Spatial and Isotopic Analysis of Soil Erosion and Sediment Fluxes in Three Rappahannock River Tributaries, Stafford County Virginia

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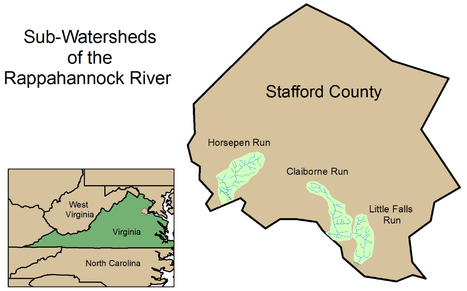
Introduction

The increasing human alterations of aquatic basins resulting in increases in soil erosion and sediment fluxes in surface water bodies due to less vegetative cover is a growing global concern. Individual pollutants bind easily to soil particles and with erosion these pollutants can be transported downstream where they eventually get concentrated into larger bodies of water such as the Chesapeake Bay. This increase in pollutants can lead to hypoxic conditions, increased water turbidity and ultimately could lead to alterations of aquatic food webs. Therefore soil erosion, sediment transport and dispersal data in the main tributaries of the Bay are needed for the development of long term land and water resources management practices for the entire basin. This study focuses on the soil erosion and sediment fluxes in the Rappahannock basin at sub-watershed scales. Spatial modeling and isotopic analysis was used to evaluate both naturally occurring and anthropogenic forces in three sub-basins of the Rappahannock River, the Claiborne Run, Little Falls Run and Horsepen Run (Figure 1).

The Rappahannock River basin was chosen for this study as it is the highest per unit area contributor to sediment in the Chesapeake Bay (Langland and Cronin 2003). The basins of three 3rd order tributaries of the Rappahannock were chosen due to their varying degrees of human impacts based on land use and cover. Claiborne Run watershed is significantly human developed with small strips of forests in between human habitat. Little Falls Run basin has approximately equal amount of both forest and human development. Whereas, Horsepen Run basin was chosen as a control because of its nearly pristine (> 80% forest) watershed.



Methods

Watershed Spatial Erosion Analysis

The model of soil erosion that was used in this study was the Revised Universal Soil Loss Equation (RULSE). The equation is expressed as (Jones et al 1996; Renard et al 1997):

$$A=R*K*LS*C*P$$

Where A is total annual soil loss from sheet, rill and interrill erosion, R is the rainfall-runoff erosivity factor, K is the soil erodibility factor, C is the land cover management factor, P is the support practice factor, and LS is the slope length and gradient factor which is calculated from the equations:

$$L = (\lambda / 22.1)^{m}$$

Where λ is the projected horizontal distance between onset of runoff and point of deposition and m is a variable slope-length exponent.

$S = 10.0 \sin\Theta + 0.03$ for slopes <9° $\quad\quad$ $S = 16.8 \sin\Theta - 0.50$ for slopes ≥9°

^{210}Pb Isotopic Analysis

^{210}Pb is a naturally occurring radioactive isotope which has a half-life of 22.2 years and is a product of the decay of ^{238}U. However, the decay chain is not a closed system. Most of the decay steps do occur within the soil, but some radon escapes as a gas into the atmosphere. This radon then goes on to decay into ^{210}Pb in two ways; within the soil or "supported" ^{210}Pb and atmospherically which eventually settles as ^{210}Pb uniformly on the surface or "unsupported" (Figure 3). For ^{210}Pb analysis surface and core samples were then sent to a CORE research lab in Winnipeg, Canada for ^{210}Pb analyses based on the method of Eakins and Morrison (1978) where ^{210}Po is distilled out of sediments at high temperature, acid digested, and then placed onto silver disks for analysis by alpha spectrometry.

Sediment Source Analysis (^{210}Pb Isotopic Sediment Fingerprinting)

A total of 56 surface soil samples were collected from each land use land cover (LULC) as well as from stream banks and the lower flood plain of the Rappahannock and compared to eleven collected suspended sediment samples which were collected from the streams during peak flow. (Table 2).

Sediment Erosional/Depositional Rate Analysis

In order to determine the rate of erosion, total ^{210}Pb concentration in the soil cores was compared to a reference site. This difference in total core inventory can determine whether a site is erosional or depositional. Based on whether a site is erosional or depositional, one of two equations is used.

