IDENTIFYING SEDIMENT SOURCES IN THE SEDIMENT TMDL PROCESS

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ABSTRACT

Sediment is an important pollutant contributing to aquatic-habitat degradation in many waterways of the United States. This paper discusses the application of sediment budgets in conjunction with sediment fingerprinting as tools to determine the sources of sediment in impaired waterways. These approaches complement monitoring, assessment, and modeling of sediment erosion, transport, and storage in watersheds. Combining the sediment fingerprinting and sediment budget approaches can help determine specific adaptive management plans and techniques applied to targeting hot spots or areas of high erosion.

INTRODUCTION

In 2014, both sediment and turbidity were the second leading cause, after pathogens, of impairment of U.S. waterways (EPA, 2014). Typically, the sediment size class of concern is fine-grained silts and clays, which can degrade habitat, affect water supply intakes and reservoirs, and often carry pollutants of concern (Larsen et al., 2010).

When a stream is identified as impaired by sediment, the Clean Water Act requires states to develop numeric targets that describe the maximum amount of pollutants that a water body can receive over time, known as the “total maximum daily load” (TMDL). As part of the sediment TMDL protocol, the EPA requires that the sources of the sediment be determined (EPA, 1999). Many of the approaches used by states to identify sediment sources involve the use of models (EPA, 2008) or assessment tools such as the Watershed Assessment of River Stability and Sediment Supply (WARSSS) (Rosgen, 2006) and the Generalized Watershed Loading Functions (GWLF) (Haith et al., 1992). The TMDL Technical Advisory Group (TAG) was formed, consisting of scientists from universities, Federal and State agencies, and non-governmental organizations, to provide guidance.

In a 2002 review of sediment TMDLs in Georgia (EPA Region IV) 2 by the TAG (Keyes and Radcliffe, 2002), the following recommendations were made:

- A carefully crafted inventory of the potential sediment sources and pathways by which sediment enters the water body should be developed.
- To the greatest extent possible, problem identification should be based on currently available information, including water-quality monitoring data, watershed analyses, information from the public, and any existing watershed studies.

- It is also critical to have a thorough understanding of the relative contribution from various sediment sources. It is highly recommended that thorough onsite watershed surveys be conducted.
- Follow-up monitoring is a key component of the TMDL process and should be emphasized in the Phase 1 TMDLs.

Sediment is considered a nonpoint source pollutant when it originates from diffuse sources such as construction sites, crop and forest lands, and eroding streambanks (EPA, 2012). In a review of TMDL implementation, which included sediment, the U.S. Government Accountability Office (USGAO, 2013) reported that long-established TMDLs were not helpful for attaining reductions in nonpoint source pollution. In Pennsylvania, of the nearly 1,000 parts of water bodies identified as impaired by sediment, only two have been restored (USGAO, 2013).

These reviews clearly indicate a need for effective sediment-source identification in the TMDL process. In this paper, we describe combining sediment budgets and sediment fingerprinting, and present findings from a case study to demonstrate the effectiveness of sediment-source identification. The approaches we discuss are field efforts that may accompany modeling efforts to identify sediment sources supporting the TMDL process. These methods are part of a larger protocol for identifying sediment sources that is under development by the authors for EPA Regions III and V.

SEDIMENT-SOURCE INVENTORY

Sediment sources in any given watershed vary with location and time. In general, sediment sources can be divided into two broad categories: (1) upland sediment sources, and (2) channel sediment sources. Upland sediment sources include various land-use and land-cover types: forest, cropland, pasture, construction sites, roads, etc. Channel sediment sources can include the streambanks, beds, flood plain, and gullies. It is important to apportion sediment derived from uplands versus channels because sediment reduction strategies differ by source and require different management approaches. For example, reducing sediment loads from agricultural sources might require soil conservation and tilling practices, whereas channel sources might require streambank stabilization.

Erosion on upland surfaces can occur though sheetwash, rilling, gullying, and mass movements. Periods of heavy rain that lead to saturation excess overland flow or infiltration excess overland flow can mobilize and erode upland sediment. Streambanks erode during high flows, from mass wasting, and as a result of freeze and thaw activity in cold climates. The channel bed can be a source of sediment in incising channels. However, fine-grained sediment from channel beds has not traditionally been considered a sediment source, since in the absence of significant channel incision, sediment mobilized from the channel bed is typically thought to represent temporary storage of sediment originating from upstream sources (Gellis et al., 2009).

