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A Manual to Identify Sources of Fluvial Sediment

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Land Remediation and Pollution Control Division

A Manual to Identify Sources of Fluvial Sediment

by

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Foreword

The U.S. Environmental Protection Agency (USEPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, USEPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) within the Office of Research and Development (ORD) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments, and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

Sediment is one of the most common causes for the loss of stream-biologic integrity. Identifying sediment sources is an important step in the USEPA’s sediment TMDL process. The objective of this study was to develop a guidance document for sediment source analysis. The guidance document developed synthesized studies that incorporate sediment fingerprinting and sediment budget approaches in agricultural and urban watersheds.

Cynthia Sonich-Mullin, Director
National Risk Management Research Laboratory

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Acronyms and Abbreviations

3-D	Three-dimensional
AC	Acre
ADS	ADS Environmental Services
ASTL	Acoustic Sensing Technology, Ltd. (United Kingdom)
ATV	All-Terrain Vehicle
BC	Brown and Caldwell
CCTV	Closed-Circuit Television
CIP	Cast Iron Pipe
DE	Dissipation Energy
DEM	Digital Elevation Model
DFA	Discriminant Function Analysis
GIS	Geographic Information System
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
QAPP	Quality Assurance Project Plan
RPD	Relative Percent Difference
SFM	Sediment Fingerprinting Model
TMDL	Total Maximum Daily Load
TOC	Total Organic Carbon
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Executive Summary

Sediment is an important pollutant of concern that can degrade and alter aquatic habitat. A sediment budget is an accounting of the sources, storage, and export of sediment over a defined spatial and temporal scale. This manual focuses on field approaches to estimate a sediment budget. We also highlight the sediment fingerprinting approach to attribute sediment to different watershed sources. Determining the sources and sinks of sediment is important in developing strategies to reduce sediment loads to water bodies impaired by sediment. Therefore, this manual can be used when developing a sediment TMDL requiring identification of sediment sources.

The manual takes the user through the seven necessary steps to construct a sediment budget:

1. Decision-making for watershed scale and time period of interest
2. Familiarization with the watershed by conducting a literature review, compiling background information and maps relevant to study questions, conducting a reconnaissance of the watershed
3. Developing partnerships with landowners and jurisdictions
4. Characterization of watershed geomorphic setting
5. Development of a sediment budget design
6. Data collection
7. Interpretation and construction of the sediment budget
8. Generating products (maps, reports, and presentations) to communicate findings.

Sediment budget construction begins with examining the question(s) being asked and whether a sediment budget is necessary to answer these question(s). If undertaking a sediment budget analysis is a viable option, the next step is to define the spatial scale of the watershed and the time scale needed to answer the question(s). Of course, we understand that monetary constraints play a big role in any decision.

Early in the sediment budget development process, we suggest getting to know your watershed by conducting a reconnaissance and meeting with local stakeholders. The reconnaissance aids in understanding the geomorphic setting of the watershed and potential sources of sediment. Identifying the potential sediment sources early in the design of the sediment budget will help later in deciding which tools are necessary to monitor erosion and/or deposition at these sources. Tools can range from rapid inventories to estimate the sediment budget or quantifying sediment erosion, deposition, and export through more rigorous field monitoring. In either approach, data are gathered and erosion and deposition calculations are determined and compared to the sediment export with a description of the error uncertainty. Findings are presented to local stakeholders and management officials.

Sediment fingerprinting is a technique that apportions the sources of fine-grained sediment in a watershed using tracers or fingerprints. Due to different geologic and anthropogenic histories, the chemical and physical properties of sediment in a watershed may vary and often represent a unique signature (or fingerprint) for each source within the watershed. Fluvial sediment samples (the target sediment) are also collected and exhibit a composite of the source properties that can be apportioned through various statistical techniques. Using an unmixing-model and error analysis, the final apportioned sediment is determined.

1.0 Introduction and Background

Sediment is an important pollutant that can lead to loss of stream-biologic integrity, whether in suspension in the water column or as deposition on a stream or lake bottom (Waters, 1995). In a summary of stream impairments for the United States compiled from state reports from 2006 to 2014, sediment and turbidity was listed as the major source of stream impairment (USEPA, 2016) (Fig. 1). Of particular concern are fine-grained silts and clays, which can degrade habitat, clog water supply intakes and fill reservoirs, and often carry phosphorus and/or contaminants harmful to humans and aquatic life (Waters, 1995; Larsen *et al*., 2010). Sediment impaired water bodies, usually identified by fair to poor macroinvertebrate index scores, are placed on the 303D list where a sediment Total Maximum Daily Load (TMDL) is implemented under the Clean Water Act (USEPA, 1999). A sediment TMDL is the maximum amount of sediment a water body can contain and still meet its water quality standards and beneficial uses. When a stream is identified as impaired by sediment, it is required in the TMDL framework to identify sediment sources (USEPA, 1999) (Fig. 2).

