IDENTIFYING SOURCES OF FINE-GRAINED SUSPENDED-SEDIMENT FOR THE POCOMOKE RIVER, AN EASTERN SHORE TRIBUTARY TO THE CHESAPEAKE BAY

Allen C. Gellis, U.S. Geological Survey, Baltimore, MD, 21237, agellis@usgs.gov; Jurate M. Landwehr, U.S. Geological Survey, Reston, VA 20192, jmlandwe@usgs.gov

Abstract: Sources of fine-grained suspended sediment in the Pocomoke River watershed draining above Willards, Maryland, were identified using a 'sediment-fingerprinting' approach. Potential sediment sources in the watershed were cropland, forest, channel and ditch banks, and ditch beds. Samples of fine-grained suspended sediment were obtained for seven storms between July 2001 and November 2002 and showed that the channel corridor (channel and ditch banks, and ditch beds) were significant sources averaging 76.5 % of the total sediment sources for the seven storms. Results indicate that sediment sources vary between events, and may be affected by seasonality and runoff conditions. Cropland was an important source of sediment for the two storms with the highest peak flow which occurred in the late summer and fall when harvesting began and vegetative cover was low. Ditch beds, which contributed an average of 46.1 % of sediment for the seven storms, were important sources of sediment over a range of peak flows (0.2 m^3/s to 15.7 m^3/s) and may also be important when crop areas have mature leaf cover.

INTRODUCTION

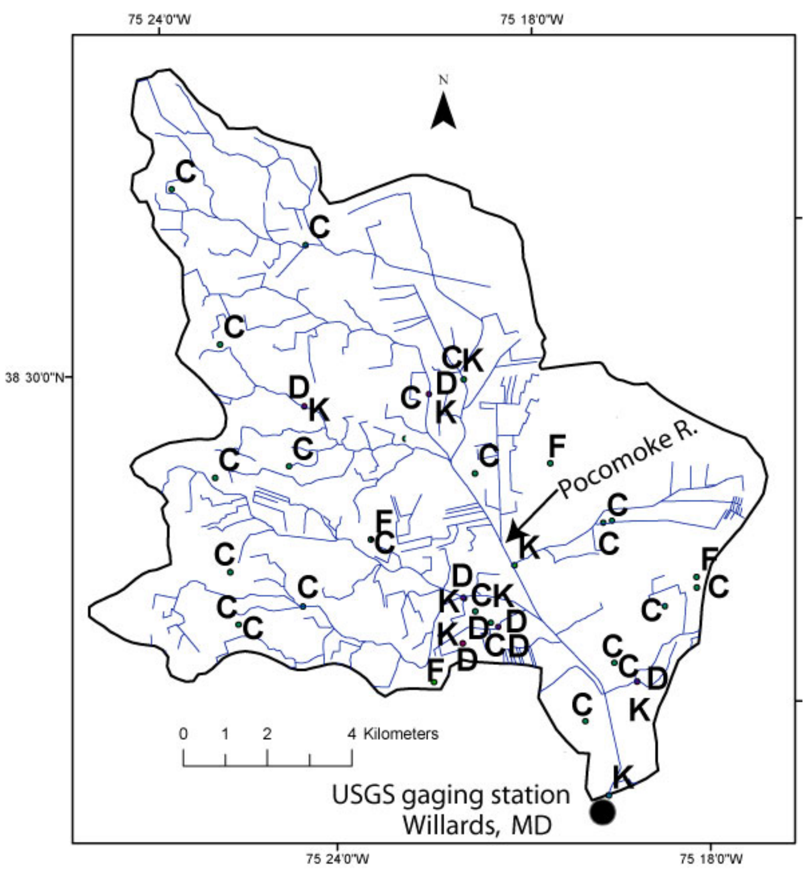
Fine-grained sediment is having an adverse effect on the habitat of the Chesapeake Bay and its watershed. To reduce sediment loadings to the Bay, it is helpful to identify the significant sources of the sediment. In 2002, the 157-km^2 watershed of the Pocomoke River above Willards, Maryland (MD), which drains part of the Eastern Shore of the Chesapeake Bay, was chosen as a watershed in which to identify sediment sources. The Pocomoke River was a focus area for previous and ongoing U.S. Geological Survey (USGS) studies (Phillips, 2001) on nutrients (Ator et al., 2004) and stream biologic health (Blazer et al., 1999). Because of the importance of fine-grained sediment in the transport of phosphorus (Walling, 2005) and its impact on water clarity (Landwehr, 2005), the identification of its sediment sources in the Pocomoke River is important to assist resource managers in development of strategies for its reduction.

