Evaluating Watershed and Stream-Channel Drivers of In-Stream Turbidity in Virginia and North Carolina

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ABSTRACT

Accurately predicting sediment delivery has been a long-standing problem in the field of water resource management. Many different watershed equations and models have been developed such as the Universal Soil Loss Equation (USLE), the Geo-spatial interface for the Water Erosion Prediction Program (GeoWEPP) and many more, however, these models have not always been able to reliably predict in-stream sediment loads. In this study, two scales, watershed and site level, are used to understand where sediment transported in-stream is being produced. At the watershed scale, USLE was used to estimate sediment yield and then different factors such as connectivity topographic indices were applied as discount factors in an attempt to improve these estimates. The different parameters were then compared to turbidity to determine the level of accuracy of each method. It was found that USLE is not able to predict in-stream turbidity levels in the study area watersheds in Virginia and North Carolina. An implicit assumption of USLE is that runoff is produced on steeper slopes and that sediment production occurs on these hillslopes. However, it was found that flatter-sloped areas were highly correlated with in-stream turbidity. It was also found that in-channel and site-specific parameters such as bank height/slope and level of confinement at higher flows were more accurate predictors of in-stream sediment levels. Overall, turbidity and in-stream sediment levels are not well predicted by models that employ USLE. The distribution of runoff source areas, and channel/bank properties appear to be good predictors of sediment production at the watershed scale. These results indicate that sediment production and transport, as conceptualized by common models and equations, often associate sediment source areas with geomorphic and hydrologic processes in ways that are not consistent with the results of this study. Our results show that sediment is most likely being sourced from the channels and in stream areas.

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GENERAL AUDIENCE ABSTRACT

Predicting how sediment moves through a watershed has been a long-standing problem in the field of water resource management. There are many equations and models that have been developed to calculated the amount of sediment that exits a watershed; such as the Universal Soil Loss Equation (USLE), the Geo-spatial interface for the Water Erosion Prediction Program (GeoWEPP) and many more. However, these models have not always been reliable or accurate in their predictions. In this study, two scales, watershed and site level, are used to understand where sediment transported within streams is being produced. At the watershed scale, USLE was used to estimate sediment leaving a system and then different factors, with different approaches to the understanding of sediment movement, were applied as discount factors in an attempt to improve these estimates. The different values that were calculated were then compared to turbidity to determine the level of accuracy of each parameter. It was found that USLE is not able to predict in-stream turbidity levels in the study area watersheds in Virginia and North Carolina. An assumption of USLE is that runoff is produced on steeper slopes and that sediment erosion occurs on these steeper sloped areas. However, it was found that flatter-sloped areas were highly correlated with turbidity. It was also found that in-channel and site-specific parameters such as bank height/slope and the level of confinement at higher flows were more accurate predictors of turbidity. Overall, USLE and models that used USLE were not able to predict turbidity. The distribution of runoff source areas and channel/bank properties appear to be good predictors of turbidity at the watershed scale. These results indicate that sediment movement, as conceptualized by common models and equations, often associate sediment source areas with watershed level morphology and hydrology in ways that are not consistent with the results of this study. Our results show that sediment is most likely being produced from the channels and in stream areas.

DEDICATION

This thesis is dedicated to my family,
for always believing in me, supporting me, and pushing me to reach my goals.

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Introduction

Sediment and sediment-associated pollutants (including turbidity, phosphorus, heavy metals, and PCBs) are the leading water-quality impairment in streams and rivers in the U.S. (USEPA, 2020). The cost of physical, chemical, and biological damages attributed to and associated with sediment in North American was estimated (in 2009) at more than $20 billion annually (Gray and Gartner, 2009). Sediment levels are playing a large role in the pollution and subsequent impairment of the Chesapeake Bay. For the restoration of the Chesapeake, the EPA is calling for a 20% reduction in sediment (and 24% reduction in phosphorus) by 2025 (USEPA, 2010). Sediment can also affect aquatic species populations, specifically fish species. In the Dan and Roanoke River basin in south central Virginia and north central North Carolina, habitat availability for fish species, such as the Roanoke log perch, is impacted by fine sediment levels in these streams. Understanding the movement of sediment through watersheds can improve the effectiveness of restoration efforts and reduce damages caused by sediment, and therefore reduce expenditures related to mitigating these damages.

Predicting sediment delivery from a watershed has been a long-standing problem in the field of water resources. There have been many approaches that attempt to understand and predict sediment delivery in watersheds, with varying levels of success. One of the most widely used methods is the Universal Soil Loss Equation (USLE), which was developed by the U.S. Department of Agriculture (Wischmeier and Smith, 1965). This empirical equation is the product of five primary factors that incorporate rainfall, soil, slope, and land cover as drivers of erosion. USLE was developed on unit plots, all variables for these unit plots were known except for the annual soil loss and the soil erodibility, which were measured over time to compile data, which was used to develop USLE (Wischmeier and Smith, 1965). The unit plots for the development of USLE were designed so that the plots were 22.1 meters long at a 9% slope (Wischmeier and Smith, 1965). This equation is often applied to estimate average annual soil loss from a watershed (Atoma et al., 2020; Boakye et al., 2020; Li et al. 2020; Mirakhorlo, et al., 2020). However, USLE was originally developed at the plot scale and it was not intended to be used at the watershed scale; however, despite the uncertainties and issues related with scaling this equation to an entire watershed, it is being used in this way. The equation also has underlying assumptions that can lead to inaccurate estimations. For example, there are many different methods for calculating the slope factors and these methods are typically not process based but instead are empirical (Bircher et al., 2019; Liu et al., 2011; Zhang et al., 2013). USLE assumes that erosion occurs on the hillslopes of the watershed and does not consider in-channel and bank-erosion processes. It also only considers sediment detachment, however, it is also possible for that sediment to be deposited within the watershed. USLE assumes that if sediment becomes detached it will reach the outlet; however, this is rarely the case, which can lead to over estimations of soil loss from USLE.

USLE has been updated with the following versions: Revised Universal Soil Loss Equation (RUSLE), RUSLE2, and the Modified Universal Soil Loss Equation (MUSLE). Both RUSLE and RUSLE2 are the same equations as the original USLE but RUSLE has improved factor determination and RUSLE2 is a computer model rather than a text-based model (Renard and Freimund, 1994; Renard et al., 1997), while the MUSLE estimates sediment yield for a single runoff event (Williams, 1975). The Soil Water Assessment Tool (SWAT) is a more complete watershed model. SWAT uses the equation and similar factors from USLE, however it accounts for water and sediment routing through a watershed; this model was intended to be used at the watershed scale and considers the potential for sediment deposition (Gassman et al., 2007).

Most watershed-scale sediment transport models used in professional practice to determine sediment production and transport at the watershed scale still heavily rely on aggregating local sediment erosion from uplands. Many watershed-scale models utilize the USLE/RUSLE erosion models (Renard et al., 1997), including the Soil Water Assessment Tool (SWAT; Gassman et al., 2007), and Hydrologic Simulation Program-FORTRAN (HSPF; Shenk and Linker, 2013). These aggregations are then used to estimate watershed sediment yield; this approach to estimating sediment yield used by USLE ignores the processes of deposition, storage, and river-floodplain interactions. The estimations provided by SWAT and HSPF account for deposition but still do not account for storage and river-floodplain interactions (Gassman et al., 2007; Larsen and MacDonald, 2007; Shenk and Linker, 2013).

In an attempt to remedy this overestimation by USLE, sediment delivery ratios (SDRs) were introduced (Walling, 1983). A sediment delivery ratio is the ratio between the sediment yield (sediment that reaches the outlet) and the sediment that is detached across a watershed. These ratios assume that the relationship between detachment and yield are constant between different storms and throughout the watershed. Some SDRs are a function of watershed area (Ferro and Minacapilli, 1995; Ferro, 1997). Recently, sediment connectivity frameworks have been developed to try to understand sediment delivery explicitly from watershed attributes (e.g., Borselli et al., 2008; Cavalli et al., 2013). Sediment connectivity refers to the degree to which sediment can move between difference landscape features. This framework has not been used to predict sediment yield but addresses potential sediment delivery throughout a watershed. It has potential to predict sediment delivery more accurately because it takes a process-based approach and, unlike the SDR, it moves beyond the assumption that sediment yield is a function of watershed area. This framework considers the drainage area, distance to the outlet, and slope or land cover (depending on the weighting factor) to understand sediment sources and sinks across the watershed.

The purpose of this thesis is to use a combination of USLE, watershed, sediment connectivity, and in-channel/bank erosion metrics (Table 1) to understand the variability in turbidity measured in 68 watersheds throughout Virginia and North Carolina (Figure 1). Turbidity, for this study, was considered to be a representative measurement in place of actual sediment yield (Pavanelli, et al., 2005; Rasmussen et al., 2002). USLE was used to compare to turbidity, while the connectivity indices were used to discount the USLE values to reach more realistic estimates of soil loss.

Table 1. Table of parameters for both Dan/Roanoke (left) and USGS (right) sites. Wt'd stands for weighted.

DAN/ROANOKE		**USGS**	
Categories	**Parameters**	**Categories**	**Parameters**
WATERSHED	USLE	WATERSHED	USLE
	R Factor		R Factor
	K Factor		K Factor
	L Factor		L Factor
	S Factor		S Factor
	CP Factor		CP Factor
	Borselli Connectivity Index		Borselli Connectivity Index
	Cavalli Connectivity Index		Cavalli Connectivity Index
	Topographic Index (TI)		Topographic Index (TI)
	Soil Topographic Index (STI)		Soil Topographic Index (STI)
	Wt'd USLE - Borselli Exponential		Wt'd USLE - Borselli Exponential
	Wt'd USLE - Borselli Normalized		Wt'd USLE - Borselli Normalized
	Wt'd USLE - Cavalli Exponential		Wt'd USLE - Cavalli Exponential
	Wt'd USLE - Cavalli Normalized		Wt'd USLE - Cavalli Normalized
	Wt'd USLE - TI Normalized		Wt'd USLE - TI Normalized
	Wt'd USLE - STI Normalized		Wt'd USLE - STI Normalized
	Drainage Area		Drainage Area
	Average Watershed Slope		Average Watershed Slope
	Agriculture		Agriculture
	Hay/Pasture		Hay/Pasture
	Forest		Forest
	Urban		Urban
	Sediment Delivery Ratio		Sediment Delivery Ratio
SITE	Sediment Susceptibility 2018	SITE	Channel Slope
	Sediment Susceptibility 2019	HYDROLOGIC	Turbidity 2018
	Embeddedness		Turbidity 2019
	Channel Slope		
	Average Bank Height		
	Average Max Bank Height		
	Average Min Bank Height		
	Average Bank Slope		
	Average Max Bank Slope		
	Average Min Bank Slope		
	Average Top Width		
	Average Hydraulic Radius		
	Average Flow		
	Minimum Flow		
	Average Velocity		
	Average Shear Stress		
	Confinement Ratio (avg Q)		
	Confinement Ratio (min Q)		
HYDROLOGIC	Turbidity Aug 2018		
	Turbidity Sept 2018		
	Turbidity July 2019		

Methods

Study Area

As can be seen in Table 1, there are two distinct datasets for this study. The first dataset is focused on the Dan and Roanoke River basins. Within the Dan/Roanoke watershed, 33 sites were visited and each site was considered an outlet, and a subbasin was delineated from this site. The Dan/Roanoke sites are the blue dots in Figure 1 and the larger Dan/Roanoke watershed can be seen in this figure as well. The Dan/Roanoke sites were visited throughout the summers of 2018 and 2019 to study the impacts of in-stream fine sediment on fish populations. This fish study included detailed measurements of channel cross sections and other stream conditions, therefore, the Dan/Roanoke dataset has more site-specific parameters. The other dataset that is being analyzed in this study, are 35 USGS sites. These sites are located within Virginia, each site is associated with a USGS gage that had a complete or near complete turbidity record for the years of 2018 and 2019; this turbidity data was taken with a sensor and measurements were taken every 15 minutes. Just like with the Dan/Roanoke sites, the USGS gages were considered outlets and a subbasin was delineated. The location of the USGS gage sites are the red dots in Figure 1. Tables 4 and 5 in appendix A, shows a list of the Dan/Roanoke and USGS sites with names and site numbers, respectively. The USGS gages used in this study were mostly water quality sites and so most of the sites do not have stage/discharge measurements. Therefore, the field