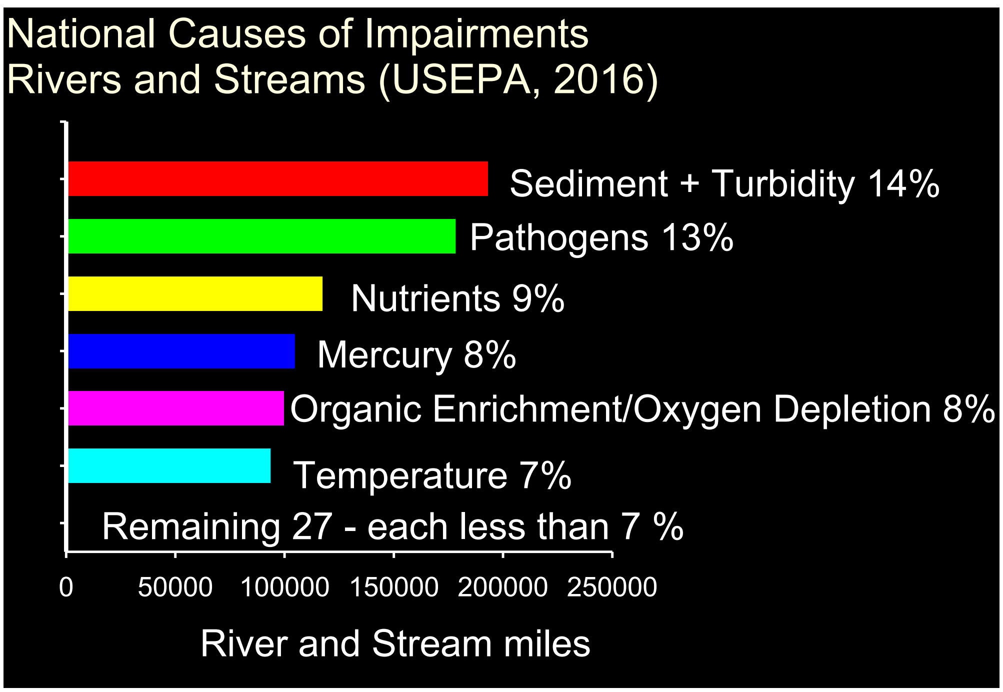

Figure 1. Causes of impairments in rivers and streams of the United States shown by percentage of impairments (USEPA, 2016).

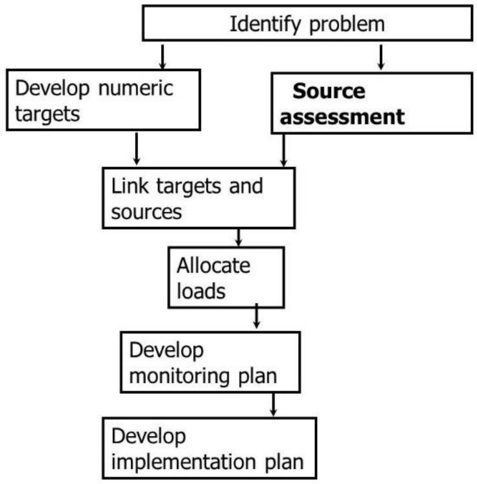

Figure 2. Components in a sediment TMDL process.

The TMDL Technical Advisory Group (TAG), a group composed of scientists from universities, Federal and state agencies, and non-governmental organizations, made the following recommendations in a 2002 review of sediment TMDLs in Georgia (USEPA Region 4) :

- Develop a carefully crafted inventory of the potential sediment sources and pathways by which sediment enters the water body.
- Use currently available information, including water quality monitoring data, watershed analyses, information from the public, and any existing watershed studies.
- Conduct thorough onsite watershed surveys that help determine the relative contribution of sediment from various sources.
- Conduct follow up monitoring with special emphasis for Phase I TMDLs.

The objectives of the sediment-source assessment should be to characterize the types, magnitudes, and locations of the source(s) of sediment loading by compiling an inventory of all potential sources through identification on maps, existing data, and field surveys (USEPA, 1999). Monitoring, statistical analyses, and modeling are recommended in order to determine the relative magnitude of sediment-source loadings and watershed-delivery processes (USEPA, 1999). Understanding the role of stream-related fluvial processes in transporting sediments from watershed sources, delivery, and storage is a key focal point of this manual. Understanding fluvial processes is especially useful for determining the relative magnitude of sources from upland soil erosion compared to fluvial erosion and river-related mass wasting. It may also add insights as to the relative sources of particulate-phase phosphorus sources, transport, and storage within channels and near channel areas. Human activity, such as construction and urbanization, can alter hydrology and runoff, which can lead to increased rates of fluvial erosion and river-related mass wasting (Wilkinson and McElroy, 2007; Fitzpatrick *et al*., 1999). In the process of identifying specific sources of sediment and the magnitude of the problem, the results can be used to develop an implementation plan based on the proximity of active sediment sources to important areas within a river system, such as spawning beds, water intakes, and drinking water reservoirs (USEPA, 1999). Calculations of sediment loading from specific sources can help determine if those loadings differ from natural or background rates.

It is of utmost importance to determine, measure, and monitor sediment loads and identify the sources causing a sediment or nutrient problem early on in the TMDL process (Fig. 1) (USEPA, 1999). The U.S. Geological Survey (USGS), in coordination with many other Federal, state, and local agencies, monitors suspended-sediment loads and concentrations at watershed outlets to evaluate the success of land use conservation practices on reducing sediment and nutrients in impaired watersheds (Shipp and Cordy, 2002; Jastram, 2014). Monitoring sediment loads is an important step in the TMDL process but for management purposes it is important to identify the sources for the loading. Currently, jurisdictions across the United States use a variety of approaches to identify sediment sources (Williamson, *et al*., 2014). These approaches focus on identifying watershed sources usually related to soil erosion and monitoring suspended sediment concentration and loads at watershed outlets.

Soil erosion and sedimentation are priority problems being addressed through additional programs besides the TMDL process by other Federal agencies including the U.S. Department of Agriculture (NRCS, 2007), the U.S. Army Corps of Engineers and International Joint Commission (Reidel *et al*, 2010; Hayter *et al*., 2014), and the Bureau of Reclamation (Bureau of Reclamation, 2007). Several large regional initiatives are in place that include sediment reduction goals, including the Chesapeake Bay Restoration Initiative, the Great Lakes Sediment and Nutrient Reduction Program (http://keepingitontheland.net/projects-glri/), the Upper Mississippi River Healthy Watersheds Initiative (http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/programs/initiatives/?cid=nrcsdev11_023896), and the Gulf of Mexico Hypoxia Task Force (http://www2.epa.gov/ms-htf/hypoxia-task-force-nutrient-reduction-strategies). Agricultural watersheds are of special interest because of the strong relation between sediment and particulate-bound phosphorus. In addition to TMDL development, the approaches presented in this manual may be useful to these other Federal programs for sediment management.