BACKGROUND

The sediment-fingerprinting approach provides a direct method for quantifying watershed sources of fine-grained suspended sediment (Collins et al., 1997; Motha et al., 2003; Walling, 2005). This approach entails the identification of specific sources through the establishment of a minimal set of physical and/or chemical properties, i.e. tracers that uniquely define each source in the watershed. Suspended sediment collected under different flow conditions exhibits a composite, or fingerprint, of these properties that allows them to be traced back to their respective sources. Tracers that have successfully been used in the sediment-fingerprinting approach include mineralogy, radionuclides, trace elements, magnetic properties, and stable isotope ratios ($^{15}N/^{14}N$ and $^{13}C/^{12}C$) (Walling and Woodward, 1992; Collins et al., 1997; Motha et al., 2003; Papanicolaou et al., 2003). Sources of watershed sediment include upland sources (i.e. agriculture, urban construction, and forest) and the channel corridor (beds, banks, ditches, and floodplains). Sampling sediment at these sources and linking the fingerprints to sediment in transport using a statistical mixing model enables quantification of the source(s).

STUDY AREA

The Pocomoke River drains entirely within the Coastal Plain Physiographic Province (Miller, 1967). Surficial geology in the watershed consists primarily of unconsolidated sand and some clay-silt of the Parsonburg Sand and Omar Formations (Denny et al., 1979). Land use in the Pocomoke River watershed in 1992 was 52 % agriculture (35 % in cultivated crops), 38 % forests, and 10 % wetland, and less than one percent urban (U.S. Geological Survey, 2003). Land-use categories considered to be relevant sediment sources for this study included cropland and forest. Cultivated crops in the Pocomoke River watershed are primarily corn and soy. Depending on soil moisture conditions, planting for corn and soy can occur from April to May and crop harvesting from August to September. The Pocomoke River has been channelized in selected portions as early as the 1600's and continuing into the 20th century (Ross et al., 2004). Ditching on agricultural lands in the Pocomoke River watershed is an extensive practice that has been used to drain wetlands (Fig. 1).



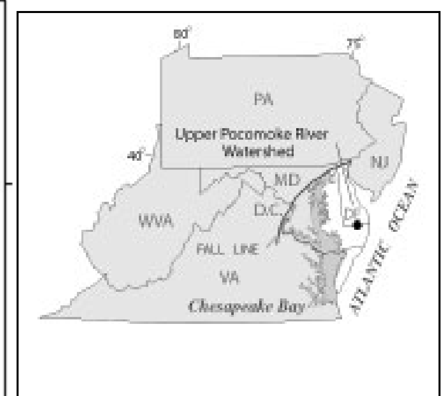


Figure 1 Sampling sites for sediment source areas in the Pocomoke River watershed above Willards, MD. Linear features in the figure are ditches.

C=cropland, K=Bank, D=Ditch bed, F=Forest.

Suspended-sediment samples were collected in the Pocomoke River near Willards, MD (USGS Station ID 01485000) from October 23, 2000, through April 29, 2002, for discharges ranging from 0.39 to 10.8 m^3/s. Samples were also collected in a tributary to the Pocomoke River, Nassawango Creek near Snowhill, MD (USGS Station ID 01485500), from October 28, 1998, through April 18, 2000, for discharges ranging from 0.04 to 36.8 m^3/s (U.S. Geological Survey, 2005). These samples all had low suspended-sediment concentrations, which never exceeded 60 mg/L. These low suspended-sediment concentrations may be a function of the gradual slope of the Coastal Plain Province, as well as low streampower.