SEDIMENT BUDGET

The sediment budget approach quantifies the erosion, deposition, and storage of upland and channel elements in a watershed. A sediment budget can be presented as an equation:

$$I + \Delta S = O \qquad (1)$$

Where I is the sediment input, ΔS is the change in sediment storage, and O is the sediment output.

The steps to generate a sediment budget for a given watershed are:

1. Choose the watershed scale of interest for the sediment budget.
2. Distinguish a time period of interest for the sediment budget.
3. Determine the geomorphic elements contributing to (I) or storing sediment (ΔS).
4. Ascertain what size sediment class is to be budgeted.
5. Determine approaches to quantify steps 1 through 4 (Table 1)
6. Define the watershed output (O) point and approaches to quantify sediment transported out of the watershed (Table 1).
7. Estimate or measure I, ΔS, and O over desired time period.
8. Extrapolate measurements of I and ΔS to the entire watershed to obtain a volume.
9. Using the density of soil or sediment representative of each geomorphic element, convert volume measurements from step 8 to a mass per unit time.
10. Sum mass per unit time values from step 9 for each geomorphic element and compare the results to the output (O).
11. Communicate results and provide error analysis.

In the first two steps of sediment budgeting, initial decisions on spatial and temporal scales of interest are made that will influence the design of the sediment budget. These scales will be determined by the management questions of interest. The watershed scale for the sediment budget can range from hillslopes (m^2) to major river basins (>100,000's km^2) (i.e. the Mississippi River). For this paper, it is assumed that small to medium watershed scales of up to hundreds of kilometers are of interest.

Time periods for which the sediment budget is developed can also vary, from single storm events to thousands of years (Reid and Trustrum, 2002). In regions that have had widespread land clearing from agriculture or clearcut logging, long-term time scales are of interest in order to compare
pre- and post-disturbance differences (Knox, 2001; Fitzpatrick and Knox, 2000). Budgets that include flood-plain sedimentation are useful for time scales of decades to centuries (Knox, 2001; Trimble, 1999; Fitzpatrick et al., 2009). For modern sediment budgets that cover a few years, sediment loads are typically measured at the watershed outlet (Gellis and Walling, 2011).

In step 3 of the sediment budget approach, potential sources of sediment can be identified in a watershed using a geographic information system (GIS) analysis, reconnaissance of the entire basin, "riverwalks" or reconnaissance along channels, field experiments, monitoring, and photogrammetric analysis using aerial photographs. Sources of sediment are then defined as a combination of geomorphic elements and human uses (i.e. streambanks, upland cropland, pastured gullies, and forests). Next, the outlet of the watershed is defined and appropriate techniques are used to quantify the sediment transported out of the watershed over a specified period of time (Mg/yr) (Table 1). The sediment size of interest is also decided initially (step 4) and can include all sediment sizes or individual size classes. If both fine and coarse sediment are of interest, watershed outlet measurements need to consider both suspended- sediment load and bedload (Edwards and Glysson, 1999).