Examination of several sediment TMDL reports produced by jurisdictions throughout the United States indicated a reliance on models, Geographic Information System (GIS) analysis, and best judgment to identify sediment sources in the TMDL framework. These reports did not include a field-based approach to identify and target sediment sources. The practitioner charged with reducing riverine sediment loads through identifying sediment sources should have a variety of tools at his or her disposal. The objective of this manual is to provide practitioners with approaches to identify the important sources of sediment in a watershed and budget the erosion, storage, and delivery of this sediment. The manual emphasizes the sediment budget and sediment fingerprinting approaches and discusses the benefit of combining both approaches. This manual does not provide in-depth descriptions of the many models that are used in agricultural upland sediment-source assessment. Information on models that are used in sediment-source analysis can be found in Chapter 8 of a USEPA (2008) report on non-point source pollution. This manual discusses field- based approaches that may rely on or benefit from photogrammetric methods, GIS, and models, to identify sediment sources and budget sediment- with special emphasis on techniques for measuring sources and sinks within the stream corridor. The techniques are divided into major sections; first, describing how to construct a sediment budget and second, how to design and sample for a sediment fingerprinting study. It is the a goal of this manual to educate practitioners on field-based approaches using sediment budget and sediment fingerprinting approaches as tools to identify sediment sources in the sediment TMDL process. This manual expands on the methods introduced in Chapter 5 of the sediment TMDL protocol (USEPA, 1999) by further describing how an integrated sediment budget and sediment fingerprinting approach complement existing techniques. The approaches presented in this manual are largely field based and are presented not to eliminate current approaches but to be used in conjunction with existing approaches. The sediment fingerprinting approach is one of the tools that we highlight in this manual.

2.0 Background on Sediment Budgets

Sediment is composed of inorganic and organic particulate material that is transported by a stream in suspension and as bedload. Both suspended sediment and bedload can lead to the impairment of streams and receiving water bodies. This manual primarily focuses on identification of the sources and flux of suspended sediment specifically with respect to the fine-grained fraction (<0.063 mm). However, many of the approaches suggested in this manual for measuring erosion and deposition in stream corridors can be applied to bedload and total sediment loads.

The sediment fingerprinting approach apportions the relative contribution of the potential sediment sources in a watershed delivered to a point in the watershed. The sediment budget approach provides information on the magnitude of the fluxes and the links between sources, storage, and sediment output. Combining the two approaches can provide resource managers with information on where to target measures to reduce erosion, sediment delivery, and the net transport of sediment.

2.1 Definition of a Sediment Budget

A sediment budget is an accounting framework that can be used to understand processes of sediment erosion, transport, storage, delivery, and linkages among these elements that occur in a watershed (Leopold *et al*., 1966; Swanson *et al*., 1982; Gellis *et al*., 2012). The most basic form of the sediment budget equation is:

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

where: I = the sediment input

ΔS = the amount in sediment storage, and

O = the sediment output

In general, the units in equation (I, S, O) correspond to sediment mass over time (i.e., kg/yr), although volumes can also be used in a sediment budget (m^3/yr). Because sediment is transported episodically during large floods, the time scale of reference for each source and sink component is extremely important. Thus, whether sediment is budgeted over a single storm, to years, to decades is important. Furthermore, the measurements used to quantify erosion and deposition (I, S) can be linear (m), cross sectional (m^2), or volumetric (m^3). For source apportionment, a volumetric or mass rate is needed for all components.

This manual will provide a review of measurements available to quantify O, I, and S and how to use these measurements to construct a sediment budget. Often measurements are made in small areas (i.e., a point, cross section, or reach), and extrapolation to the entire watershed is needed to construct the sediment budget. For example, to budget channel changes, bank measurements can be made with pins, i.e., linear (cm) measurements that are averaged over the bank face to get a cross sectional area change (m^2). The cross sectional area change is extrapolated to a selected stream length (m) to calculate a volume (m^3). The volume of change in streambanks is converted to a mass by multiplying the volumetric change (m^3) by the density of bank material (g/cm^3) to determine a mass (kg).

In the construction of a sediment budget, the terms 'gross' erosion and 'net' delivery are used to describe sediment eroded from an area of interest, which can range from the plot scale to the entire watershed, that is delivered to a site further downstream (de Vente *et al*., 2007). The sediment delivery ratio (SDR) is the ratio of delivered sediment, expressed as a yield per unit area, divided by the gross erosion, usually expressed as a percent:

$$\mathrm{SDR} = \frac{\text{Sediment Yield (sediment delivered to the point of interest)}\left(\frac{kg}{km^2}/yr\right)}{\text{Gross erosion}\left(\frac{\frac{\mathrm{kg}}{km^2}}{\mathrm{yr}}\right)} \text{ x } 100 \qquad (2)$$

In most cases, gross erosion is greater than the sediment yield, the difference being due to sediment that goes into storage (S in Eq. 1) as it is transported through the watershed. Although gross erosion in the literature usually refers to upland erosion, it can and should include fluvial erosion (de Vente *et al*., 2007). SDRs estimated from sediment budgets can range from zero to 100 % (Smith and Dragovich, 2008; Walling and Collins, 2008). Walling (1983) plotted contributing area versus the SDR and noted that as drainage area increases, the SDR decreases, reflecting the increase in storage areas with increasing area (Fig. 3). Roehl (1962) depicted the SDR as an area power law relation:

$$\mathrm{SDR} = \alpha A^{\beta} \qquad (3)$$

where:

A is the basin area (km^2), α is a constant, and β is a scaling function (0.01 to -0.25).