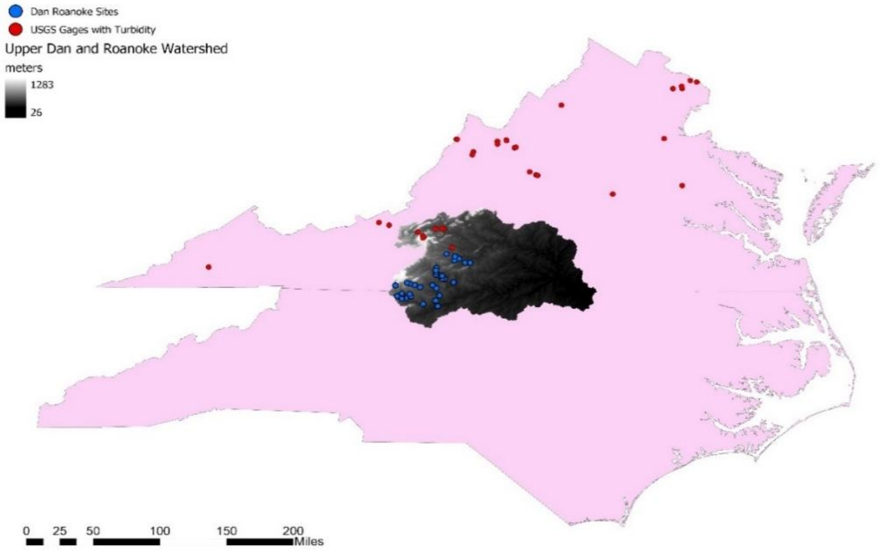


Figure 1. Study area map of sites from the Dan and Roanoke River basin in south central Virginia and north central North Carolina and sites located at USGS gages throughout Virginia.

measurements that are necessary to derive channel properties are not available for most of these USGS sites.

Watershed Characteristics

Watershed Area

Watershed area was calculated for all 68 subbasins in the Dan/Roanoke watersheds and for the USGS gage watersheds. These watersheds were delineated using ArcGIS Pro with a 10m DEM, downloaded from the USGS National Map (2018).

Watershed Slope

Average watershed slope was calculated for all subbasins within the Dan/Roanoke River basin as well as the USGS subbasins. Watershed slope was calculated from the 10m DEM, using the Slope tool in ArcGIS Pro. The slope tool in ArcGIS calculates the maximum downhill slope for each cell. The tool compares the elevation of the cell of interest to the elevations of the eight neighboring cells and determines the steepest downhill direction from that cell. Then the average slope degree over the entire watershed was extracted from the raster layer for each subbasin.

Watershed Land Cover

The National Land Cover Dataset (NLCD) was downloaded from the Multi-Resolution Land Characteristics Consortium (MLRC, 2016). The land cover data is divided into 15 land cover classes. For this portion of the study, the land cover classes were divided into four major classes: forest, hay/pasture, agriculture, and urban (Table 2). Then using ArcGIS Pro, the total number of cells were determined for each subbasin, then the number of cells that fell into one of those four categories were summed and divided by the total cell count to find the percent of the watershed that was covered in forest, agriculture, hay/pasture, and urban development.

Table 2. This table shows the major categories of land cover that this study focused on.

4 Major Land Cover Classes	**Land Cover Classes Included**
Urban	Developed, Open Space
	Developed, Low Intensity
	Developed, Medium Intensity
	Developed, High Intensity
Forest	Deciduous Forest
	Evergreen Forest
	Mixed Forest
Pasture/Hay	Pasture/Hay
Agriculture	Cultivated Crops

Universal Soil Loss Equation

The USLE is a product of the following factors: R is the rainfall erosivity factor (mm/yr), K is the soil erodibility factor (tons-ac-hr/hundreds of ac-ft-ton-in), L is the slope length factor, S is the slope steepness factor, C is the crop management factor, and P is the conservation practice factor. The product of these terms yields the annual soil loss for each pixel in the watershed, Y (tons/ha/yr).

$$Y = RKLSCP \tag{1}$$

This equation was used in ArcGIS Pro to yield an annual soil loss estimation for each pixel in the Dan/Roanoke subbasins, as well as for the USGS gage subbasins. Each factor of the USLE was calculated as follows.

R FACTOR

The rainfall erosivity factor was calculated using the equation developed by Renard and Freimund (1994) for the continental United States. This equation was executed in ArcGIS Pro with the PRISM 30-year annual average precipitation in mm as an input, which was downloaded from NACSE (2010). For the following equation, P is the mean annual precipitation in mm.

$$R = 0.04380P^{1.610} \tag{2}$$

K FACTOR

The soil erodibility factor is a soil characteristic that is provided in the SSURGO dataset for the entire United States (USDA-NRCS, 2017). Gridded SSURGO data for Virginia and

North Carolina were downloaded using the USDA geospatial data gateway. The K factor, with rock fragments included (K_f), was then extracted using ArcGIS Pro.

L FACTOR

The slope length factor, L, was calculated following the method presented by Desmet and Govers (1996). This factor used the 10m DEM as an input for slope calculations. The L factor also required drainage area, which was calculated by taking the product of flow accumulation and cell area. However, according to Renard et al. (1997), the drainage area factor must be limited, because the flow paths being considered would be too large if it was not limited. Following the method for limiting the L factor presented in Renard et al. (1997), the slope length should not exceed 1000 feet, so the drainage area was limited to 3100 m^2. The L factor included variables related to the watershed slope, which were calculated using the equations below, where θ is watershed slope, in radians for ArcGIS Pro.

$$\beta = \frac{(\sin\theta)/(0.0896)}{3\sin\theta^{0.8} + 0.56} \tag{3}$$

$$m = \frac{\beta}{1+\beta} \tag{4}$$

Finally, the L factor was calculated using the equation presented by Desmet and Govers (1996), where A is the limited drainage area and d is the cell length, which was 10m.

$$L = \frac{(A + d^2)^{m+1} - A^{m+1}}{d^{m+2} \times 22.13^m} \tag{5}$$

S FACTOR

To calculate the slope factor, S, the 10m DEM was used in the Slope tool function in ArcGIS Pro. Then using the slope, it was possible to calculate the S factor using the equations that were presented in the revised USLE (RUSLE) paper, by Renard et al. 1997. The S factor equations are below, where θ is the slope angle in degrees.

$$S = 10.8 \times \sin\theta + 0.03 \; for \; \theta < 5.1° \tag{6a}$$

$$S = 16.8 \times \sin\theta - 0.5 \; for \; \theta \geq 5.1° \tag{6b}$$

CP FACTOR

The crop management factor, C, and the conservation practice factor, P, are based on land cover types, which are provided by the NLCD. The 15 land cover classes were assigned a crop management factor (C) based on previous literature (Table 1). For this study it was assumed the conservation practice factor was one, $P = 1$.

Table 3. C factors for each land cover class and associated references.

Land Cover Type	**C Factor**	**Citation**
Open Water	0.000	Kim, Y. (2014), Gaffer et al. (2008), Haan et al. (1994)
Developed, Open Space	0.003	Haan et al. (1994), Kim (2014), Wischmeier and Smith (1978)
Developed, Low Intensity	0.013	Haan et al. (1994), Kim (2014)
Developed, Medium Intensity	0.200	Haan et al. (1994), Kim (2014)
Developed, High Intensity	0.450	Haan et al. (1994), Kim (2014)
Barren Land	1.000	Fayas et al. (2019), Haan et al. (1994), Kim (2014)
Deciduous Forest	0.003	Haan et al. (1994), Kim (2014), Ranzi et al. (2012), Wischmeier and Smith (1978)
Evergreen Forest	0.003	Haan et al. (1994), Kim (2014), Ranzi et al. (2012), Wischmeier and Smith (1978)
Mixed Forest	0.003	Haan et al. (1994), Kim (2014), Ranzi et al. (2012), Wischmeier and Smith (1978)
Shrub/scrub	0.100	Wischmeier and Smith (1978)
Herbaceous/Grassland	0.030	Wischmeier and Smith (1978)
Hay/Pasture	0.030	Wischmeier and Smith (1978)
Cultivated Crops	0.180	Gaffer et al. (2008)
Woody Wetlands	0.000	Assumed to be zero
Emergent Herbaceous Wetlands	0.000	Assumed to be zero

Connectivity Indices

Sediment connectivity indices were calculated for all 68 subbasins within the Dan/Roanoke River basins and the USGS subbasins.

BORSELLI INDEX

The first sediment connectivity index for this study was the index presented by Borselli et al. (2008). The connectivity index (IC) is defined by Borselli et al. (2008) in the following equation; where D_{up} and D_{dn} are the upslope and downslope components of connectivity.

$$IC = log_{10}(\frac{D_{up}}{D_{dn}}) \tag{7}$$

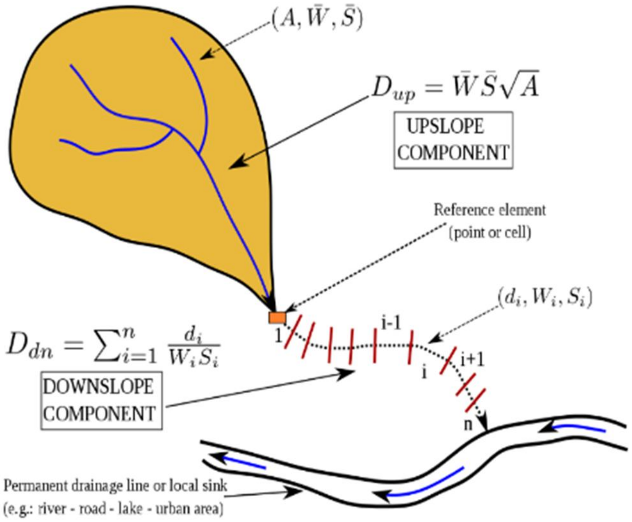


Figure 2. Diagram of upslope and downslope components for the connectivity indices. This image was reproduced from Borselli et al. (2008).

The upslope component (D_{up}) is proportional to the probability that sediment from the upslope area will reach a reference pixel. This component is the potential for sediment, produced from the upslope, to be routed to a reference pixel. The upslope component is calculated with the following equation, where $\overline{W}$ is the average weighting factor of the upslope contributing area, $\overline{S}$

is the average slope of the upslope contributing area (m/m), and A is the upslope contributing area (m^2).

$$D_{up} = \overline{W}\,\overline{S}\sqrt{A} \tag{8}$$

The downslope component (D_{dn}) is inversely proportional to the probability that sediment produced from a reference pixel will reach the target outlet. This component considers the flow path that a particle from the reference pixel would travel to reach the target outlet. The downslope component was calculated with the following equation; where d_i is the length of the flow path along the i^{th} cell (m), W_i and S_i are the weighting factor and the slope gradient of the i^{th} cell.

$$D_{dn} = \sum_i \frac{d_i}{W_i S_i} \tag{9}$$

The method presented by Borselli et al. (2008) uses the C factor from USLE as the weighting factor. To calculate the Borselli index the C factor was constrained to 0.001 - 1 to avoid a zero in the denominator in the calculations for D_{dn}.

CAVALLI INDEX

The second sediment connectivity index used in this study was the index presented by Cavalli et al. (2013). This index approximates the overall connectivity of each pixel based on surface roughness and slope rather than land cover. The model used to calculate this index follows the same procedure as the method presented by Borselli et al. (2008); however, this method uses a weighting factor that assumes surface roughness as the main driver in landscape connectivity. The weighting factor was calculated following the method presented in Cavalli et al. (2013), with the 10m DEM as the input, where the mean elevation of a 5×5 square of pixels was taken. The standard deviation of the difference between the original DEM values and the 5×5-cell mean is the roughness index (RI). The weighting factor was then calculated using the equation presented by Cavalli et al. (2013), where RI_{max} is the maximum value of RI.

$$W = 1 - \left(\frac{RI}{RI_{max}}\right) \tag{10}$$

The weighting factor was then limited to $0.001 \leq W$ to ensure there was not a zero in the denominator for the calculation of D_{dn}.