Erosional:

$$R = [(I - \lambda A) / (AH + yID)] * (DH / P\Delta t)$$

Where R is the erosion rate (kg/m^2 per year), I is the unsupported ^{210}Pb deposition flux, is the decay constant, A is the total ^{210}Pb inventory, H is a constant representing depth of penetration of fallout (4.0 kg/m^2), y is the proportion of the annual ^{210}Pb fallout that is susceptible to erosion prior to incorporation into the soil profile (0.3 unitless), D is the cumulative mass depth representing the average plow depth, P is the ratio of ^{210}Pb concentration of the mobilized sediment to that of the original soil (1.0 unitless), and t is the number of years the equation represents (1.0 yr^{-1})(Walling & He, 1999).

Depositional:

$$Rf = A_{ex}/(C_{ss} * T)$$

Where Rf is equal to the soil deposition rate (g/cm^2 per year), A_{ex} represents the excess unsupported ^{210}Pb concentration, C_{ss} is equal to the unsupported ^{210}Pb concentration, C_{ss} is equal to the unsupported ^{210}Pb concentration that is being deposited (Bq/kg), and T represents the number of years that a site has been depositional (Blake et. al., 2002).

RULSE

Table 3 shows the soil loss for the three watersheds in 2011 as well as 2006 for Horsepen and Little Falls Run. The results are as expected with Claiborne Run having the most soil loss in 2011 due to the amount of human development present. Likewise, Horsepen Run has the least soil loss due to dominance of forest in the watershed. Recently abandoned pasture lands in Horsepen Run are slowly being reclaimed as forested environments; this is the likely cause for less soil loss in 2011 than in 2006. Due to an increase in human development, Little Falls Run is experiencing an increase in soil loss from 2006 to 2011.

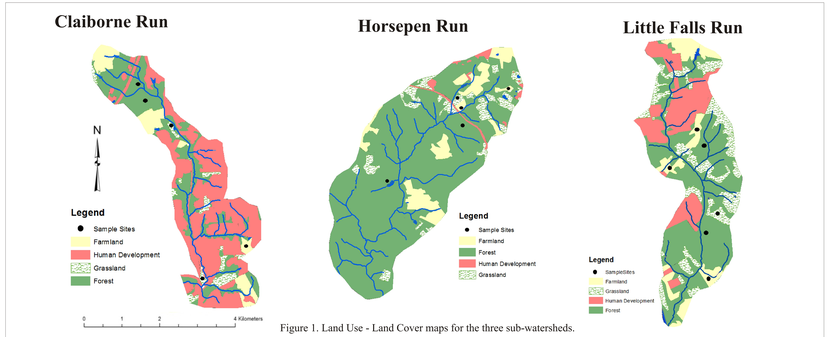


Figure 1. Land Use - Land Cover maps for the three sub-watersheds.

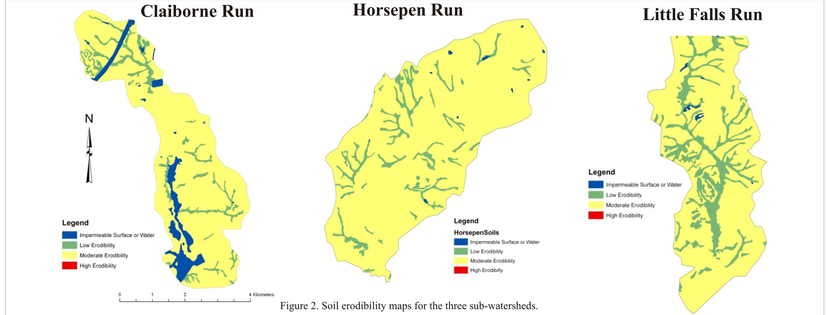


Figure 2. Soil erodibility maps for the three sub-watersheds.

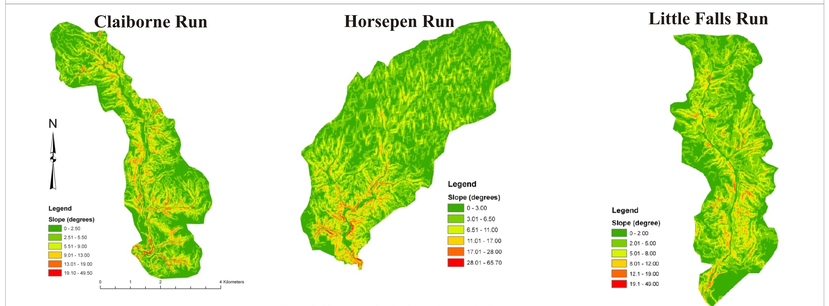


Figure 3. Slope maps for the three sub-watersheds.