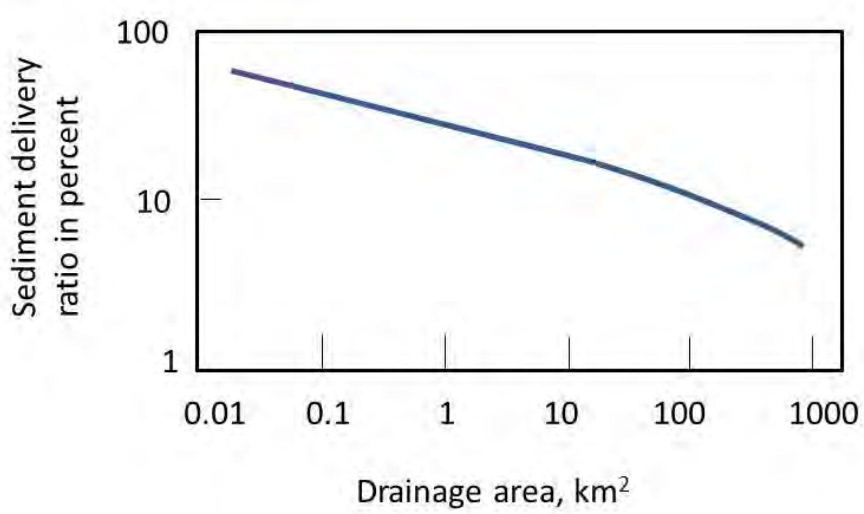

Figure 3. Drainage area plotted against the sediment delivery ratio (after Walling, 1983).

The differences in gross erosion and delivered sediment are important to the land manager. If knowledge of watershed soil loss or erosion directly at a site is needed, then measurements of gross erosion may suffice. If knowledge of sediment delivery to a point in the watershed or to lakes, estuaries and the ocean is needed, then constructing a sediment budget and determining sediment delivery is necessary. Sediment delivery is also needed for identifying possible lag times between upland best management practices and downstream stream water quality (Meals *et al*., 2010; Sharpley *et al*., 2013). For example, in large watersheds, efforts to reduce sediment may take less than 10 to more than 50 years to produce measurable differences at the watershed outlet (Meals *et al*., 2010).

Sediment budgets can be used for a variety of purposes:

- Sediment source identification for pollutant purposes - TMDLs
- Assess the effects of land use practices - i.e., agriculture
- Monitor the effectiveness of management actions to reduce sediment - i.e., stream restoration
- Determine sediment contributions from natural factors, e.g., erosion following a wildfire or the contributions from landslides after a major storm
- Determine the long-term effect of stressors - i.e., dams or climate change
- Put current sediment budget results in the context of historical sediment budget rates
- Determine the input from tributaries
- Determine how different geologic areas contribute sediment

Sediment budgets have been performed on all continents, at varying spatial and temporal scales, and using a variety of techniques (Table 1).

Table 1. Literature review on sediment budget studies completed over a range of spatial and temporal scales with errors reported for each study (Modified from Gellis et al., 2012).

Continent	Spatial scales	Time scales	Methods
North America (Leopold et al., 1966; Costa, 1975; Dietrich and Dunne, 1978; Trimble, 1983; Knox, 1985; James, 1989; Phillips, 1991; Sutherland, 1991; Beach, 1994; Faulkner and McIntyre, 1996; Knox, 2002; Gaugush, 2004; Allmendinger et al., 2007; Renwick, et al. 2005; Fitzpatrick et al., 1999; 2009; 2015) **South America** (Meade et al., 1990; Trauth et al., 2003) **Europe** (Macaire et al., 2002; Gruszowski et al., 2003; Belyaev et al., 2005; Evans and Warburton., 2005; Houben et al., 2006; Rommens et al., 2006; Van der Perk and Jetten, 2006) **Asia** (Schick and Lekach, 1993; Oguchi, 1997) **Africa** (Dunne, 1979; Sutherland and Bryan; 1991; Wijdenes, and Bryan, 2001; Walling et al., 2003; Garcin et al., 2005), **Australia** (Loughran et al., 1992; Brizga and Finlayson, 1994; Page et al., 1994; Wasson et al., 1998; Wallbrink et al., 2002) **Antarctica** (Pollard and DeConto, 2003)	**m^2** (Brunton and Bryan, 2000) **ha** (Sutherland, 1991; Wijdenes and Bryan, 2001; Wallbrink et al., 2002; Polyakov et al., 2004; Evans and Warburton., 2005; Hart and Schurger, 2005) **10 - 100's km^2** (Trimble, 1983; Knox, 1985; James, 1989; Beach, 1994; Faulkner and McIntyre, 1996; Oguchi, 1997; Knox, 2002; Slaymaker et al., 2003; Walling et al., 2003; Garcin et al., 2005 Fitzpatrick et al., 1999; 2009; 2015) **>1,000 km^2** (Costa, 1975; Meade et al., 1990; Phillips, 1991; Brizga and Finlayson, 1994; Gaugush, 2004; Renwick et al., 2005; Houben et al., 2006)	**days** (Page et al., 1994; Springer et al. 2001; Van der Perk and Jetten, 2006) **months** (Sutherland and Bryan, 1991; Polyakov et al., 2004; Belyaev et al., 2005) **years** (Leopold et al., 1966; Schick and Lekach,1993; Phillips, 1991; Gruszowski et al., 2003; Gaugush, 2004; Renwick, et al. 2005; Rovira et al., 2005; Fitzpatrick et al., 2009; 2015) **centuries** (Costa, 1975; Trimble, 1983; Knox, 1985; James, 1989; Beach, 1994; Faulker and McIntyre, 1996; Wasson et al., 1998; Knox, 2002; Fitzpatrick et al., 1999; 2009; 2015) **millennia** (Knox, 1985; Oguchi, 1997; Macaire et al., 2002; Slaymaker et al., 2003; Houben et al., 2006; Rommens et al., 2006)	**field measurements** (Leopold et al., 1966; Costa, 1975; Knox, 1985; James, 1989; Phillips, 1991; Sutherland and Bryan, 1991; Beach, 1994; Faulkner and McIntyre, 1996; Knox, 2002;Gaugush, 2004; Evans and Warburton, 2005; Rovira et al., 2005; Fitzpatrick et al., 1999; 2009; 2015) **radionuclides** (Ritchie et al., 1974; Sutherland, 1991; Wallbrink et al., 2002; Walling et al., 2003; Fitzpatrick et al., 2009) **multiple geochemical fingerprints** (Walling and Woodward, 1992; Nimz, 1998; Wasson et al., 2002; Gruszowski et al., 2003; Walling, 2005) **pond and lake sedimentation** (Foster et al., 1988; Erskine et al., 2002; Phippen and Wohl, 2003; Renwick, et al. 2005) **sediment cores** (Costa, 1975; Knox, 1985; 2002; James, 1989; Beach, 1994; Faulkner and McIntyre, 1996; Slaymaker et al., 2003; Belyaev et al., 2005; Houben et al., 2006; Rommens et al., 2006; Fitzpatrick et al., 1999; 2009; 2015), **models** (Phillips, 1991; Belyaev et al., 2005; Renwick, et al. 2005) **maps and photogrammetry** (James, 1989; Brizga and Finlayson, 1994; Faulkner and McIntyre, 1996; Wasson et al., 1998; Garcin et al., 2005; Renwick, et al. 2005; Fitzpatrick et al., 1999; 2009)