Topographic Indices

The topographic wetness indices were calculated for all Dan/Roanoke subbasins and USGS gage watersheds.

TOPOGRAPHIC WETNESS INDEX

The topographic wetness index, or topographic index (TI) is used to estimate the effect of topography on the generation of runoff across a landscape. The TI was then computed with the equation presented by Beven, and Kirkby (1979), where A is the upslope contributing area or specific catchment area (m^2) and θ is the local slope gradient.

$$TI = \ln\left(\frac{A}{\tan\theta}\right) \tag{11}$$

Both the slope and the upslope contributing area were calculated from the 10m DEM in ArcGIS. The slope was computed using the Slope tool in ArcGIS Pro and the upslope contributing area was calculated as the product of flow accumulation and cell area.

SOIL TOPOGRAPHIC INDEX

The soil topographic index (STI) is a modified version of the topographic index developed by Beven and Kirkby (1979). STI includes soil transmissivity in its runoff calculations, which is the product of soil depth and hydraulic conductivity, in an attempt to incorporate soil characteristics in the role of runoff production across the landscape. The STI was calculated using the equation produced by Lyon et al. (2004) where A is the upslope contributing area or specific catchment area (m^2) and θ is the local slope gradient (radians), D is the soil depth (cm), and K_s is the saturated hydraulic conductivity (cm/day).

$$STI = \ln\left(\frac{A}{\tan\theta\, DK_s}\right) \tag{12}$$

The slope and upslope contributing area, as with the TI, were calculated from the 10m DEM. While the soil depth and saturated hydraulic conductivity were extracted from the gridded SSURGO data.

Weighted Universal Soil Loss Equation

USLE provides an estimate of annual soil loss across the watershed; however, it only considers sediment detachment and therefore is generally an overestimate of sediment yield. To mitigate this over estimation various discount factors were applied to the USLE outputs in an attempt to more accurately determine the spatial locations of sediment production in the watersheds being studied.

SEDIMENT DELIVERY RATIO

A sediment delivery ratio (SDR) was calculated for both the Dan/Roanoke sites and the USGS sites. This SDR was developed by USDA-NRCS and is calculated based on the drainage area of the watershed (USDA-NRCS, 1983). The SDR is then used as an additional factor in the USLE equation, in an attempt to produce a more accurate sediment yield calculation. The equation for the SDR used can be seen below, where A is the drainage area (mi^2).

$$SDR = 0.417762 \times A^{-0.134958} - 0.127097 \tag{13}$$

$$Y_{SDR} = (\mathrm{RKLSCP}) \times \mathrm{SDR} \tag{14}$$

BORSELLI INDEX

Normalized

The Borselli sediment connectivity index was normalized between zero and one with the following normalization formula.

$$Bor_{Norm} = \frac{Bor - Bor_{min}}{Bor_{max} - Bor_{min}} \tag{15}$$

This normalized connectivity was then used as an additional factor in USLE.

$$Y_{BN} = (RKLSCP) \times Bor_{Norm} \tag{16}$$

Exponential

The Borselli sediment connectivity index was normalized using an exponential function with the following formula.

$$Bor_{Exp} = 10^{Bor} \tag{17}$$

This exponentially normalized index was used as an additional factor in USLE.

$$Y_{BE} = (RKLSCP) \times Bor_{Exp} \tag{18}$$

CAVALLI INDEX

Normalized

The sediment connectivity index was normalized between zero and one with the following normalization formula.

$$Cav_{Norm} = \frac{Cav - Cav_{min}}{Cav_{max} - Cav_{min}} \tag{19}$$

This normalized connectivity was then used as an additional factor in USLE.

$$Y_{CN} = (RKLSCP) \times Cav_{Norm} \tag{20}$$

Exponential

The Cavalli sediment connectivity index was normalized using an exponential function with the following formula.

$$Cav_{Exp} = 10^{Cav} \tag{21}$$

This exponentially normalized index was used as an additional factor in USLE.

$$Y_{CE} = (RKLSCP) \times Cav_{Exp} \tag{22}$$

TOPOGRAPHIC INDEX

The topographic index was normalized between zero and one with the following normalization formula.

$$TI_{Norm} = \frac{TI - TI_{min}}{TI_{max} - TI_{min}} \tag{23}$$

This normalized TI was then used as an additional factor in USLE.

$$A = (RKLSCP) \times TI_{Norm} \tag{24}$$

SOIL TOPOGRAPHIC INDEX

The soil topographic index was normalized between zero and one with the following normalization formula.

$$STI_{Norm} = \frac{STI - STI_{min}}{STI_{max} - STI_{min}} \tag{25}$$

This normalized STI was then used as an additional factor in USLE.

$$A = (RKLSCP) \times STI_{Norm} \tag{26}$$

Site Specific Characteristics

Sediment Susceptibility

The 33 sites in the Dan/Roanoke River basins were qualitatively assessed for their susceptibility to erosion. Each site was given an overall sediment susceptibility score which was a value between 0 and 60; 0 being little to no erosion potential and 60 being extremely high erosion potential. The susceptibility value was a synthesis of qualitative observations with a 1-5 ranking, taken at each site, about conditions in channel, on banks, in riparian areas, and in floodplains. Some of the observations included, but were not limited to; presence of fine sediments/bedrock/wood, vegetation density, bank steepness, floodplain depositions, slump blocks, etc. The summary tables for the sediment susceptibility for both 2018 and 2019 can be found in Tables 6 and 7 in Appendix A.

Embeddedness

Embeddedness is the measure of how much coarse particles on the streambed are surrounded by, or embedded into, a finer substrate. This was estimated by taking the bed material and approximating the percent that the particles were buried in fine sediment. Specifically, the embeddedness was measured by picking multiple streambed particles and measuring the height of the embeddedness line. Embeddedness lines can be a silt line, stain line, or the edge of periphyton growth, the embeddedness line is then considered as the percentage of the total height of the particle (Fitzpatrick et al., 1998; Sennatt et al., 2006; Sutherland et al., 2010). These measurements were taken for the 33 subbasins in the Dan/Roanoke River Basins.

Channel Slope

The slope of the channel at the outlet of each subbasin was extracted from the National Hydrography Dataset (USGS and EPA, 2012).

Channel Geometry

BANK HEIGHT

Cross sections at 33 sites in the Dan/Roanoke River basins were surveyed. The survey for each site consisted of three representative cross sections of the channel; these cross sections were spaced about one to two channel widths apart. For each of the three cross sections top of bank and toe of bank were determined and from these elevations bank height was calculated as the change in elevation between those two points. For each site there were six bank heights, left and right bank heights for cross sections one, two, and three; these heights were synthesized in the following ways. An example of channel geometry measurements taken for each cross section can be seen in Figure 3.

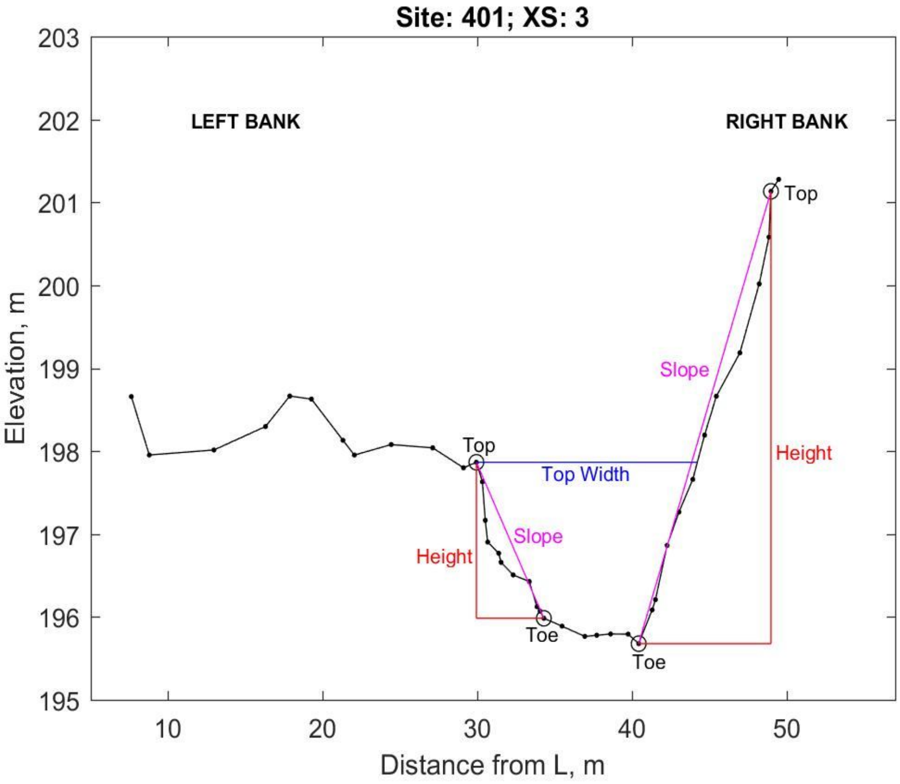


Figure 3. Diagram of channel properties from the third cross section of site 401.

Average Bank Height

The average of all six bank heights across the site.

Average Maximum Bank Height

The maximum bank height for each individual cross section was determined. This synthesized the heights to three measurements for each site. Then the average of these three maximum bank heights were taken.

Average Minimum Bank Height

The minimum bank height for each individual cross section was determined. This synthesized the heights to 3 measurements for each site. Then the average of these three minimum bank heights were taken.

BANK SLOPE

The slope for each bank of each cross section for the Dan/Roanoke sites were determined as bank height over the horizontal distance between top and toe of the bank (Figure 3). As with the bank heights, there were six bank slope measurements, which were synthesized in the same manner as the bank heights.

Average Bank Slope

The average of all six bank slopes across the site.

Average Maximum Bank Slope

The maximum bank slope for each individual cross section was determined. This synthesized the slope to 3 measurements for each site. Then the average of these three maximum bank slopes were taken.

Average Minimum Bank Slope

The minimum bank slope for each individual cross section was determined. This synthesized the slope to 3 measurements for each site. Then the average of these three minimum bank slopes were taken.

TOP WIDTH

For each cross section of the Dan/Roanoke sites, the side of the bank with the lower top of bank was determined. Then from the elevation of the lower bank, a line was drawn across the channel to determine the top width of the channel before any water would spill into the floodplain (Figure 3).

VELOCITY

Using the channel slope from the NHDPlus dataset and channel geometry from the cross-section data, the discharge at each cross section was calculated using Manning's equation. Where V is velocity (m/s), n is the Manning's roughness coefficient, which was assumed to be 0.035 at all sites, R is the hydraulic radius (m), and S is the channel slope (m/m)

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{23a}$$

The average velocity across the three cross sections was taken as the representative velocity for each of the sites in the Dan/Roanoke basins.

DISCHARGE

Discharge was calculated using the following equation, where Q is discharge (m^3/s), V is velocity (m/s), and A_{cs} is the cross section area.

$$Q = VA_{cs} \tag{23b}$$

These calculations resulted in a total of three discharge measurements, one per cross section for each site, which were synthesized in the following way.

Average Discharge

The average was taken of the three discharge measurements (Q_{avg}).

Minimum Discharge

The minimum of the three discharge measurements was taken (Q_{min}).

BED SHEAR STRESS

The bed shear stress was calculated for each cross section using the following equation where τ is the bed shear stress (Pa), ρ is the density of water which is 1000 kg/m^3, g is acceleration due to gravity which is 9.81 m/s^2.

$$\tau = \rho g R S \tag{24}$$

The average shear stress across the three cross sections was taken as the representative shear stress for each of the sites in the Dan and Roanoke basins.

CONFINEMENT RATIO

For this study, two confinement ratios were computed. The confinement ratio is the calculated discharge for each site (Q_{avg} and Q_{min}) divided by the 2-yr discharge for each site, which was obtained from USGS StreamStats (USGS, 2018). The discharge in this case was calculated as the flow that fills the channel up to the top of its lowest bank, or in other words the largest discharge that is still confined to the channel. The confinement ratio for this study is the ratio of the bankfull flow, or when the lowest bank is overtopped, to the 2-year flow.