METHODS

Suspended sediment in the Pocomoke River at Willards, MD, was pumped into 83-L plastic containers using a submersible pump placed at mid-depth in the center of the channel. The sample was brought back to the laboratory and centrifuged with a continuous-flow centrifuge. The sediment obtained from the centrifuge was wet-sieved through a 63-micron sieve to remove sand and dried at 60C, with appropriate care taken to avoid cross-contamination.

Soil samples from cropland and forest areas were taken from the top 0.5 cm of the soil surface. Channel and ditch bank samples were sampled from the top to the bottom of the bank face. If banks were exposed on both sides of the channel, samples were taken on both banks and composited into one sample. Ditch-bed samples were taken from the top 0.5 cm of the ditch bed. The channel bed of the Pocomoke River was not considered to be a source in this study because this sediment may only represent temporary storage from upstream sources and is not a true source by itself. Because the ditch beds are deep and straight, dredged periodically, and extend over much of the watershed, they were considered a potential sediment source.

Upland and channel corridor samples were taken back to the laboratory, dried at 60^0C, disaggregated using a pestle and mortar, and dry-sieved through a 63-micron sieve to remove the sands. The silt and clay portion of suspended sediment, upland, and channel corridor samples was sent for analysis of radionuclides (^{137}Cs and unsupported ^{210}Pb), stable isotopes (δ^{13}C and δ^{15}N), and total carbon, nitrogen, and phosphorus. Unsupported ^{210}Pb refers the atmospheric deposition of ^{210}Pb and is reported in terms of disintegrations per minute per gram of sample (DPM/g).

The mass fraction of the sample that was composed by weight of total carbon, total nitrogen, and total phosphorus (w(C), w(N), w(P)) was analyzed at the University of Maryland's Chesapeake Biological Laboratory (Solomons, Maryland). Methods of analysis are accessible on the web at: *http://www.cbl.umces.edu/nasl/index.htm*. Stable isotopes (δ^{13}C and δ^{15}N) were analyzed at the USGS Stable Isotope Laboratory in Reston, Virginia and methods for analysis are described in the laboratory's web site at: *http://www.isotopes.usgs.gov*. Carbon-stable isotope ratios are reported relative to VPDB (Vienna Pee Dee Belemnite). Nitrogen isotopes are reported relative to nitrogen in air.

Radionculides were analyzed at three different laboratories: Case Western Reserve University in Cleveland, Ohio: the U.S Geological Survey Geologic Division Laboratory in Denver, Colorado: and the U.S Geological Survey Geologic Division Laboratory in St. Petersburg, Florida. At all three laboratories, radionuclides were analyzed by gamma spectroscopy using a Canberra HPGe photon detector.[**] At Case Western Reserve University and the USGS lab in Denver, an EG&G Ortec[**] was also used. The technique used for counting efficiencies can be found in Wilson et al., (2003).

Statistical Methods: Several steps were taken to finalize which tracers were most appropriate to determine the relative contributions from each source for each sampled flow event. A requirement of sediment fingerprinting is that the fluvial tracers must be conservative and not change during transport from the source to the sampling point. Consequently, values for the fluvial tracers must be within the range of the tracer values measured for all sources. Any tracers that did not satisfy this constraint within measurement error were considered to be nonconservative and removed from further consideration. In addition, a Kruskal-Wallis H-test (Swan and Sandilands, 1995) was used to determine if there were significant differences ($p \leq 0.05$) between the medians of the measured tracer values in the source areas. Any tracers that did not satisfy this constraint were considered nondiscriminatory and removed from further consideration. Finally, each tracer should distinguish a specific source, but not necessarily separate all other sources. Conversely, each source should be statistically distinguishable from all others on the basis of at least one tracer. A students t-test (unpaired data with unequal variance) as well as a nonparametric Wilcoxon-Mann-Whitney test (Swan and Sandilands, 1995; Conover, 1999) were performed for each tracer between each pair of source areas (significance test at $p \leq 0.05$) to confirm that each source area was distinguished from all other source areas by at least one tracer and to identify redundant tracers for elimination.