A substantial number of tools and approaches used to measure or estimate *I*, S, and *O* in Eq. 1 are available (Table 2) and selection will depend upon many factors, such as financial resources and temporal and spatial aspects of the study. We highlight a few approaches in this manual that are favorites among the authors and that have worked well in USEPA Regions 3 and 5. References provided or searches on the Internet can be used to identify other approaches. It is also anticipated that many of these approaches will change in the future due to technological advances.

2.2 Major Sediment Sources and Sinks in a Watershed

In general, watershed sediment sources can be separated into two broad categories based on their origin: 1) uplands and hillslopes, and 2) stream corridors (Gellis and Walling, 2011). Upland sediment sources most often include soil erosion from various land use and land cover types, such as forest, cropland, pasture, construction sites, and roads (Fig. 4). Stream corridor sources include streambanks and channel beds. Also included in stream corridor sources is sediment derived from mass wasting where channels intersect valley sides and terrace walls. Gullies span the two sources but are usually included as channel sources. Hillslope erosion is usually included in upland erosion. Floodplains and alluvial fans are usually sediment sinks, but can become sources during large floods. Differentiating between these two broad categories (upland and channel sources) is important because sediment-reduction management strategies differ by source and require very different approaches -- reducing agricultural sources may involve soil conservation and tilling practices, whereas reducing channel sources of sediment may involve stream restoration, bank stabilization, and grade control to arrest downcutting.

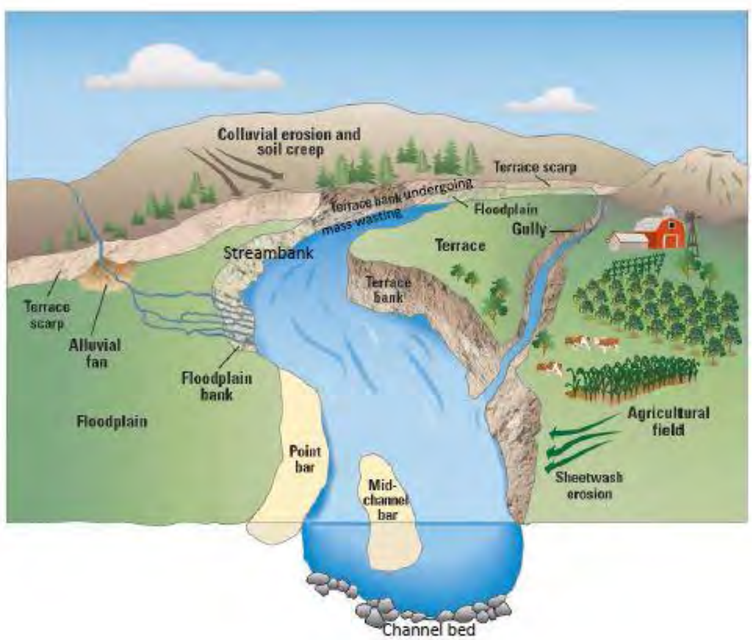

Figure 4. Watershed sources and sinks diagram.

It is important to note that sediment sources and sinks can vary by location in the watershed and by season, and, therefore, the rates and the time scale of interest for the sediment budget become important. For example, in the agricultural Midwestern United States, soil erosion is most prevalent during the spring months when large areas of soils are bare, compared to late summer when crops thickly cover any bare soil. Streambank erosion can often be greater in winter months, if the location undergoes freeze thaw cycles (Wolman, 1959).

Table 2. Methods used in sediment budget analysis.[NA = not applicable]

Sediment budget element (I = input, S = storage, O = output)	Method	Can be used to quantify	Dimensions measured	Time scale of measurements
Channels (I)	Aerial photography & LiDAR	Channel changes in width, depth, sinuosity, bar formation, and channel pattern	m, m^2,m^3	Years, decades
Channels (I)	Bank pins	Bank erosion and deposition	m, m^2,m^3	Days (individual storms) to years
Channels (I, S)	Rapid geomorphic assessments	Qualitative condition of the erosional/depositional characteristic of the streambanks	NA	NA
Channels (I,S)	Scour chains	Quantify change in the channel bed	m, m^2	Days to years
Channels (I,S)	Surveys	Changes in channel width, depth, and slope	m, m^2, m^3	Per storm (days) to years
Channels (S)	Stratigraphy	Identification of time horizons (anthropogenic, geologic, Radionuclides), to estimate changes in deposition rates	NA	Years, decades, millennia
Deposition (S)	Floodplain pads	Floodplain deposition rates	m, m^2, m^3	Per storm (days) to years
Sediment transport (O)	Collection of suspended sediment and bedload	Sediment transport and loads	kg	Per storm (days), years to decades
Uplands (I)	Aerial photographs	Qualitative description of areas that may contribute sediment (agriculture, mining, landslides, roads, etc.)	NA	NA
Uplands (I)	Aeolian dust traps	Quantify eolian deposition	g	Years
Uplands (I)	Sediment traps and nets	Sediment yield in contributing area	Kg	Per storm (days) to years
Uplands (I) and channels (I)	Sediment fingerprinting	Quantify the contribution of sediment from source areas	%	Days to years
Uplands (I,S)	^{137}Cs	Upland erosion and deposition rates	tons/hectare	Decades (50 years)
Uplands (I,S)	Dendrochronology	Coring trees and counting rings to determine deposition and erosion rates	cm	Decades
Uplands (I,S)	Pins, erosion bridges	land surface erosion, unpaved roads	mm	Per storm (days) to years
Uplands (I,S,O)	Lake/pond bathymetric surveys	Sediment loads and sediment yield in contributing area, changes in sedimentation over time	kg	Years, decades

2.2.1 Upland Sediment Sources and Sinks

Upland sediment sources are those that occur outside the stream corridor and involve mainly soil erosion on varying land use and land covers, as well as more infrequent events such as mass wasting (landslides), and erosion from areas affected by fire. Erosion on upland surfaces occurs through sheetwash, overland flow, rilling, and gullying (USDA, 2007). Upland areas have sediment sinks in flat areas at the base of slopes that are not bisected by channels. This may happen at the grassy fenced edge of a field or at the base of a hillslope.