Average Discharge

The first confinement ratio was determined using the average discharge for each site using the following equation. Where CR_{avg} is the confinement ratio for the average calculated discharge, Q_{avg} is the average discharge for each site, and Q_{SS} is the 2-yr discharge from the USGS StreamStats data (USGS, 2018)

$$CR_{avg} = \frac{Q_{avg}}{Q_{SS}} \tag{25a}$$

Minimum Discharge

The second confinement ratio was determined using the minimum discharge for each site using the following equation. Where CR_{min} is the confinement ratio for the minimum calculated discharge, Q_{min} is the minimum discharge for each site, and Q_{SS} is the 2-yr discharge from the USGS StreamStats data (USGS, 2018).

$$CR_{min} = \frac{Q_{min}}{Q_{SS}} \tag{25b}$$

Hydrologic Characteristics

Turbidity

Synoptic turbidity data was used for each Dan/Roanoke site. The Dan and Roanoke River basin sites' turbidity data was recorded using a YSI Professional Digital Sampling System (ProDSS), this instrument was used to measure the turbidity levels in stream with the ProDSS turbidity sensor. The sensor was calibrated before each turbidity dataset using a 2-point calibration at 0 and 124 NTU. Turbidity measurements were recorded for the majority of the sites during storm events in August 2018, September 2018, and July 2019.

The USGS sites that were chosen for this study all had time series data for the turbidity data. Each USGS gage had varying time series that the data was recorded during; however, each of the 35 sites selected had complete or near complete 15-minute turbidity data for both 2018 and 2019. The turbidity data for the USGS sites were recorded using YSI EXO sonde, which is an instrument that collects water quality data, including turbidity. The same instrument, the YSI EXO, was used at each of the USGS sites for both years of turbidity data collection, so turbidity data was comparable across USGS sites. The annual average for 2018 and 2019 were used for the USGS gage watersheds.

Results

Each of the parameters previously discussed were compared using a linear regression to determine the correlations amongst the different characteristics. The correlation plot for all the parameters for the Dan/Roanoke sites as well as the USGS gage sites can be seen in Figures 4a and 4b.

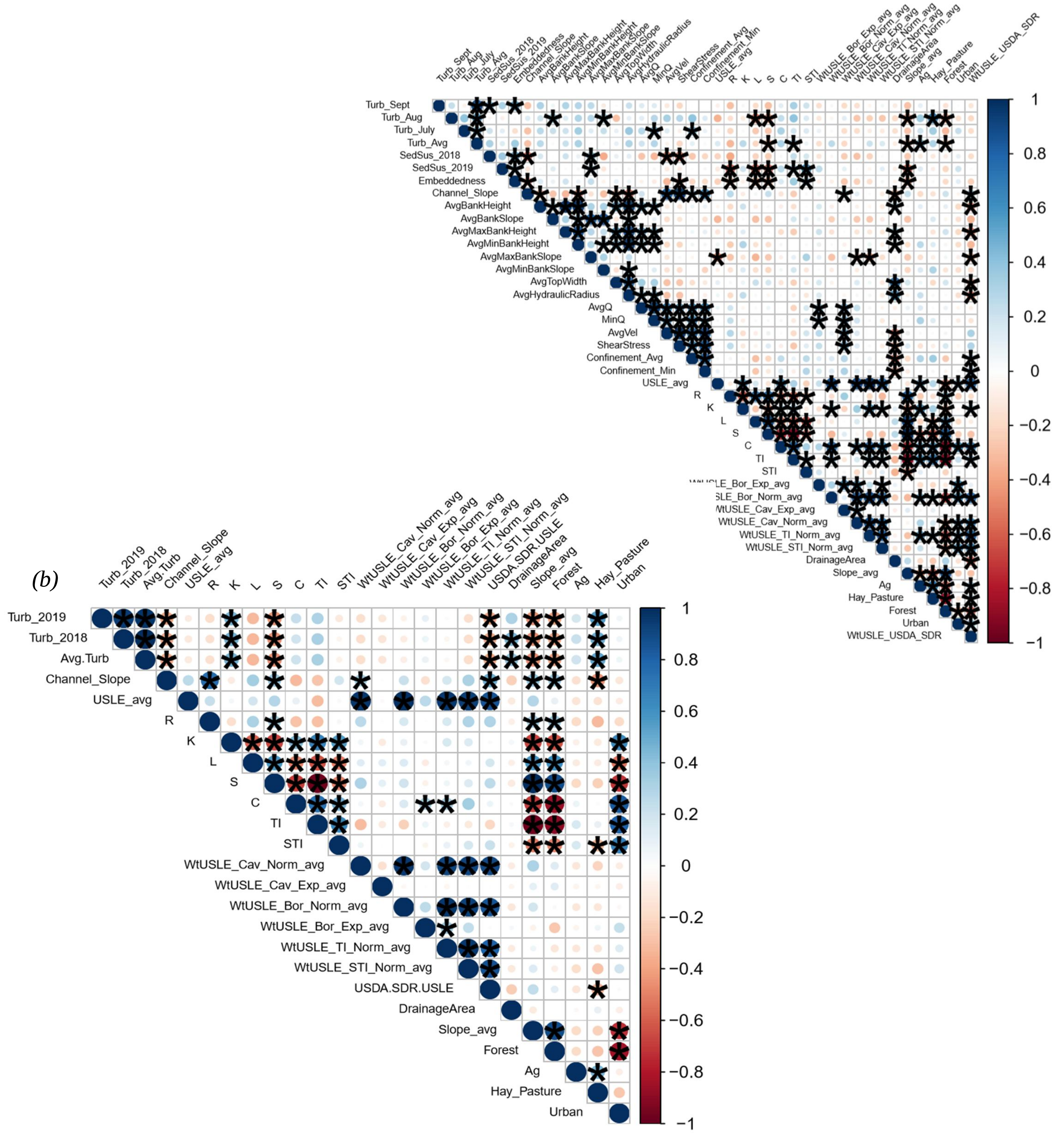


Figure 4. Correlation plots for all parameters for both the Dan/Roanoke (a) and the USGS (b) sites. The colors of the dots indicate the R for the relationships and the size of the dots signify the strength of the correlation or its significance. The asterisks (*) indicate that those correlations are significant at the 5% level.

Figure 5. Displays the parameters for the Dan/Roanoke sites ranked from having the best correlation (left) to worst correlations (right) with the July turbidity data. The blue dots indicate site-specific parameters, green diamonds indicate watershed characteristics, pink triangles indicate topographic indices, and orange rhombuses indicate USLE parameters.

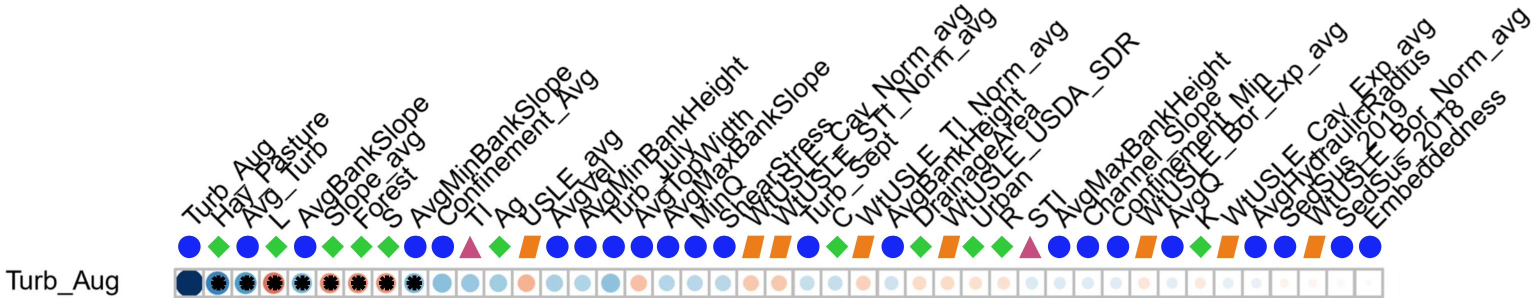


Figure 6. Displays the parameters for the Dan/Roanoke sites ranked from having the best correlation (left) to worst correlations (right) with the August turbidity data. The blue dots indicate site-specific parameters, green diamonds indicate watershed characteristics, pink triangles indicate topographic indices, and orange rhombuses indicate USLE parameters.

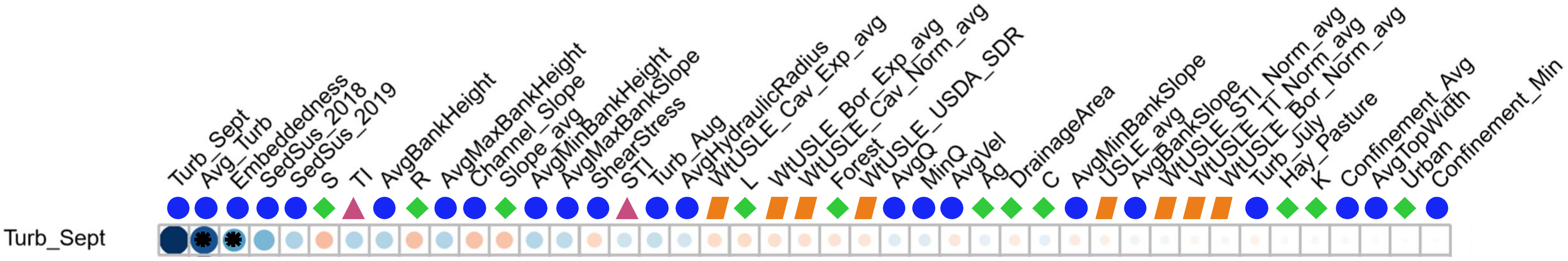


Figure 7. Displays the parameters for the Dan/Roanoke sites ranked from having the best correlation (left) to worst correlations (right) with the September turbidity data. The blue dots indicate site-specific parameters, green diamonds indicate watershed characteristics, pink triangles indicate topographic indices, and orange rhombuses indicate USLE parameters.

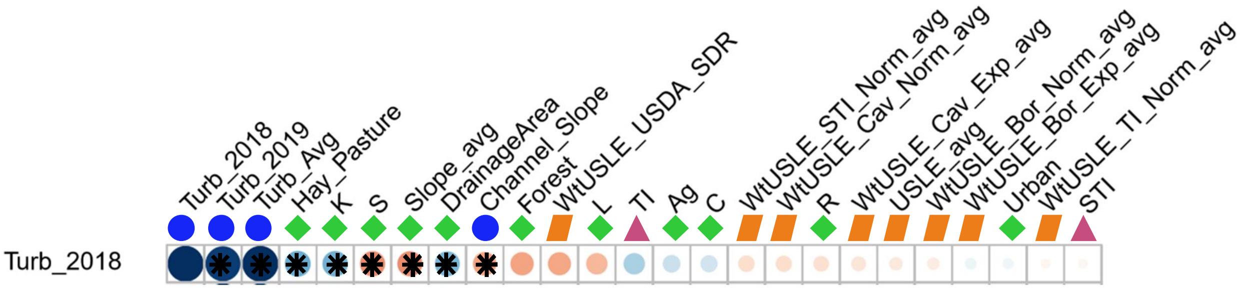


Figure 8. Displays the parameters for the USGS sites ranked from having the best correlation (left) to worst correlations (right) with the 2018 average annual turbidity data. The blue dots indicate site-specific parameters, green diamonds indicate watershed characteristics, pink triangles indicate topographic indices, and orange rhombuses indicate USLE parameters.