The literature suggests many different mathematical forms by which the fingerprint may be decomposed into the relative contributions by source. In this study, the fluvial sample is considered to be composed of a mixture of sediment from the different source areas. To determine the relative source contributions to the fluvial samples, we defined an "unmixing" variable E (equation 1) in terms of normalized scores (Snedecor and Cochran, 1980). “E” is defined as the average absolute difference between each tracer value measured in the fluvial sample and as would occur in the proposed mixture, scaled by the relevant standard deviation of the mixture. The best model is considered to be that for which the set of the relative contributions from each source will provide the closest match to the fluvial tracer value, that is, provide a minimal value for E. The best mixture model was considered to be that set of fractional values (f_s, s=1 to 4) which minimizes the expression E as given below. Note that the f_s must sum to one. The minimizing function E, expressed in standard deviation units, is defined as

$$E = (1/T) \sum_{t=1}^{T} \left| \left\{ v_t - \sum_{s=1}^{S} f_s A_{st} \right\} \right| / \mathrm{sqrt}\left\{ \sum_{s=1}^{S} f_s^2 \, VAR_{st} \right\} \quad (1)$$

where t is a specific tracer, T is the total number of tracers, v_t is the value of the tracer t in the fluvial sample, s is a specific source area, S is the total number of source areas, and A_{st} and

[**] Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

VAR_{st} are the estimated average and variance of the measured values of tracer t in source area s, respectively.

RESULTS

Seven storm suspended-sediment samples were collected from July 2001 to November 2002. The source data set consisted of a total of 43 samples from the 4 source areas (channel and ditch banks, ditch beds, croplands, and forest) with samples taken at n = 9, 8, 22, and 4 sites, respectively (Fig. 1). The amount of sand in the sources was high, averaging 70% + /- 27% for banks, 86 % +/- 20 % for ditch beds, 87% +/- 5% for croplands, and 94% +/- 2% for forest. The sand content in the source samples reflects the high abundance of sand composition in the Coastal Plain sediments.

Examination of the fluvial tracer values compared to the source samples showed that the measured values for three tracers, $m(^{137}Cs)$, $w(P)$, and $w(C)/w(N)$, were outside the range of measured values in 4, 6, and 5 cases, respectively. These tracers were deemed not conservative and were not used. One fluvial sample had a $\delta^{15}N$ value that was outside the range of the source $\delta^{15}N$ values, but it was within measurement error of a measured source site value and was retained. A Kruskal-Wallis test performed for each of the remaining five potential tracers (^{210}Pb, $w(C)$, $w(N)$, $\delta^{13}C$, and $\delta^{15}N$) confirmed that there were statistically significant differences between the medians of the measured tracer values in the four source areas.

Results were in agreement of the students t-test (unpaired data and not assuming equal variance) as well as a nonparametric Wilcoxon-Mann-Whitney test performed among all pairs of source areas for the five remaining tracers, namely ^{210}Pb, $w(C)$, $w(N)$, $\delta^{13}C$, and $\delta^{15}N$, were in agreement. The results confirmed that the tracers could distinguish between sources. $w(N)$ and $w(C)$ provided comparable distinctions between source areas, so that use of both tracers was redundant. Because $w(N)$ has a higher measurement error, particularly as grain size diminishes, this tracer was eliminated. The only tracer capable of significantly distinguishing between bed and bank was ^{210}Pb. Thus, the number of relevant tracers was T=4 (^{210}Pb, $w(C)$, $\delta^{13}C$, and $\delta^{15}N$). Results for one fluvial sample – that of August 29, 2002 – had an outlier for ^{210}Pb, however, and the analysis for this date was performed with T=3 tracers. The fluvial sample values for the final four tracers are shown in Table 1. Average tracer values for the four source areas are shown in Table 2. Variance of the tracer values is shown in Table 3. Results of the minimizing model are shown in Table 4. In using the minimizing model, the f values were incremented in steps of 0.025, computing over 69,000 possible solutions for E. Note that the E terms, expressed in standard deviation units, are all less than 2, which implies that we cannot reject the hypothesis that the fluvial sediment and the proposed mixture of sediment sources for each event are significantly different.