Table 1 Examples of approaches and methods used in sediment budgets

Sediment budget element (I = input, S= storage, O=output)	Method	Method is used to quantify	Measurement dimension	Time scale of measurements
Channels (I,S)	Aerial photography airborne light detection and ranging (Lidar)	Channel morphologic changes in channel width, sinuosity, bar formation, and channel patterns (Thoma et al., 2005; Kessler et al., 2013)	m	Years, decades
Channels (I,S)	Surveys	Changes in channel width, depth, and slope (Gellis et al., 2012)	m	Per storm (days) to years
Channels (I,S)	Bank pins; Terrestrial LiDAR	Bank erosion and deposition (Hupp et al., 2009; O'Neal and Pizzuto, 2011; Schenk et al., 2012)	cm, m	Per storm (days) to years
Channels	Rapid geomorphic assessments	Qualitative condition of the erosional/depositional characteristic of the streambanks (Simon and Downs, 1995)	NA	NA
Channels (S)	Stratigraphy	Identification of time horizons (anthropogenic, geologic, radionuclides) to estimate changes in deposition rates (Allmendinger et al., 2007; Trimble, 1983)	cm	Years, decades, millennia
Channels (I,S)	Scour chains	Quantify change on the channel bed (Leopold et al., 1966)	cm	Days to years
Flood-plain Deposition (S)	Feldspar Pads	Flood-plain deposition rates (Hupp et al., 2008)	mm	Per storm (days) to years
Uplands (I,S,O)	Lake/Pond surveys using ^{137}Cs	Sediment loads and sediment yields, and changes in sedimentation over time (Gellis et al., 2006)	kg/m^2	Years, decades
Uplands (I,S)	^{137}Cs	Upland erosion and deposition rates (Gellis et al., 2009; Walling and He, 1999)	tons/hectare	Decades (50 yrs)
Uplands (I)	Sediment traps	Sediment yield (Gellis et al., 2012)	kg/m^2	Per storm (days) to years
Uplands (I,S)	Pins (nails)	Land-surface erosion (Gellis et al., 2012)	cm	Per storm (days) to years
Uplands (I)	Nets, silt fences	Erosion and sediment yield (Robichaud and Brown, 2002)	kg/m^2	Days to years
Uplands (I)	Aerial photographs	Qualitative description of areas that may contribute sediment (agriculture, mining, landslides, roads, etc.) (Reid and Dunne, 1996)	NA	NA
Uplands (I,S)	Dendro-chronology	Coring trees and counting rings to determine deposition and erosion rates (Hupp and Bazemore, 1993; Allmendinger et al., 2007)	cm	Decades
Uplands (I)	Eolian traps	Quantify eolian deposition (Gellis et al., 2012)	g	Years
Uplands (I) and Channels (I)	Multiple geochemical fingerprints	Quantify the contribution of sediment from source areas (Walling et al., 2008; Gellis and Walling, 2011)	%	Days to years
Sediment transport (O)	Collection of suspended sediment and bedload	Sediment loads (Gellis et al., 2006, 2012)	kg	Per storm (days), years to decades

The erosion and storage of sediment is determined for each geomorphic element (step 7) over the measurement period using the approaches outlined in Table 1. Most of the measurements in Table 1 produce linear (cm) or cross sectional area (cm^2) rates of change that are extrapolated for each geomorphic element (step 8) over the entire watershed to obtain a volume (m^3) which is then converted to mass (kg) using the density (g/cm^3) of eroded/deposited sediment. Extrapolation can be performed using different independent variables, including, but not limited to, stream order, stream type, landscape feature, geomorphic landform, and geologic areas (Fitzpatrick and Knox, 2000; Fitzpatrick et al., 2009; Gellis et al., 2012). For example, bank pins might be used to measure erosion or deposition in centimeters. Erosion and deposition are then averaged for a bank face (cm) to obtain an area of bank change (cm^2). This value is extrapolated to a channel length (m) representative of that bank (i.e. stream order) to obtain a volume of bank change (m^3). Finally, mass (kg) is obtained by multiplying the density of the bank sediment (g/cm^3) by the volumetric change (m^3). Density can be measured by inserting core samplers of known volumes into the streambank.

For 30- to 50-m high valley bluff failures along tributaries to Lake Superior, aerial photograph analyses of bluff retreat rates, along with field measurements of bluff retreat, length, height, and stratigraphy, were used to determine that the bluffs were a major source of the eroded sediment that was causing burial and scouring of spawning gravels downstream (Fitzpatrick and Knox, 2000; Fitzpatrick et al., 2014). Flood-plain cores and interpreted sedimentation rates were extrapolated over appropriate areas based on geomorphic landform and cultural features such as bridges, railroads, and levees that influence the distribution of sediment deposition during floods (Fitzpatrick et al., 2009).

The erosion and deposition of each geomorphic element is summed and values are compared to the sediment measured at the outlet (step 10). Theoretically, all sediment inputs and storage terms should balance to the output (Eq. 1), however, this rarely happens (Kondolf and Matthews, 1991). Kondolf and Matthews (1991) reported imbalances > 100% of the total sediment output. The error represents the cumulative uncertainty of measurements and estimates over the range of both spatial and temporal scales. Error analysis can be performed by displaying the range of sediment budget results on each geomorphic element as confidence intervals around the mean (i.e. 10^{th} and 90^{th} percentiles).