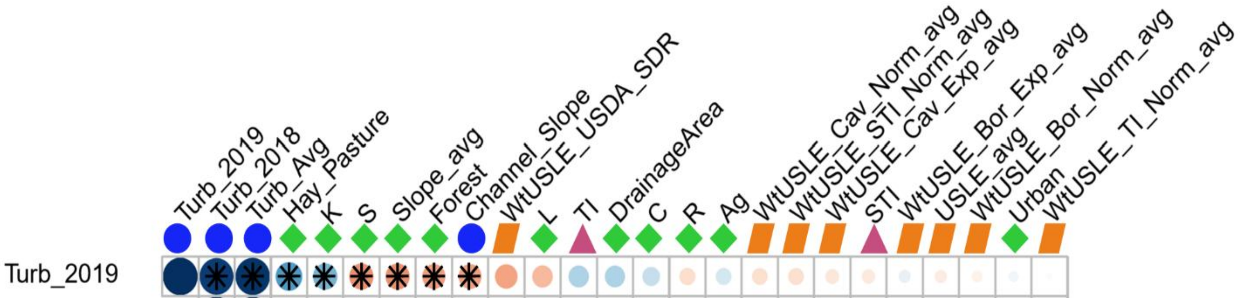


Figure 9. Displays the parameters for the USGS sites ranked from having the best correlation (left) to worst correlations (right) with the 2019 average annual turbidity data. The blue dots indicate site-specific parameters, green diamonds indicate watershed characteristics, pink triangles indicate topographic indices, and orange rhombuses indicate USLE parameters.

The USGS sites had fewer parameters in total than the Dan/Roanoke sites. Despite the difference in total number of parameters, some similar trends can be seen between the two datasets. In figures 5, 6, 7, 8, and 9 it can be seen that in general in-channel and overall watershed characteristics were better correlated with turbidity datasets; whereas USLE and TI parameters were not well correlated.

Watershed Characteristics

Universal Soil Loss Equation

USLE, as previously mentioned, was calculated for all the Dan/Roanoke sites and the USGS sites. A map of each USLE factor and the output for the USLE calculations for site 401 from the Dan/Roanoke study area can be seen in Figures 10 and 11.

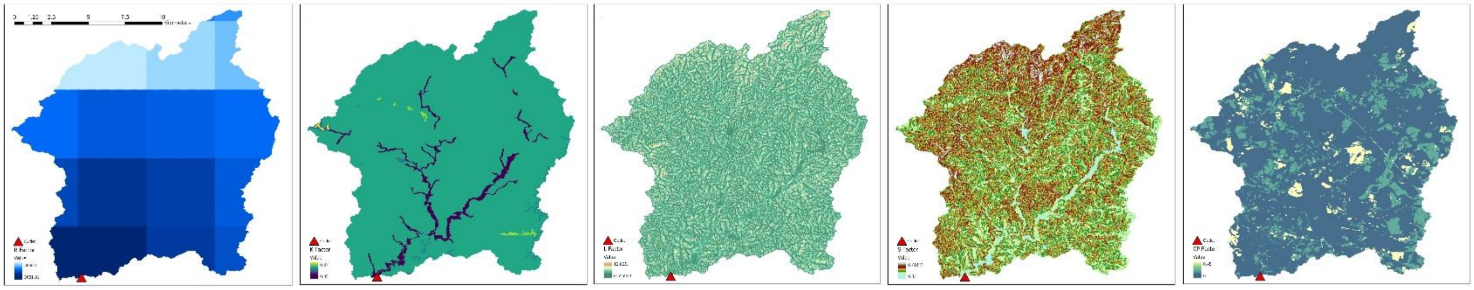


Figure 10. Displays the different factors used to calculate the USLE. R (first), K (second), L (third), S (fourth), CP (fifth).

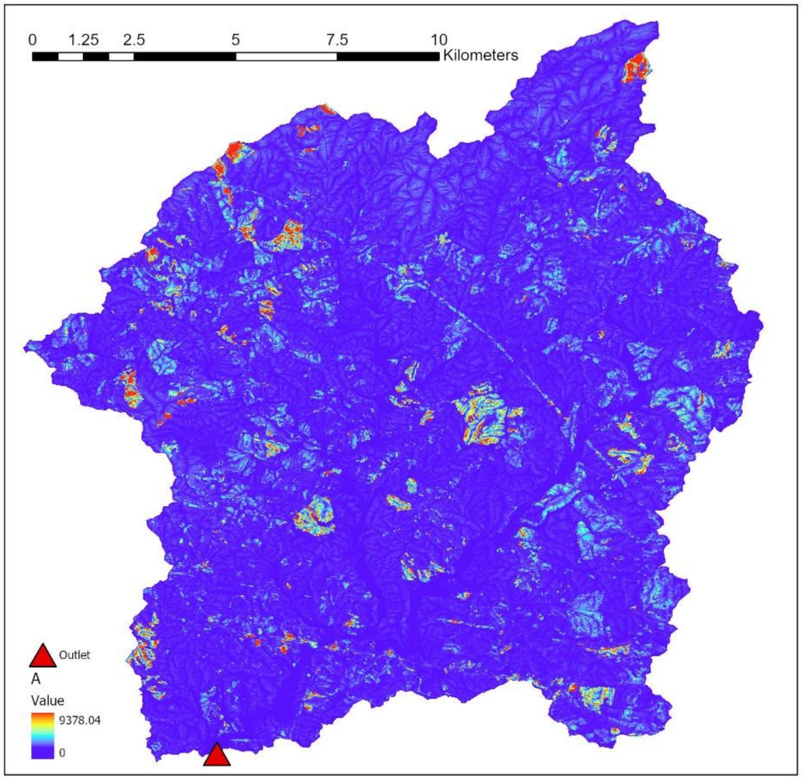


Figure 11. Displays USLE output, A (tons/ha/yr).

Connectivity Indices

BORSELLI INDEX

The Borselli index was calculated for all the Dan/Roanoke sites and the USGS sites. The map for the Borselli index calculated for site 401 from the Dan/Roanoke study area can be seen in panel A of Figure 12. As expected, this index reflects spatial variation that is closely related to the C factor because that was used as the weighting factor for this calculation.

CAVALLI INDEX

The Cavalli index was calculated for all the Dan/Roanoke sites and the USGS sites. The map for the Cavalli index calculated for site 401 from the Dan/Roanoke study area can be seen in panel B of Figure 12. The connectivity index increases as the distance from the outlet decreases and upslope area increases.

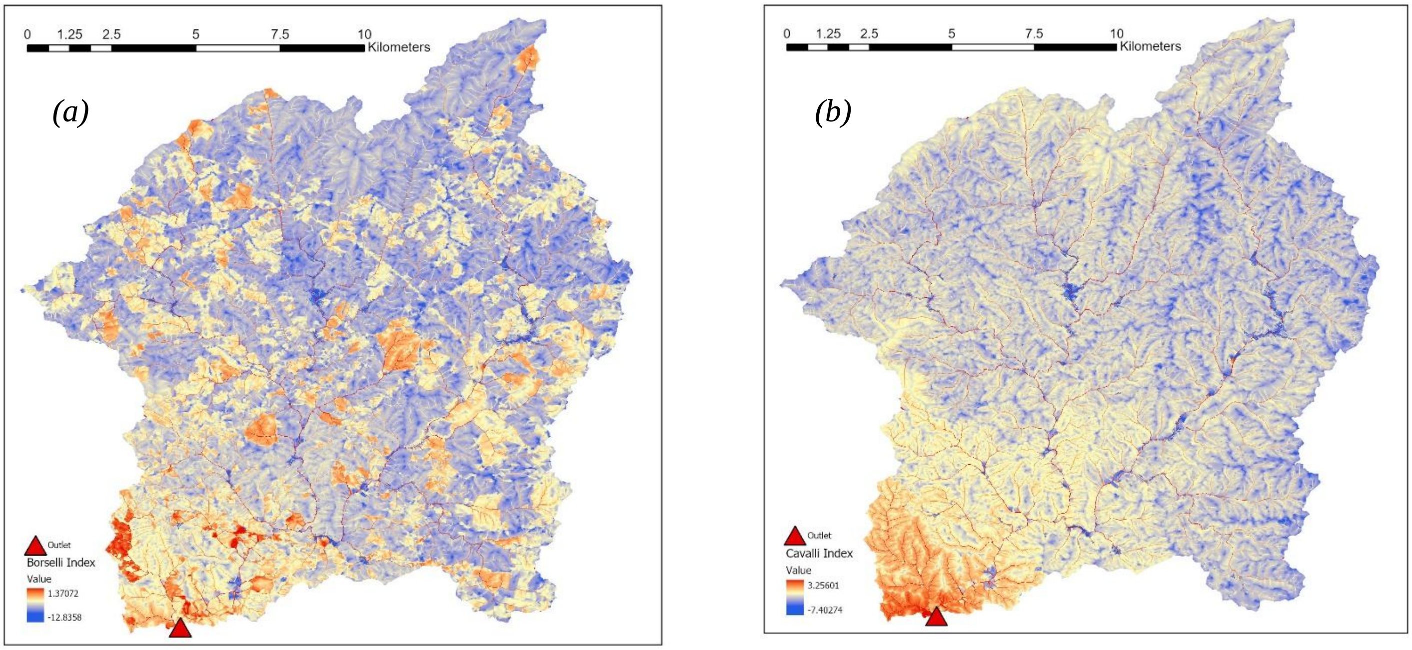


Figure 12. Map of Borselli (a) and Cavalli (b) connectivity index for site 401.

Topographic Indices

TOPOGRAPHIC WETNESS INDEX

The topographic index was calculated for all the Dan/Roanoke sites and the USGS sites. The map for TI calculated for site 401 from the Dan/Roanoke study area can be seen in panel A of Figure 13. As expected, this topographic index increases in lower sloped areas, which are generally located closer to channels.

SOIL TOPOGRAPHIC INDEX

The soil topographic index was calculated for all the Dan/Roanoke sites and the USGS sites. The map for STI calculated for site 401 from the Dan/Roanoke study area can be seen in panel B of Figure 13. The soil topographic index is closely related to the topographic index, however the soil type and depth are also playing a role in addition to slope.