The time of year is important with respect to sediment sources. Cropland may become an important sediment source during tilling in the spring and harvesting in the fall when large areas are cleared of vegetation. Tillage operations and the type of farming practices used may also affect sediment sources. No-till operations, for example, which can have greater percentages of vegetative or residue cover throughout the year can also reduce soil erosion by varying amounts (Huggins and Reganold, 2008).

2.2.2 Stream Corridor Sediment Sources and Sinks

Stream corridor sources include channel sediment that is directly eroded and transported by flowing water. Most commonly this is thought of as streambank erosion but may also be derived from incising channel beds or mass wasting where a channel intersects a valley side and terrace wall (Fig. 4). In many studies, it is assumed that the channel bed is not a source or a sink along a main stem because any deposition of sediment is thought to be temporary and originating from upstream sources and is, therefore, not treated as a separate source (Gellis *et al*., 2009). However, in agricultural lowland streams, many of which are impaired by sediment, there is significant storage of sediment in channels and adjacent floodplains; thus, storage in the channel bed cannot be assumed to be negligible (Figs. 5, 6). For example, in Pleasant Valley, a small 19 km^2 agricultural lowland stream on the Wisconsin impaired waters list, fine-grained soft sediment stored along the channel bed is estimated to be equivalent to 8 years' worth of annual loading exported from the watershed (Fig. 6). In actively eroding streams, such as arroyos or incised channels (Gellis, 2012; Fitzpatrick *et al*., 1999), the bed of the stream may be an important sediment source. In a steep forested watershed in the northern Great Lakes region, channel incision was about equal to floodplain deposition on average over a multi-decadal time scale (Fig. 5).

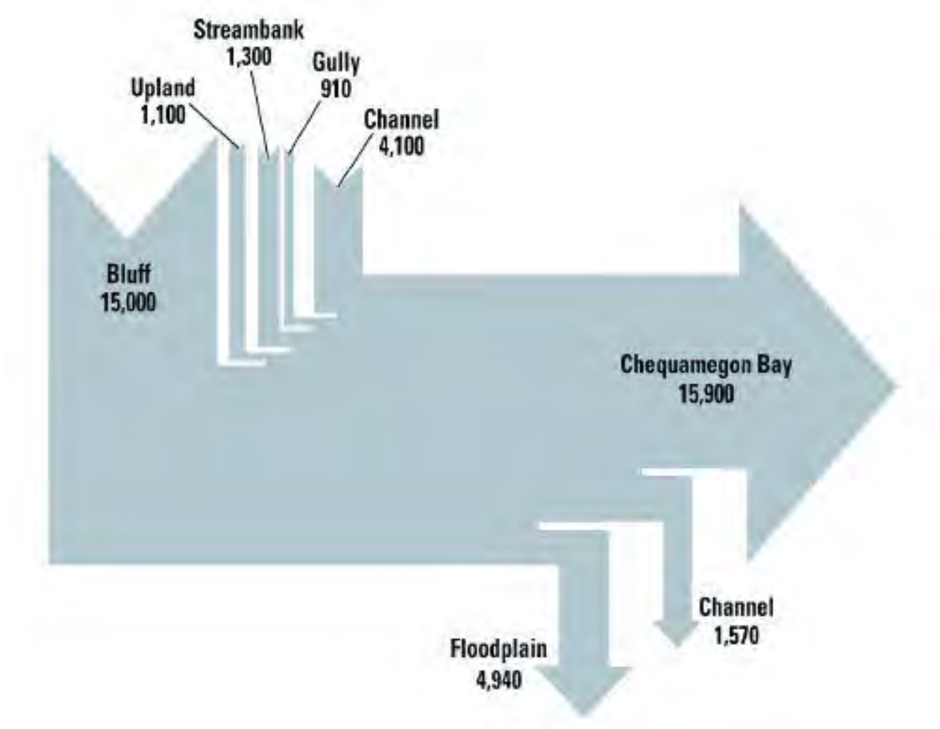

Figure 5. Example of a historical sediment budget, in tonnes per year, for a steep forested watershed in the upper Great Lakes (Fitzpatrick et al., 1999; Fitzpatrick and Knox, 2000). Bluff erosion was identified as a major source of sediment that was causing downstream sedimentation problems in fish spawning riffles.

Figure 6. Example of a sediment budget for 2007-10 from Pleasant Valley, an agricultural lowland stream on Wisconsin's impaired streams list. The sources, export, and sinks are from different methods – upland soil loss from RUSLE2, watershed export from a USGS monitoring station, bank erosion from a 2009

Streambanks can be an important sediment source and erode by three mechanisms: 1) freeze-thaw processes (Wolman 1959; Wynn 2006); 2) fluvial erosion (Julian and Torres 2006; Wynn 2006); and 3) mass wasting (Darby *et al*., 2007; Wynn, 2006). Freeze-thaw action of the bank surfaces causes the soil to expand and loosen. The material that is loosened is readily available for transport by a range of flows that inundate the bank surface (Lawler, 1986; Wolman 1959). Fluvial erosion is the detachment, entrainment, and removal of particles or aggregates from the streambank by the hydraulic forces of water. Hydraulic forces are related to the shear stress that the flow exerts on the bank. Sediment grain size, cohesiveness of grains, and vegetation are also important in whether streambanks are erodible (Wynn, 2006).