Results from a sediment budget analysis can be presented as maps, diagrams, and tables (Fitzpatrick et al., 2009). Areas of high erosion, defined using the sediment-budget approach, can be portrayed in these ways to improve communication of the results and, subsequently, inform targeted management actions.

SEDIMENT FINGERPRINTING

Sediment fingerprinting identifies the source contribution of sediment delivered to a point in the watershed. The approach entails the identification of specific sources of sediment through the establishment of a minimal set of physical and/or chemical properties, i.e. fingerprints or tracers that uniquely define each source in the watershed. Tracers that have successfully been used as fingerprints include mineralogy (Motha et al., 2003), radionuclides (Walling and Woodward, 1992; Collins et al., 1997), trace elements (Devereux et al., 2010), magnetic properties (Slattery et al., 2000), and stable isotope ratios ($^{13}C/^{12}C$ and $^{15}N/^{14}N$) (Papanicolaou et al., 2003).

By comparing the tracers of the target sediment to the tracers of the source samples, and using a statistical “unmixing” model, the sources of the target sediment can be apportioned (Gellis and Walling, 2011). Target sediment can be deposited (bed sediment or flood-plain sediment) or transported (suspended sediment). Because tracer activity is largely found on fine sediment,

sediment fingerprinting is typically conducted on sediment less than 63 microns in diameter (Gellis and Walling, 2011).

Sediment sources in sediment fingerprinting are typically the same sources accessed in the sediment budget. In sediment fingerprinting, sediment samples from upland areas (i.e. agriculture, forests, and construction sites) are collected from the top 1.0 cm of the soil surface with a plastic hand shovel. A plastic shovel is used to protect the sample from metal contamination. To account for variability in tracer properties, sediment is collected across transects and composited. A representative sample of the streambank is collected 1 cm into the vertical bank and along the entire bank. Three to five transects spaced 10 m apart along the stream reach are sampled and composited into one sample.

Several statistical procedures are used to identify the optimum set of properties that will be used in the final composite fingerprint to distinguish the potential sources and establish their relative contribution to the sediment flux at the watershed outlet (Figure 1). The goal is to determine those properties that clearly identify the potential sources and to select a small subset that optimizes the discrimination provided by the composite fingerprint. The statistical steps outlined in Figure 1 were run using the free software statistical package R (R Core Team, 2013) from a Microsoft Access database platform*. Field data are entered into the database and the program guides the user through the necessary statistical procedures to produce relative source contribution results and an error analysis.