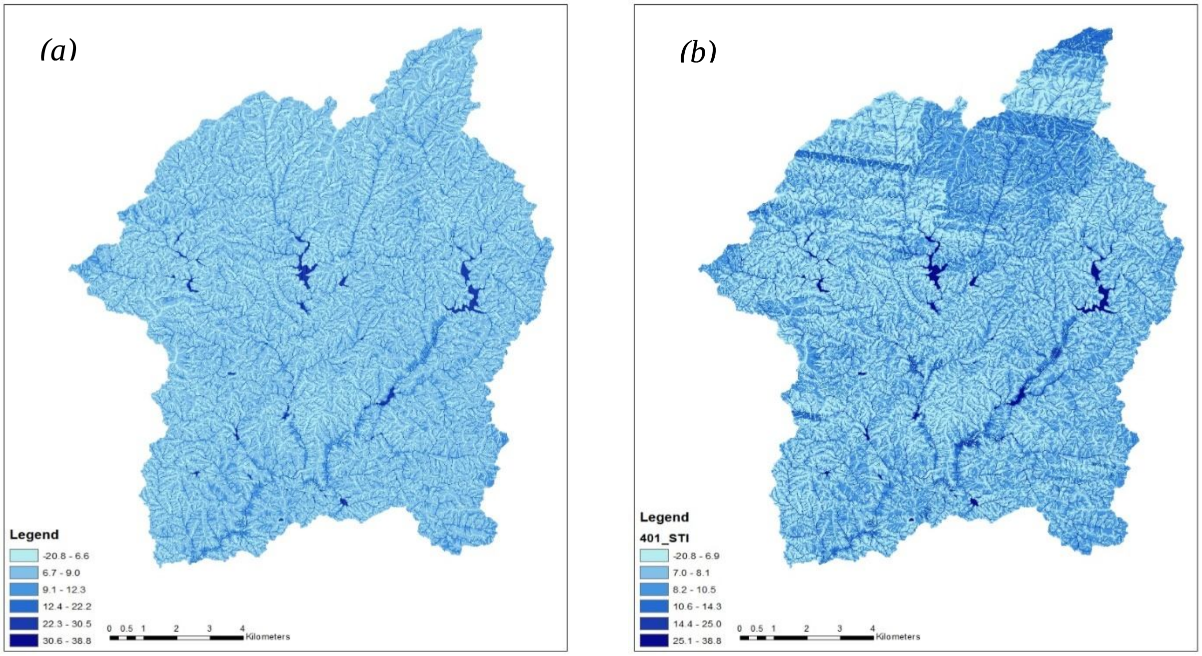
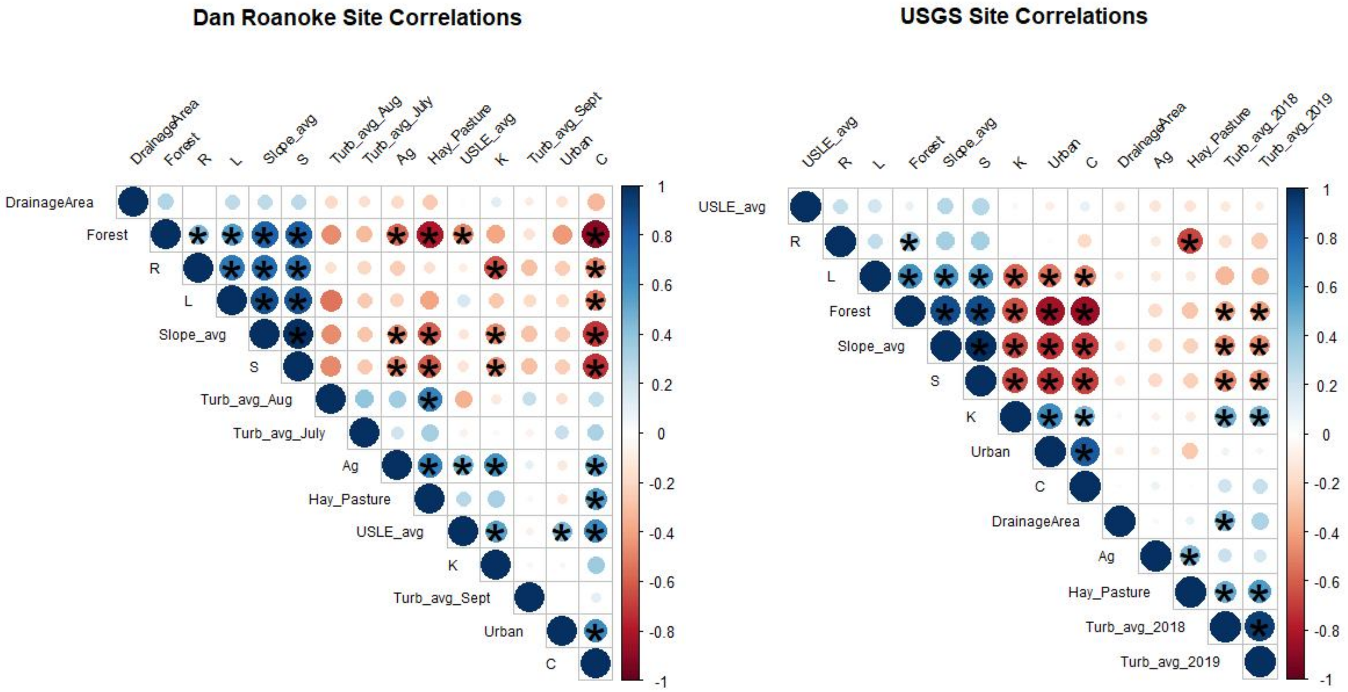


Figure 13. Map of topographic wetness index (a) and soil topographic index (b) for site 401.

Correlations

The correlation between the different watershed characteristics were highly variable and can be seen in Figure 14. The USLE, connectivity indices, and topographic indices were not significantly correlated with turbidity for the Dan/Roanoke and the USGS sites, which can be seen in Figure 4. Significant and important relationships for the watershed parameters include slope, forest, and hay/pasture vs. turbidity.


Dan Roanoke Site Correlations

USGS Site Correlations

Figure 14. Correlation plots of watershed parameters for both the Dan/Roanoke (left) and USGS (right) sites. The colors of the dots indicate the R for the relationships and the size of the dots signify the strength of the correlation or its significance. The asterisks (*) indicate that those correlations are significant at the 5% level.

For both the Dan/Roanoke sites and the USGS sites, the calculated USLE values were not well correlated to the turbidity. The scatter plots for both datasets are displayed in Figure 15. While the USLE values were not well correlated to the turbidity, other watershed parameters were better correlated with the turbidity data. Both average watershed slope and forest cover displayed negative correlations with the turbidity data, these comparisons can be found in Figures 16 and 17. The relationships between forest/slope and turbidity were significant for the USGS sites.

The Dan/Roanoke sites comparisons of USLE and August/September/July turbidity measurements had R^2 values of 0.11, 0.01, and 0.01 and p values of 0.15, 0.72, and 0.67. The

Dan/Roanoke sites comparisons of average watershed slope and August/September/July turbidity measurements had R^2 values of 0.22, 0.08, and 0.07 and p values of 0.03, 0.15, and 0.26. The Dan/Roanoke sites comparisons of percent forest cover and August/September/July turbidity measurements had R^2 values of 0.21, 0.02, 0.10 and p values of 0.04, 0.48, and 0.20. The USGS sites comparisons of USLE and 2018/2019 turbidity measurements had R^2 values of 0.01 and 0.01 and p values of 0.53 and 0.60. The USGS sites comparisons of average watershed slope and 2018/2019 turbidity measurements had R^2 values of 0.21 and 0.20 and p values of 0.01 and 0.01. The USGS sites comparisons of percent forest cover and 2018/2019 turbidity measurements had R^2 values of 0.15 and 0.17 and p values of 0.02 and 0.01.

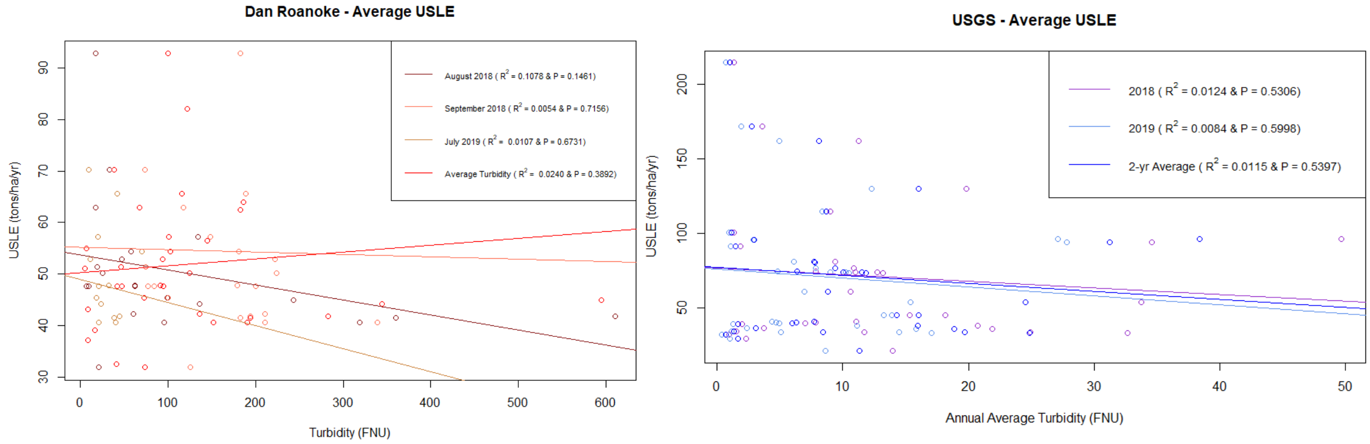


Figure 15. Scatter plot of average USLE vs. turbidity for both Dan/Roanoke (left) and USGS (right) sites.

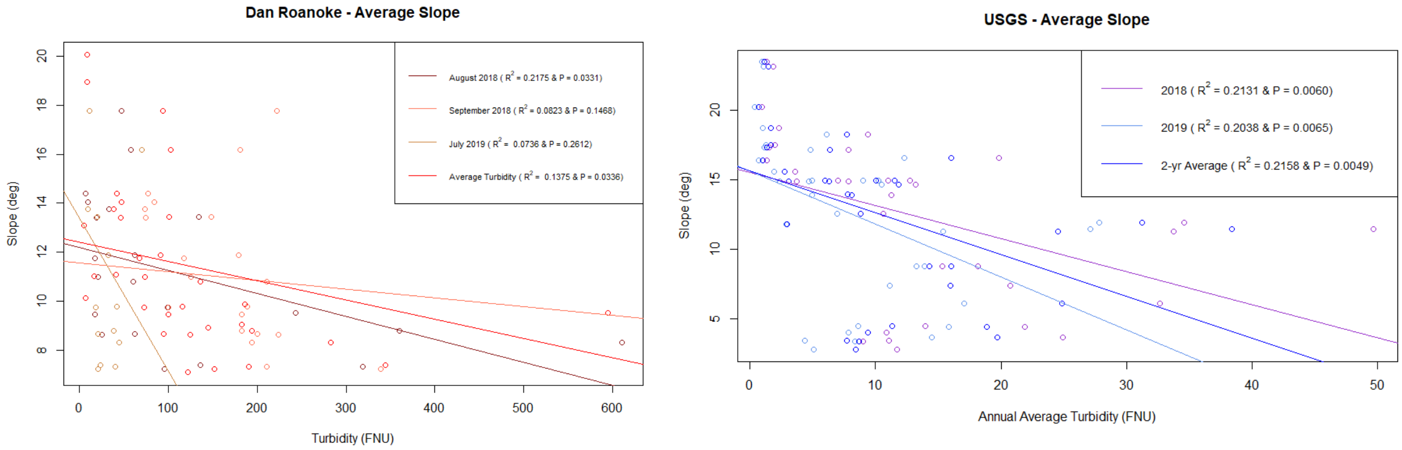


Figure 16. Scatter plot of average watershed slope vs. turbidity for both Dan/Roanoke (left) and USGS (right) sites.

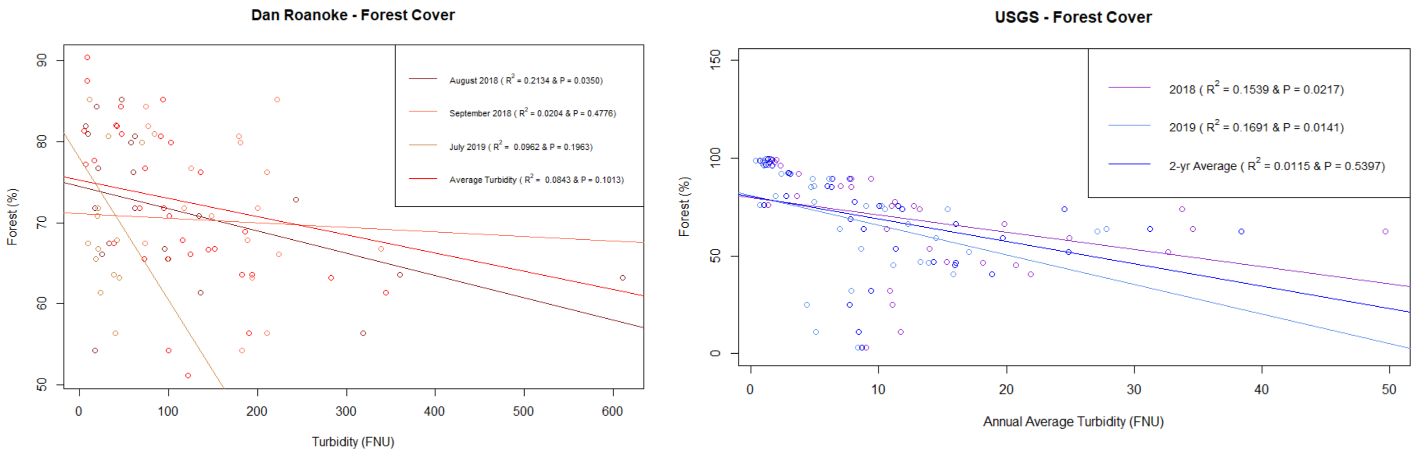


Figure 17. Scatter plot of percent forest cover vs. turbidity for both the Dan/Roanoke (left) and USGS (right) sites.