The composition of streambanks may be highly variable depending on whether the stream is cutting through floodplain deposits, older terrace fills, or valley sides of potentially glacial deposits, colluvium, or bedrock. Floodplain deposits can also range from coarse to fine-grained, depending on whether the stream is cutting through fine-grained over-bank deposits or coarse-grained older channel bar and bed deposits. Streams construct banks through the two main processes of 1) overbank deposition and 2) point bar formation (Fig. 7); both can be important in constructing floodplains (Wolman and Leopold, 1957; Moody, *et al*., 1999). Actively eroding terrace cuts and valley sides can be major sources of sediment (Fig. 4), especially in middle main stems where the meander wavelength of a stream approaches the valley width. Because their height can be quite substantial compared to floodplain elevations, they can be major sources of sediment to downstream reaches (Fitzpatrick and Knox, 2000).

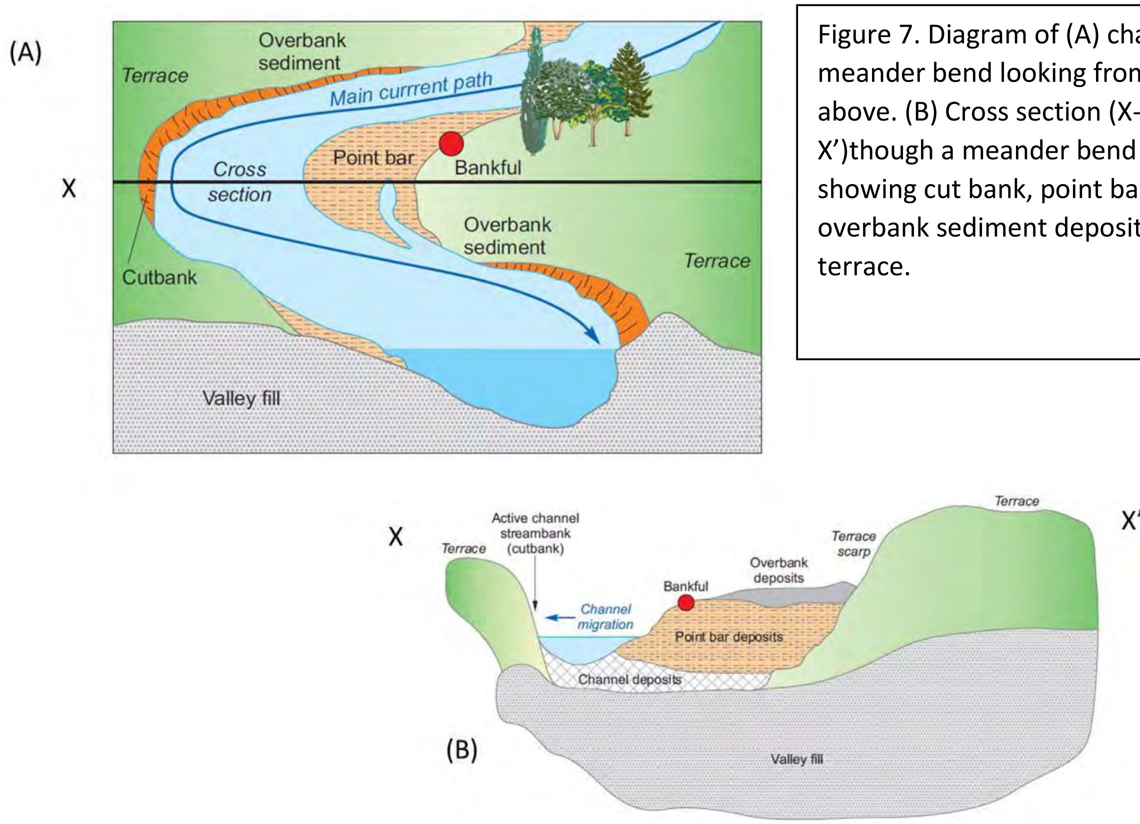

Figure 7. Diagram of (A) channel meander bend looking from above. (B) Cross section (X-X')though a meander bend showing cut bank, point bar and overbank sediment deposits, and terrace.

The age of sediment in streambanks may vary considerably in the vertical direction depending on the origin of the deposits. A good example of differing ages of the active streambanks is in the Mid-Atlantic region of the United States where the lower portion of the banks is typically composed of older geologic-aged material (in thousands of years) underlying a younger, historical sediment deposit (100's of years) (Jacobson and Coleman, 1986; Donovan *et al*., 2015). The historical sediment deposit is often related to European colonization of the Mid-Atlantic region where trees were cleared for agriculture and soil erosion and gullying of the cleared areas delivered sediment to the channel where it was deposited on the floodplain on top of older deposits. This historic sediment is often referred to as 'legacy sediment' (Jacobson and Coleman, 1986) and has resulted in thick accumulations of sediment in river bottomlands and floodplains across the United States (Lowdermilk, 1934; Happ *et al*., 1940; Leopold, 1956; Knox, 1972, 1987, 2006; Trimble, 1974; Beach, 1994; Faulkner, 1998; Montgomery, 2007) (Fig. 8). In many parts of the United States, the historical sediment was deposited in mill ponds that were later breached and incised by the channel to form the modern streambanks (Walter and Merritts, 2008). Much of the sediment eroded during the 18th, 19th, and 20th centuries still remains stored in floodplains, along channel margins, or in former mill ponds (Costa, 1975; Knox, 1972, 1977, 1986; Magilligan, 1985; Trimble, 1974; Fitzpatrick *et al*., 2009; Walling and Owens, 2002; Allmendinger *et al*., 2007). Some of the historical sediment actively eroding in streambanks has higher phosphorus concentrations compared to prehistoric counterparts, especially if a farmstead with livestock was located nearby (Fig. 9).