Averaging sediment sources for the seven events indicated that channel corridor (channel and ditch banks, and ditch beds) were major sources of sediment (76.5%), but the sources were variable over the seven sampled events (Table 4). Seasonality, rainfall intensity, and streamflow are some of the factors that may affect the contribution of a given sediment source for a given particular storm. For the two highest peak-discharge storms and the lowest peak-discharge storm, cropland was an important source of sediment (Table 4). For the range of peak flows (0.2

m^3/s to 15.7 m^3/s), the channel corridor (channel and ditch banks, and ditch beds) were important sources. Forests, as a sediment source, show up in the highest peak discharge event. Examination of source by season shows that for the late August, September, and November events, cropland was a sediment source. Corn and soy, which are grown in the Pocomoke River watershed, are harvested beginning in late summer. The depleted vegetative cover after harvesting combined with a rainfall event would make this a likely sediment source. The highest peak flow of the seven sampled events occurred in early September during this harvesting period.

CONCLUSIONS

Observed suspended-sediment concentrations in the Pocomoke River are less than 60 mg/L. Two factors make the Pocomoke River a minor contributor of fine-grained suspended sediment to the Chesapeake Bay. First, the abundance of sand in the unconsolidated Coastal Plain sediments limits the potential for transport of silt and clay. Second, the Pocomoke River watershed drains the Coastal Plain, which is relatively flat compared with other physiographic provinces in the Chesapeake Bay; this low gradient limits streampower for sediment transport. Periods of significant overland flow are rare in the upper Pocomoke River watershed, occurring only 20 % of the time when flows exceed 2.83 m^3/s (Ator et al., 2004). Analysis of storm-generated hydrographs by Ator et al., (2004) indicated that over 70 % of the flow is from ground-water discharge. Infrequent periods of overland flow in the Pocomoke River limit upland areas (cropland and forest) as significant sources of sediment, except under periods of high rainfall intensity or under saturated-soil conditions when overland flow may occur.

Samples of fine-grained suspended sediment were obtained during seven flow events between July 2001 and November 2002, to determine sediment sources using a sediment-fingerprinting technique. The seven sampled events had recurrence intervals ranging from 2 years to less than 1 year. Potential sediment sources in the Pocomoke River watershed were cropland, forests, ditch bed and banks, and channel banks. Statistical analysis indicated that the source areas could be differentiated in terms of four tracer parameters (^{210}Pb, $w(C)$, $\delta^{13}C$, and $\delta^{15}N$).

Table 1 Tracer values for sampled flow events used in the sediment source identification, in order of peak-flow rate.

Date	Collection time	Peak discharge m^3/s	^{210}Pb (DPM/g)	$10^3\delta^{13}C$	$10^3\delta^{15}N$	w(C)	Peak-flow recurrence interval †
9/2/2002	11:15	20.0	5.886	-25.48	7.60	11.40	2 yrs
11/18/2002	15:15	15.7	2.454	-26.10	9.08	8.48	1.25 yrs
11/6/2002	11:30	6.3	6.96	-27.40	11.85	11.30	<1yr
3/21/2002	9:45	2.5	0.001	-27.88	8.64	11.40	<1yr
7/19/2001	10:00	1.6	0.001	-27.29	10.99	11.72	<1yr
8/29/2002	14:00	0.3	*	-27.41	8.72	12.60	<1yr
8/30/2002	9:00	0.2	0.001	-26.65	8.37	8.17	<1yr

** Data value in error, † Recurrence intervals of peak flow were determined using the USGS peak- flow program (PEAKFQ) (Thomas et al., 1998).*

Table 2 Average tracer values for the source samples used in sediment source identification.