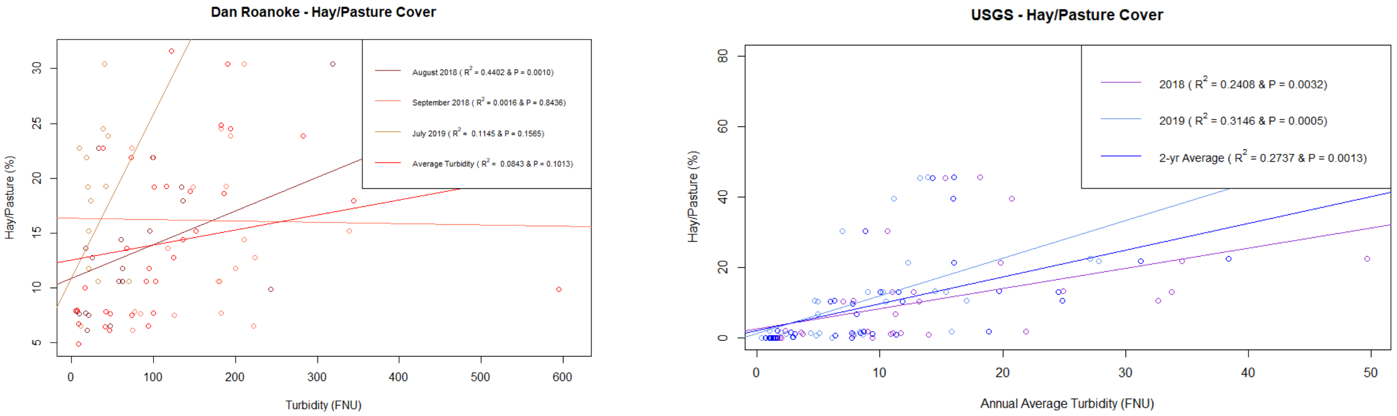


Figure 18. Scatter plot of percent hay/pasture cover vs. turbidity for both the Dan/Roanoke (left) and USGS (right) sites.

Finally, the turbidity data was positively correlated with percent hay/pasture cover for both the August and July Dan/Roanoke turbidity datasets and both of the USGS turbidity datasets, these relationships can be seen in Figure 18. The correlations were significant for all the USGS turbidity datasets, and for the August turbidity dataset for the Dan/Roanoke sites. Upon further investigation, it was found that hay/pasture and average watershed slope were negatively correlated. This indicates that watersheds/areas with lower slopes are correlated with higher levels of hay/pasture cover, which can be seen in Figure 8. For the Dan/Roanoke sites the R^2 for average watershed slope vs. hay/pasture cover was 0.36 and the p-value was 0.0002, which is a significant correlation. For the USGS sites, the R^2 for average watershed slope vs. hay/pasture cover was 0.05 and the p-value was 0.19.

In addition to the overall correlations between slope and hay/pasture cover, a cell-by-cell analysis determined how these variables varied spatially in these different subbasins. For both the Dan/Roanoke and USGS watersheds, slope was split into five classes, using natural breaks in the data to create these classes, 1 being low slopes and 5 being high slopes; the slope class values can be found in Table 8 in Appendix A. Then each cell for the watersheds were classified as being in one of these five classes. Then the same was done with the hay/pasture, each cell was assigned a 1 for having hay/pasture or a 0 for not having hay/pasture. Then it was determined how these two variables co-varied for both the Dan/Roanoke subbasins and the USGS subbasins. It can be seen in Figure 19, that in both the Dan/Roanoke and the USGS subbasins more than 60% of the hay/pasture cover occurs on the three lower slope classes.

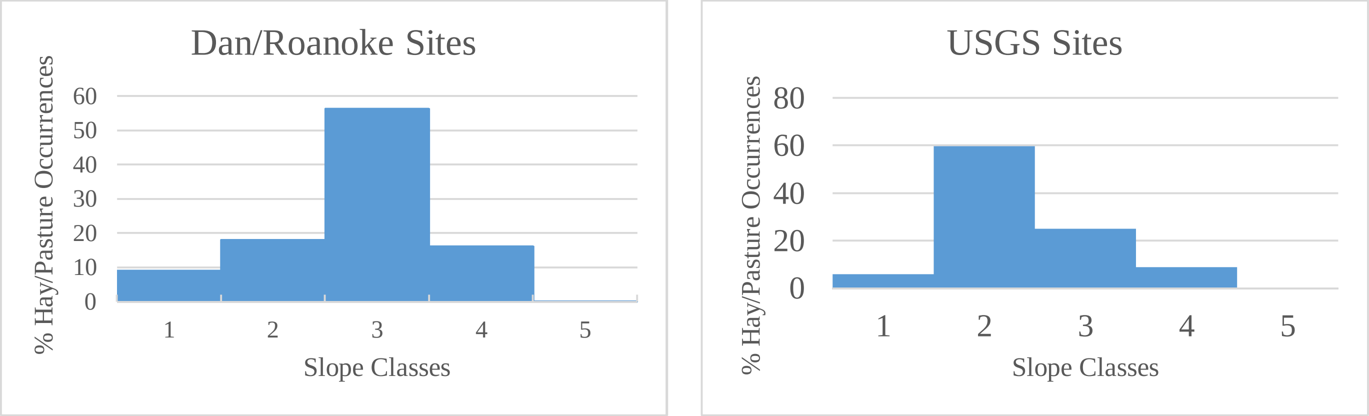


Figure 19. Displays the percent occurrences of hay/pasture cover to the classified slope values on a pixel basis for both the Dan/Roanoke (left) and USGS (right) sites.

The Dan/Roanoke sites comparisons of percent hay/pasture cover and August/September/July turbidity measurements had R^2 values of 0.44, 0.002, and 0.11 and p values of 0.001, 0.84, and 0.16. The USGS sites comparisons of percent hay/pasture cover and 2018/2019 turbidity measurements had R^2 values of 0.24 and 0.31 and p values of 0.0032 and 0.0005.

Site Specific Characteristics

The site-specific parameters, other than channel slope, were only available for the Dan/Roanoke sites. The correlations for these parameters are displayed in Figure 20. The August turbidity data has significant positive correlations with average bank slope and the average minimum bank slope. However, there does not seem to be significant relationships between the other site-specific parameters and turbidity. Channel slope appears to have negative correlations with bank heights and hydraulic radius. Finally, the average confinement ratio is positively correlated with the July and August turbidities, and channel slope parameters.

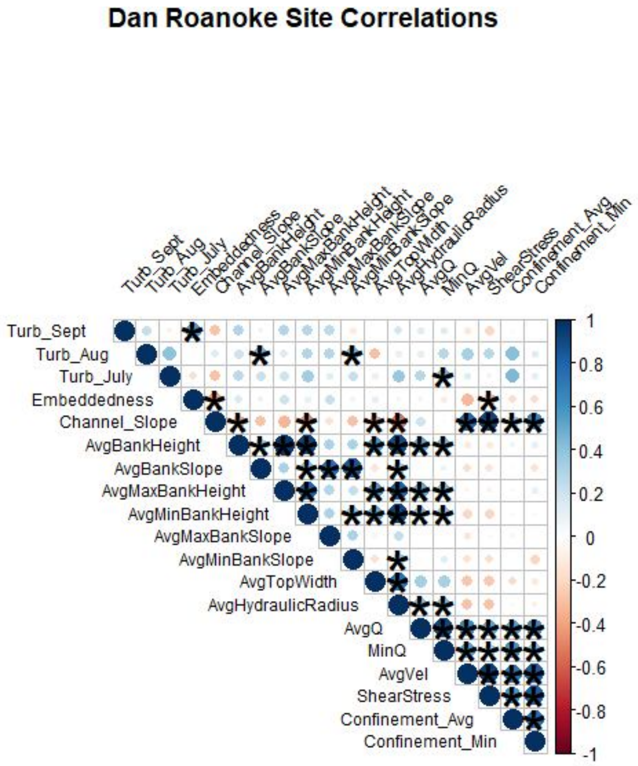


Figure 20. Correlation plots of site-specific parameters for the Dan/Roanoke sites. The colors of the dots indicate the R for the relationships and the size of the dots signify the strength of the correlation or its significance. The asterisks (*) indicate that those correlations are significant at the 5% level.

The Dan/Roanoke sites comparisons of average bank slope and August/September/July turbidity measurements had R^2 values of 0.22, 0.004, and 0.05 and p values of 0.03, 0.75, and 0.38. The Dan/Roanoke sites comparisons of average minimum bank slope and August/September/July turbidity measurements had R^2 values of 0.21, 0.01, and 0.05 and p values of 0.04, 0.61, and 0.36. Comparisons of average bank height August/September/July turbidity measurements had R^2 values of 0.04, 0.09, and 0.07 and p values of 0.38, 0.12, and

0.27. The Dan/Roanoke sites comparisons of average minimum bank height and August/September/July turbidity measurements had R^2 values of 0.09, 0.08, and 0.11 and p values of 0.20, 0.15, and 0.16. Embeddedness had highly variable correlations between the different turbidity datasets; however, it had a strong positive correlation with the September turbidity with an R^2 of 0.32 and a p value of 0.004. The confinement ratio had strong positive correlations with the August/July turbidity measurements with R^2 values of 0.16 and 0.23 and p values of 0.07 and 0.04.

Discussion

In this study, turbidity measurements were used as a surrogate of sediment yield (Pavanelli, et al., 2005; Rasmussen et al., 2002). It was assumed that, in general, if a site experienced higher sediment yields that would be reflected in the turbidity measurements. This relationship is not direct and turbidity is not being treated as such, it was simply being used to rank the sites based on relative sediment delivery. The goal being, that while it would never be a one-to-one comparison, turbidity should be correlated with USLE values if hillslope erosion is the major contributor to watershed sediment delivery.

Multiple levels of parameters were explored in an effort to find the most effective and accurate tool for predicting in-stream sediment levels. The USLE values were used to capture the hillslope erosion that might occur within the watershed. Then the USLE values discounted with the connectivity indices and topographic indices attempted to capture the hillslope erosion and the potential for deposition and storage within the watershed. Finally, the bank and channel parameters were used in an effort to capture sediment being produced near/in channels, which was not being captured with the watershed level parameters.

As mentioned in the previous section, turbidity data were not correlated with the USLE values for any of the datasets being studied. This was not what was expected; generally, it is assumed that USLE is not a good predictor of exact sediment yields but that it is still somewhat accurate. However, based on the data in this study, it appears that USLE is not accurate, even for ranking different watersheds on level of expected erosion. USLE assumes that steeper hillslopes are where the majority of sediment is produced.

For these watersheds, it was also found that lower, flatter, slopes were more correlated with higher turbidity levels. USLE assumes that more runoff is produced on higher, steeper, slope areas, and therefore there would be more sediment from the higher sloped areas. However, we are seeing that the opposite is actually the case for these watersheds, therefore based on the underlying assumptions within USLE, it is not appropriate for use in these watersheds.

There appeared to be two possible explanations for the lack of correlation between the USLE values and the turbidity readings. Either the runoff mechanisms in these watersheds were actually the opposite of what is assumed to be true in the USLE; or hillslope areas are not contributing sediment but rather sediment production occurs in banks and near-channel areas.

In an attempt to determine which of these explanations was true in these watersheds the TI and STI were calculated. These topographic indices assume that as slope decreases, runoff production will increase; which is the opposite of the runoff assumption in USLE. The idea is that if the runoff mechanism in these watersheds is the opposite of USLE, then the TI and STI would be better predictors of in stream sediment levels; however, there was not a strong correlation between the TI/STI and the turbidity.

In-channel parameters, for the Dan/Roanoke sites, had varying correlations with in-stream turbidity. In general, the average bank heights and slopes had positive correlations with all the turbidity datasets. This shows that in-channel properties are connected with in-stream sediment levels. This supports the idea that USLE, TI/STI, along with other watershed models, are not adequately capturing the different runoff mechanisms in these watersheds and therefore are not accurately predicting in-stream sediment. However, it appears that hillslopes are not producing the bulk of sediment and while runoff is being produced on the higher-sloped areas in these watersheds it may not be producing as much sediment as the runoff from lower-sloped areas. The average confinement ratio also shows a strong positive relationship with both the July and August turbidity datasets. As confinement ratio increases this indicates that the 2-year flow is more likely to be contained in the channel, which causes higher shear stress levels in the channel. The positive correlation between the confinement ratio and turbidity indicate that high flows are often contained within the channel, which is connected to higher in-stream sediment levels.

