowest for the highest DEM and computational resolution.

DISCUSSION AND CONCLUSIONS

We were able to qualitatively calibrate the model to observed erosion conditions. However, the WCS Sediment Tool overestimates sediment yield from forest roads. While accuracy did increase with the use of finer DEMs and computational grids, the predicted sediment yields were biased and error increased non-linearly with observed erosion rates. We found that the 90m and 30m resolutions of commonly available DEMs were too coarse to provide reliable predictions of sediment yield from forest roads.

With a perfect model, predicted results will exactly match observed results along a linear function, slope = 1 and intercept = 0. The error we observed in our residuals is non-linear with respect to observed sediment yields. There are two likely sources for this error. First, the sediment routing equations in the WCS sediment tool are non-linear. Thus, error or bias that would propagate through these equations would become non-linear. Second, sediment routing predicted at a point (kg) is essentially one-dimensional while erosion is predicted over a two-dimensional watershed space (kg/ha). Thus, erosion estimate error propagating from 2 dimensional space into the 1 dimensional transport space will increase by a factor of $2^{1/2}$.

Gardiner and Meyer (2001) reported similar results in their investigation into the role of modeling resolution on the accuracy of predicted rates of erosion and sediment transport in the nearby Little Tennessee River watershed. Given various data and modeling resolutions, the accuracy of their sediment yield predictions was non-linearly dependent upon their sediment yield model. There are two important differences that must be noted. First, Gardiner and Meyer were working with a 966 km^2 watershed whereas our study areas are six orders of magnitude smaller. Secondly, Gardiner and Meyer used erosion and yield results from their finest resolution modeling as the standard to which they compared the coarser resolution model results whereas we used observed data. Despite these differences, it is clear that sediment yield predictions resulting from the application of the USLE in a finite element model are strongly