Table 1: Revised Universal Soils Loss Equation Results

Watersheds	2006 Soil Loss (Mg/yr)	2006 Soil Loss (Mg/acre/yr)	2011 Soil Loss (Mg/yr)	2011 Soil Loss (Mg/acre/yr)	2011 Pristine (Mg/acre/yr)
Claiborne Run	N/A	N/A	332	0.21	0.04
Little Falls Run	298	0.25	130	0.18	0.04
Horsepen Run	234	0.12	212	0.11	0.02

^{210}Pb Fingerprinting Results

Table 1 shows that in the Claiborne Run watershed the dominant source of suspended sediments was stream banks. This is most likely due to the increase of human development as more impermeable infrastructure allows storm water to travel more rapidly to the stream, thus increasing peak flow and velocity which in turn increases the steam's erosive power on steam banks. For Horsepen Run the average concentrations of all the LULC types are similar to the suspended sediment concentration. It is known that forested and grassland environments contribute to stability and therefore are unlikely sediment sources. Due to Horspen's pristine nature it is also unlikely stream banks is a dominant source. In Little Falls Run, similarly to Claiborne Run, has average concentrations for suspended sediments less than that of all the other LULCs pointing towards stream banks being the main contributor as well.

Table 2: Watershed LULC & ^{210}Pb Concentrations

Claiborne Run Landuses	Average ^{210}Pb Concentration (dpm/g)	Number of Samples	Horsepen Run Landuses	Average ^{210}Pb Concentration (dpm/g)	Number of Samples	Little Falls Run Landuses	Average ^{210}Pb Concentration (dpm/g)	Number of Samples
Forest	12.00	8	Forest	10.38	7	Forest	9.21	5
Grassland	11.70	10	Grassland	10.89	8	Grassland	9.35	3
Farmland	11.04	5	Farmland	10.86	5	Farmland	9.46	4
Steam Bank	10.12	4	Steam Bank	11.48	4	Steam Bank	N/A	3
Suspended Sediment	10.26	4	Suspended Sediment	10.63	6	Suspended Sediment	8.85	1

^{210}Pb Erosional Rates

Erosion and depositional rates were calculated from the Pb^{210} concentrations from each sampling location. Erosional rates for grassland areas range from 0.02 to 2.5 tons/hectare year and depositional rates for farmland areas range from 0.32 to 0.36 tons/hectare year (see Table 2). Due to the prevalence of vegetative cover in Horsepen Run the erosion rate is much lower than the other watersheds.

Table 3: Erosion and Deposition Rates Results

Watersheds	Erosion Rate of Grassland LULC (tons/hectare/year)	Deposition Rate of Farmland LULC (tons/hectare/year)
Claiborne Run	1.6	0.32
Horsepen Run	0.02	0.33
Little Falls Run	2.5	0.36

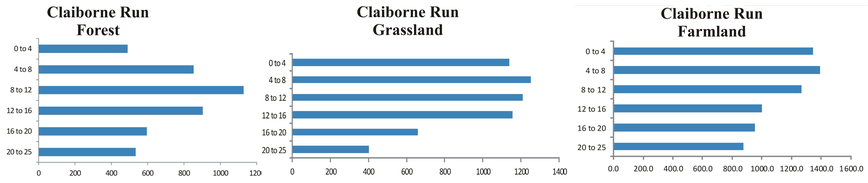


Figure 4. Example ^{210}Pb profiles of each sampled Land Use.

Conclusions

Based upon spatial modeling using the Revised Universal Soils Loss Equation, annual sediment fluxes for each sub watershed were calculated. Through the model Claiborne Run, as predicted, has the highest annual soil loss most likely due to the amount of human development nearby. Horsepen Run has the lowest soil loss due to its near pristine condition. Little Falls Run is rapidly increasing in soils loss which is most likely due to increased urbanization in the area.

Based on our isotopic fingerprinting results, the major sources of sediment flux into Claiborne, Horsepen and Little Falls Run watersheds were able to be identified and are comparable to the RUSLE equation. Stream banks are the likely source of sediment influx for both Claiborne and Little Falls Run due to similarities especially in the amount of human development.. Horsepen Run has a lack of runoff due to the dominance of its pristine environment; however due to the slope characteristics Horspen Run can see large negative impacts through soil loss. More effective mitigation to minimize soil loss into river systems can be implemented such as planting trees in open spaces, placing rip rap along stream banks and closing ATV trails.

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