Tracer Source Area	^{210}Pb DPM/g	Range ^{210}Pb (DPM/g)	w(C)	Range w(C)	$10^3\ \delta^{13}$C	Range $10^3\ \delta^{13}$	$10^3\ \delta^{15}$N	Range $10^3\ \delta^{15}$N
Bank	2.629	0.743 to 5.09	7.802	4.99 ro 11.8	-27.38	-27.76 to -26.78	7.203	4.57 to 10.6
Bed	1.075	0.001 ro 2.91	6.236	1.08 to 11.0	-27.683	-29.05 ro -25.95	8.414	6.63 to 9.83
Cropland	4.385	1.25 to 15.3	7.334	2.90 to 14.2	-24.005	-26.60 to -22.4	8.823	4.85 to 11.5
Forest	6.432	13.3 to 18.8	21.825	17.1 to 24.8	-27.268	-27.79 to -26.15	-1.238	-2.06 to -0.470

Table 3 Variance of tracer values for the source samples used in sediment source identification.

Tracer Source Area	^{210}Pb DPM/g	w(C)	$10^3\delta^{13}$C	$10^3\delta^{15}$N
Bank	2.57	4.59	0.15	3.85
Bed	0.85	10.22	1.57	1.10
Cropland	10.55	5.47	1.02	3.22
Forest	15.36	10.91	0.57	0.56

Table 4 Minimizing model results showing the contribution from each source area (in percent) for each of the seven sampled runoff events.

Date	Peak discharge m^3/s	Channel and ditch banks %	Ditch bed %	Cropland %	Forest %	Minimum E
9/2/2002	20	15	0	57.5	27.5	0.577
11/18/2002	15.7	0	57.5	42.5	0	0.350
11/6/2002	6.3	100	0	0	0	1.689
3/21/2002	2.5	0	100	0	0	0.789
7/19/2001	1.6	97.5	0	2.5	0	1.391
* 8/29/2002	0.3	0	95	5	0	0.812
8/30/2002	0.2	0	70	27.5	2.5	0.639
Average		30.4	46.1	19.3	4.3	

*This sample was fit using only 3 tracers, namely *w*(C), δ^{13}C, and δ^{15}N because the *unsupported* ^{210}Pb value was in error in the fluvial sample.

Results of applying an "unmixing" equation developed for this study indicated that the channel corridor (channel and ditch banks, and ditch beds) was a major source of sediment, averaging 76.5% of the total sediment sources for the seven sampled flow events; however, the contributions from the sources were variable between sampled events. Cropland was an important source for the two highest discharge events (peak flow of 20 m^3/s and 15.7 m^3/s) and was also a sediment source in late August and September. The channel corridor (channel and ditch banks, and ditch beds) were important sediment sources over a range of peak flows (0.2 m^3/s to 15.7 m^3/s).

From this limited data set, several conclusions on sediment sources for the Pocomoke River watershed above Willards, MD can be presented. One conclusion is that higher runoff events, presumably associated with higher rainfall, increase the potential for upland erosion, and cropland is a sediment source. Forests, which is another upland sediment source, also appeared as a sediment source in the highest peak-discharge event. At intermediate and lower peak flows, which are associated with moderate to low rainfall events, the channel corridor (channel and ditch banks, and ditch beds) is an important source. During periods when cropland is devoid of vegetation, such as before planting and after harvesting (late August to May), cropland is an important sediment source. When crop cover is mature, the ditch beds are an important sediment source.

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