Slope was also found to have a significant positive correlation with forest cover. This means that higher slope areas typically have forest cover and forested areas typically produce less sediment as well, which was reflected in a negative correlation between forest cover and turbidity. Percent hay/pasture was found to have a positive correlation with turbidity data and a negative correlation with slope. This shows us that hay/pasture typically occur on lower slope areas and therefore may play a role in the higher levels of sediment sourcing from low slope areas.

The major hypothesis for where sediment is coming from is low slopes with runoff generation and near-channel. The comparisons were not always consistent across turbidity datasets; however, these values indicate that slope, forest cover, hay/pasture cover, average bank slope, and average minimum bank slope have strong relationships with the in-stream sediment levels, even if not all the relationships are significant. These numbers also indicate the lack of predicting power of USLE in relation to in-stream sediment levels.

Therefore, of the potential sediment sources the near-channel and low-sloped areas had the strongest correlations with turbidity measurements. While these comparisons may not all be significant they had the strongest relationship with the turbidity data, therefore in-stream sediment is most likely coming from near-channel sources because these low slope areas correspond with areas found closer to stream channels.

Typically, USLE would be expected to be correlated with sediment erosion and, by extension, in-stream turbidity. There is not a direct one-to-one relationship between turbidity and USLE; but, it was expected that the USLE would be able to rank the sites' turbidity levels. However, USLE was not able to rank the turbidity for the Dan/Roanoke sites or the USGS sites.

In the future, it will be important to explore the site specific and hydraulic parameters in more depth, this study simply touched on these topics but there are more models that could be explored. Sediment fingerprinting is another source of data that may corroborate the idea that sediment is coming from in-channel/banks rather than the hillslopes. It will be important to understand the erosion mechanisms at work in these watersheds to ensure that there is a more appropriate tool in the future, because USLE is no longer an appropriate tool for predicting sediment yield in these watersheds (Boomer et al., 2008). It has been found that near-channel erosion is a major source of in-stream sediment levels through monitoring bed and suspended loads, bank-erosion pins, and sediment fingerprinting (Belmont et al., 2011; Massoudieh et al., 2013; Kronvang et al., 2013; Neal and Anders, 2015).

Conclusion

The goal of this research was to compare different sediment transport metrics and parameters and assess those metrics/parameters' accuracy in predicting synoptic turbidity for watersheds in Virginia and north central North Carolina. The sediment transport parameters used could be divided into two major scales: watershed and site parameters. In general, the parameter accuracy was highly variable across these scales.

Many of the watershed level factors used in this study, USLE and the sediment connectivity indices, assume that sediment production is predominantly driven by hillslope factors. However, for the watersheds in this study the opposite was found to be true. Higher slopes correlated with lower turbidity values. Therefore, USLE and the connectivity indices were not able to capture the sediment transport mechanisms for these watersheds. This is important to note specifically for USLE, this equation has been used to guide decisions about hydrology for policy. This study found that USLE was not able to rank turbidity in streams, this is problematic because USLE and other watershed models based on the same principles are being used to manage sediment in the Chesapeake watershed, among others (USEPA, 2010). However, based on the findings in these watersheds it appears that due to the underlying assumptions within USLE, it is not appropriate to use this equation in watersheds where hillslopes factors are not driving the amount and delivery of sediment to streams.

Some in-channel/bank factors were explored in this study in an attempt to explain where sediment is being sourced in these watersheds. There were positive relationships with bank heights/slopes with turbidity data; which supports the idea that in-channel and bank characteristics may be a stronger driver of sediment production. Other site specific and hydraulic parameters were studied however; they did not show strong correlations with the turbidity datasets. In subsequent studies it may be advantageous to investigate in-channel and bank parameters to determine the major source of in-stream sediments in watersheds of the mid-Atlantic region.

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Appendix A

Table 4. Displays the site number, name, latitude, and longitude, for the Dan and Roanoke sites.

Dan/Roanoke			
Site No.	**Site Name**	**Latitude**	**Longitude**
2	Big Creek	36.47	-80.33
3	Big Creek	36.47	-80.37
9	Dan River	36.53	-80.37
10	Big Beaver Island Creek	36.38	-79.98
12	Big Beaver Island Creek	36.44	-80.00
23	Beaver Creek	36.69	-79.91
25	Jordan Creek	36.70	-79.93
27	Smith River	36.73	-79.95
29	Big Chestnut Creek	36.93	-79.75
30	Big Chestnut Creek	36.91	-79.80
39	Little Doe Run	36.95	-79.80
46	Pinch Gut Creek	36.47	-80.37
50	Peters Creek	36.49	-80.27
60	Snow Creek	36.88	-79.69
201	Reed Creek	36.73	-79.93
202	Blackberry Creek	36.74	-80.00
203	Town Creek	36.82	-79.99
204	Peters Creek	36.52	-80.29
205	Dan River	36.62	-80.44
206	Big Creek	36.50	-80.42
301	Smith River	36.77	-80.00
302	S. Mayo River	36.60	-80.17
302b	S. Mayo River	36.62	-80.23
305	Horse Pasture Creek	36.59	-79.99
306	Pigg River	36.98	-79.89
401	Leatherwood Creek	36.66	-79.81
403	Turkeycock	36.88	-79.63
501	Paw Paw Creek	36.50	-79.96
502	Snow Creek	36.41	-80.14
503	North Mayo Creek	36.62	-80.04
504	Town Creek	36.79	-80.00
505	Poorhouse Creek	36.64	-80.28
506	South Mayo Creek	36.65	-80.31

Table 5. Displays the site number, name, latitude, and longitude, for the USGS sites.

USGS			
Site No.	**Site Name**	**Latitude**	**Longitude**
1622459	Middle River At Route 721 Near Churchville, VA	38.20	-79.15
1622464	Middle River Above Route 250 Near Churchville,VA	38.21	-79.13
1632900	Smith Creek Near New Market, VA	38.69	-78.64
1645704	Difficult Run Above Fox Lake Near Fairfax, VA	38.88	-77.33
1645762	S F Little Difficult Run Above Mouth Nr Vienna, VA	38.91	-77.34
1646000	Difficult Run Near Great Falls, VA	38.98	-77.25
1646305	Dead Run At Whann Avenue Near Mclean, VA	38.96	-77.18
1656903	Flatlick Branch Above Frog Branch At Chantilly, VA	38.88	-77.43
1668000	Rappahannock River Near Fredericksburg, VA	38.31	-77.53
1673000	Pamunkey River Near Hanover, VA	37.77	-77.33
2015729	Cowpasture River At Route 627 Nr Williamsville, VA	38.16	-79.60
2015742	Cowpasture River At Route 678 Nr Green Valley, VA	38.12	-79.61
2020246	Ramseys Draft At Route 716 Near West Augusta, VA	38.28	-79.34
2020258	Ramseys Draft At Route 629 Near West Augusta, VA	38.24	-79.33
2035000	James River At Cartersville, VA	37.67	-78.09
2054750	Roanoke River At Route 117 At Roanoke, VA	37.27	-80.01
2055080	Roanoke River At Thirteenth St Br At Roanoke, VA	37.26	-79.92
3171597	Little Stony Creek Ab Archer Trail Nr Pembroke, VA	37.34	-80.62
3524740	Clinch River At Route 65 At Dungannon, VA	36.83	-82.46
162246747	Buckhorn Creek Abv Tributary Nr Lone Fountain, VA	38.29	-79.24
162246784	Buckhorn Creek Above Rt 250 Nr Lone Fountain, VA	38.29	-79.24
162588440	South Fork Back Creek Below Rt 814 Nr Sherando, VA	37.93	-78.99
201144558	Warwick Run Above Lick Draft Near Mill Gap, VA	38.30	-79.78
201144806	Warwick Run Below Lick Draft Near Mill Gap, VA	38.30	-79.77
202848919	Spruce Creek Above Route 151 Near Nellysford, VA	37.89	-78.92
202848938	Spruce Creek At Route 627 Near Nellysford, VA	37.88	-78.90
205373075	Bottom Creek Along Route 612 Nr Bent Mountain, VA	37.19	-80.14
205373228	Bottom Creek Above Confluence Nr Bent Mountain, VA	37.17	-80.14
205373422	Bottom Creek Bl Poor Mtn Rd Near Bent Mountain, VA	37.16	-80.14
205450393	Roanoke River Along Route 626 At Lafayette, VA	37.23	-80.20
205450495	Roanoke River Above Route 11 At Lafayette, VA	37.23	-80.20
205551460	Lick Run Above Patton Avenue At Roanoke, VA	37.28	-79.94
205696042	Blackwater River Above Maple Branch Nr Redwood, VA	37.05	-79.83
205696095	Blackwater River Below Maple Branch Nr Redwood, VA	37.06	-79.83
317154954	Sinking Creek Along Route 604 Near Newport, VA	37.31	-80.51

Table 6. Displays the summarized 2018 sediment susceptibility assessment for the Dan/Roanoke sites, where the overall sediment susceptibility is a score out of 45.

Site No.	Instream deposition potential	Bank erodibility	Floodplain sediment trapping	Overall sediment susceptibility
2	6.0	11.0	11.5	28.5
3	7.7	13.0	11.0	31.7
9	7.0	11.0	10.0	28.0
10	11.0	15.0	10.0	36.0
12	10.0	11.0	9.0	30.0
23	11.0	10.5	9.0	30.5
25	11.0	12.0	10.0	33.0
27	10.0	16.0	11.0	37.0
29	8.0	13.0	9.0	30.0
30	7.0	14.0	7.0	28.0
39	8.0	12.0	10.0	30.0
46	8.0	12.0	7.0	27.0
50	8.0	12.3	9.7	30.0
60	9.0	15.0	11.0	35.0
201	6.0	16.0	11.0	33.0
202	13.0	14.0	10.0	37.0
203	8.0	7.0	11.0	26.0
204	9.0	10.0	7.0	26.0
205	6.0	9.0	12.0	27.0
206	10.0	13.0	11.0	34.0
301	7.0	10.0	8.0	25.0
302	8.0	14.0	14.0	36.0
302b	7.0	10.0	10.0	27.0
305	11.0	13.0	12.5	36.5
306	7.0	15.0	10.0	32.0
401	13.0	14.0	12.0	39.0
403	10.0	13.0	11.0	34.0

Table 7. Displays the summarized 2019 sediment susceptibility assessment for the Dan/Roanoke sites, where the overall sediment susceptibility is a score out of 45.

Site No.	Instream deposition potential	Bank erodibility	Floodplain sediment trapping	Overall sediment susceptibility
2	8.0	9.5	10.5	28.0
3	6.5	11.5	8.5	26.5
9	8.0	11.0	13.0	32.0
10	11.0	14.0	11.0	36.0
12	10.0	14.0	12.0	36.0
23	9.0	11.0	11.0	31.0
25	10.0	11.0	12.0	33.0
27	9.0	7.0	11.0	27.0
29	10.0	10.5	4.0	24.5
30	6.0	15.0	10.0	31.0
39	8.0	11.0	10.0	29.0
46	8.0	9.5	10.0	27.5
50	10.0	9.5	9.0	28.5
60	8.0	13.0	11.0	32.0
201	8.0	10.0	9.0	27.0
202	10.0	12.0	11.0	33.0
203	9.5	9.0	10.0	28.5
204	10.0	11.5	10.0	31.5
205	7.0	9.5	8.0	24.5
206	8.0	9.0	9.0	26.0
301	8.0	8.5	11.0	27.5
302	9.0	12.5	6.5	28.0
302b	5.5	9.5	7.0	22.0
305	11.0	12.0	9.0	32.0
306	9.0	14.0	6.0	29.0
401	10.0	11.5	11.0	32.5
403	9.0	9.0	11.7	29.7
501	10.0	12.0	10.0	32.0
502	9.0	14.0	10.0	33.0
503	10.0	13.0	8.0	31.0
504	9.0	11.0	10.0	30.0
505	8.0	8.5	9.0	25.5
506	9.0	6.7	9.0	24.7

Table 8. Slope classes used for the Dan/Roanoke subbasins.

Dan/Roanoke	
Slope Class	**Slope Range (degrees)**
1	0-16
2	17-33
3	33-50
4	51-67
5	68-84

Table 9. Slope classes used for the USGS subbasins.

USGS	
Slope Class	**Slope Range (degrees)**
1	0-14
2	15-28
3	29-43
4	44-57
5	57-72