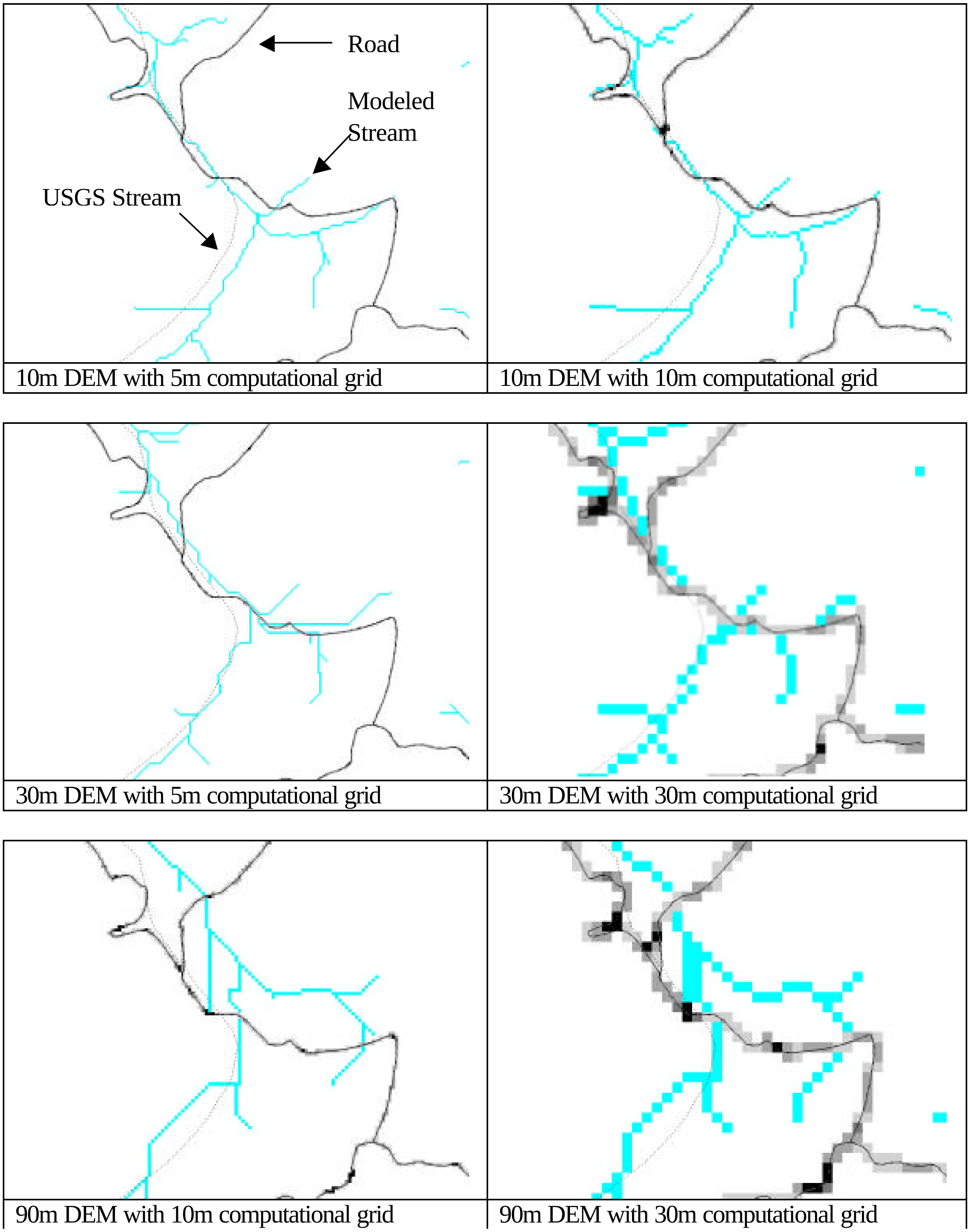

Figure 4: Influence of DEM and computational grid resolution on accuracy of stream delineation and road erosion. Severity of road erosion is indicated by shade; light gray is below average and black is extreme. Scale 1:4,500, stream is 2m wide, road is 4 m wide.

dependent upon data and element resolution. Van Rompay, et al (2001) cites numerous examples of the application of these types of models with coarse resolution data. In practice, a frequent justification given for using coarse data in these types of models is that using coarse data over large areas will compensate for errors due to input data resolution. Results here indicate that this was not true for our study.

While not addressed in this study, our results suggest that DEM and computational grid resolution could also be important in routing sediment to streams because streams in the study areas are only one to three meters wide. Floodplains adjacent to these streams are typically four or five meters wide. Modeling with relatively coarse DEMs will allow sediment-laden runoff to reach stream grid cells rather than settling it on floodplains. This is very important because one of the most common BMPs for forest roads is inducing sedimentation of road runoff by diverting it to flat areas adjacent to the roads.

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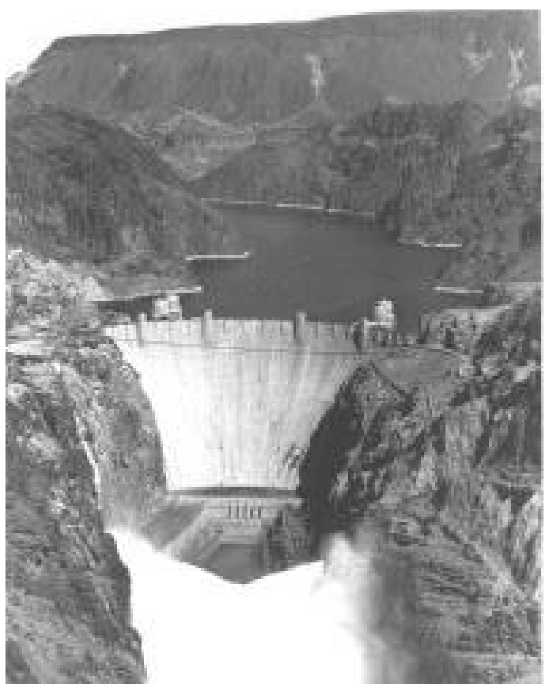

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