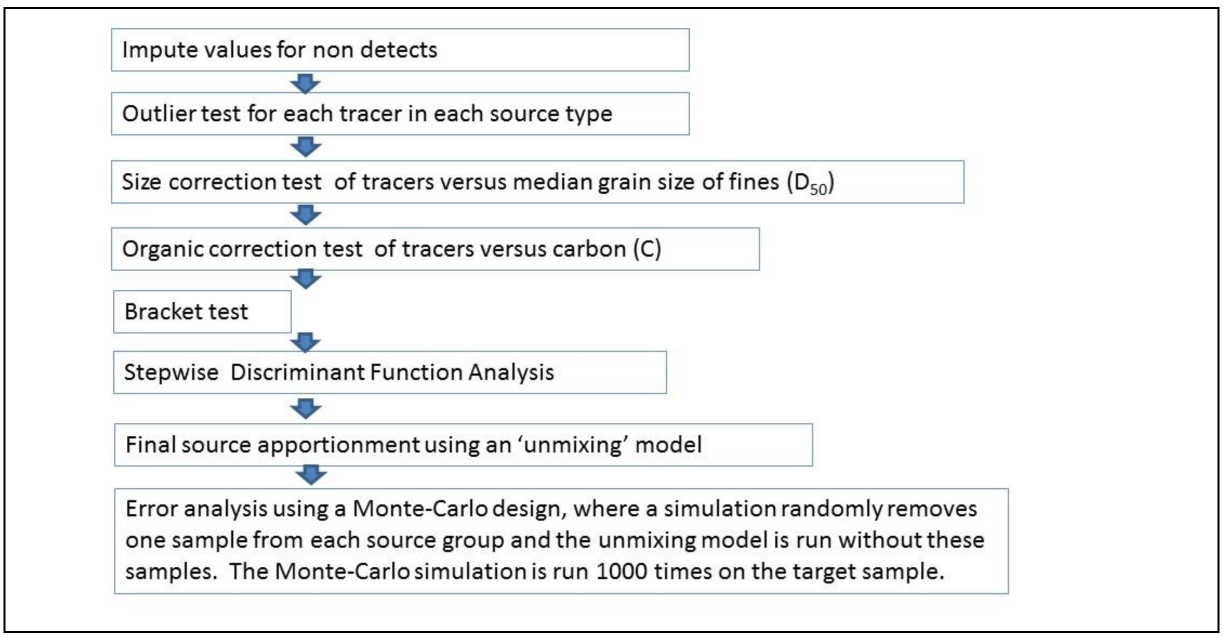

Figure 1 Statistical steps used to apportion sediment in the sediment-fingerprinting approach (From Gellis and Noe, 2013).

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

The sediment-fingerprinting approach provides an apportionment of the sources of sediment but it does not provide quantification of the rate of erosion, overall mass of delivered sediment, or target “hotspots” of erosion. For example, sediment fingerprinting may indicate that the streambanks are a major source of sediment in a watershed, but areas with the highest rates of bank erosion cannot be identified using the sediment fingerprinting approach. The sediment budget approach, however, can help target prominent sources of erosion. Erosion and deposition results from the sediment budget can be combined with the sediment fingerprinting results and provide information on sediment delivery ratios (SDRs; the amount of delivered sediment to the amount of eroded sediment) (Gellis and Walling, 2011).

CASE STUDY – Linganore Creek, Maryland

Linganore Creek, Maryland is an example of a source-identification study where both the sediment budget and sediment fingerprinting approaches were used to determine the significant sources of fine-grained sediment between 2008 and 2010 (Figure 2) (Gellis and Noe, 2013; Gellis et al., 2014). Linganore Creek drains 147 km^2 of agricultural (62%) and forested (27%) land in the Piedmont Physiographic Province of the Chesapeake Bay watershed. Sediment budget results indicated that the greatest mass of sediment was eroded from agricultural lands, followed by streambanks and forests. Sediment storage areas included flood plains and farm ponds. The final sediment budget for Linganore Creek expressed as equation 1 is shown in Table 2.

During the period of study, 194 suspended-sediment samples were collected over 36 storm events and were used to determine their sources using the sediment fingerprinting approach. Samples were collected from 40 streambanks, 24 agricultural areas (cropland and pasture), and 19 forested sites. According to the sediment fingerprinting results, agricultural lands contributed 45% of the total fine-grained sediment transported out of the watershed, streambanks contributed 52% and forests contributed 3%. Combining the sediment fingerprinting results with the sediment budget approach indicated that 96% of the eroded agricultural sediment went into storage resulting in a SDR of 4%; 56% of the eroded streambanks went into storage with a SDR of 44% ; and 92 percent of eroded forest sediment went into storage with a SDR of 8 percent. Important storage sites of sediment included ponds, which stored 15 percent and flood plains, which stored 8 percent of all eroded sediment (6.33×10^7 kg/yr).

Management Implications

The sediment fingerprinting results indicated that the two main sources of fine-grained sediment delivered out of the Linganore Creek watershed were streambanks (52 %) and agricultural land (45 %). With a higher SDR for streambanks (44 %) compared to agricultural land (4 %), management actions implemented to reduce fine-grained sediment export out of the Linganore Creek watershed may be more effective if they are directed at stabilizing eroding streambanks. In addition, it would be informative to determine the geomorphic agent responsible for the erosion, such as increased runoff. These additional geomorphic insights can help to guide specific treatments for bank erosion within a broader adaptive management plan.

Table 2 Final annual fine-grained (<0.063 mm) sediment budget for Linganore Creek, Maryland, 2008-10. [Negative values in the sediment budget indicate erosion and positive numbers indicate deposition. The output of sediment was determined from the average annual suspended-sediment load computed for Linganore Creek near Libertytown, Maryland, 2008-2010 (USGS Station ID 01642438).]

	I (Mg)	**ΔS (Mg)**	**O (Mg)**
Agriculture (pasture + cropland)	-54,800		
Forest	-2,030		
Streambanks	-6,440	1,040	
Channel Bed	80	780	
Flood Plains		5,180	
Farm Ponds		9,320	
Unaccounted for sediment in budget		41,600	
Suspended sediment export at sediment station			-5,450

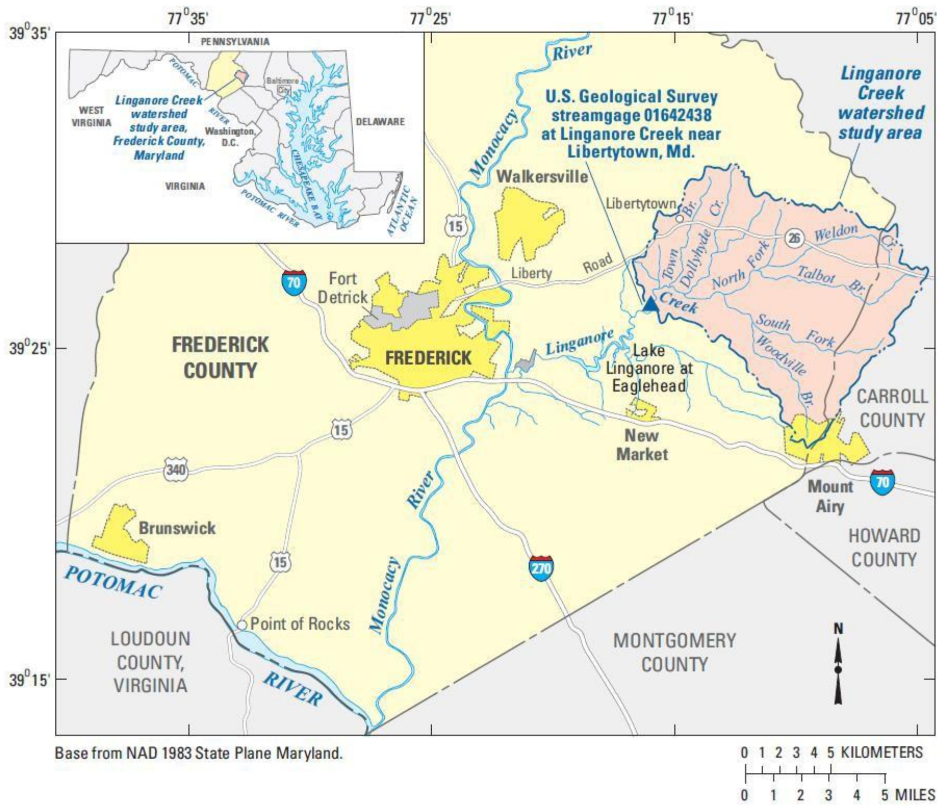

Figure 2 Location of Linganore Creek study area, Maryland.

Understanding sediment storage can be just as important as knowing where the erosion is occurring because sediment deposition influences the delivery and transport of fine-grained sediment to the measured outlet. Impoundments and flood plains were important sites of sediment storage in Linganore Creek. The ponds were estimated to store 9,320 Mg/yr of fine-grained sediment, which was 15 percent of the total eroded sediment. The estimated amount of sediment deposited on flood plains was 5,180 Mg/yr, or 8 percent of the total eroded sediment.

SUMMARY

Sediment is one of the leading causes of surface-water impairment in the United States. Two complementary approaches, sediment fingerprinting and sediment budgets, can be integrated to identify significant sources and sinks of fine-grained sediment in the sediment TMDL assessment process. These approaches can be used in addition to monitoring and assessment, as well as modeling of sediment erosion, transport, and storage in watersheds. Sediment fingerprinting determines the relative source contributions of fine-grained suspended sediment delivered out of a watershed, whereas the sediment budget approach utilizes measurements and estimates to quantify the erosion and deposition of sediment on various geomorphic elements throughout the watershed (streambanks, flood plains, channel beds, specific tributaries or land uses, and upland areas). In combination, these two approaches can help develop adaptive management plans and techniques that target specified hot spots.

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