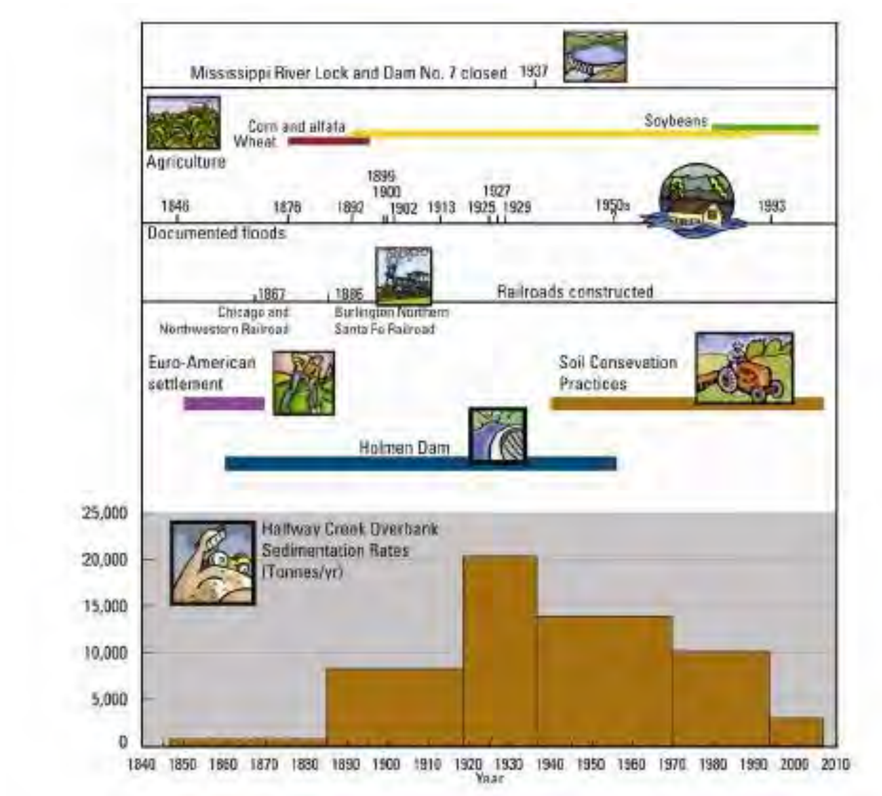

Figure 8. Historical overbank sedimentation rates for the mouth of Halfway Creek, a tributary to the upper Mississippi River. Sedimentation rates peaked in the 1920s and 1930s and have decreased since the adoption of soil conservation practices (Fitzpatrick et al., 2007).

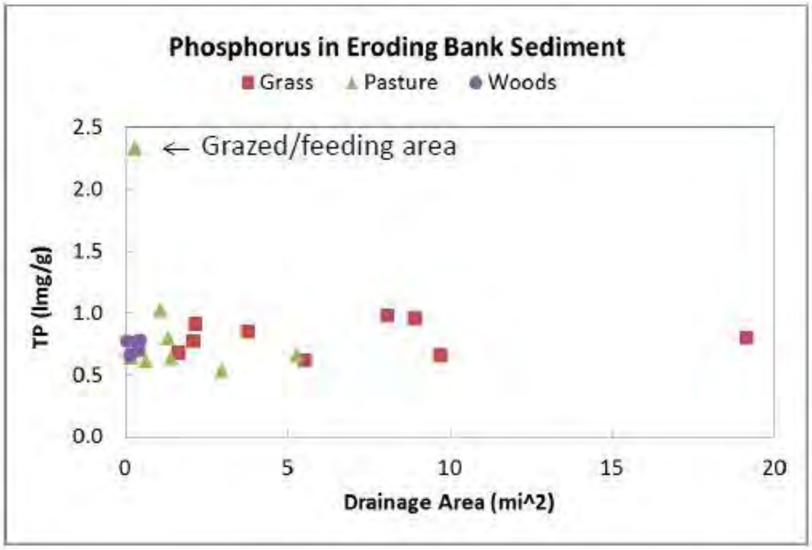

Figure 9. Concentrations of phosphorus in eroding streambank sediment in a lowland agricultural stream in the upper Mississippi River basin, Pleasant Valley , 2009. Most sediment had concentrations between 0.5 and 1.0 mg/g, except for a heavily grazed pasture with a feeding station near the stream.

Gullies fit in a category between upland erosion and channel erosion and can be important sources of sediment that propagate on upland surfaces in urban, agricultural, and forest settings (Poesen *et al*., 2003). Gullies grow and extend through several processes related to a variety of mechanisms: groundwater sapping, base-level lowering, downstream channel incision, and increased runoff (NRCS, 2007). In some cases, separating gullies from channel sources can be difficult where the difference may be related to the observation that gullies can evolve quickly from incisional to depositional states (Starkel, 2011).

Mass wasting on streambanks is the failure of all or part of the bank as a result of geotechnical instabilities. Mass failures can occur from fluvial erosion undercutting the toe of the streambanks and creating unstable conditions leading to bank failure (Simon *et al*., 2000). Bank failures and mass wasting are common during the recessional period of stormflow when seepage forces overcome the resistance of a grain's cohesion (Fox *et al*., 2007; Simon *et al*., 2000).

It is important to differentiate between streambanks of the active stream channel and fluvial terraces (Fig. 7). When streams incise, the floodplain no longer receives flows at annual intervals and forms a terrace. Many streams in the western United States, for example, have had several periods of incision or down-cutting through the Quaternary, and a flight of terraces has formed (Haynes, 1968). Terraces may only be inundated during extreme flow events. Streams may actively erode into terraces, especially in meandering systems.

Channel incision may occur in almost any setting by a number of causes such as: change in downstream base level, climate change, tectonics, channelization, or where flow or sediment have been altered, causing the channel to incise. For example, in urban areas, increased flow from impervious areas has caused many channels to incise. In the southern United States, many steams were channelized which increased channel slope, leading to channel incision (Simon, 1989). Channelized streams are often deep and the highest level, the former floodplain, is now a terrace, and a new floodplain is being constructed at some distance below the terrace.

3.0 Design of a Sediment Budget

When faced with examining sediment problems at the watershed scale, the practitioner has to decide whether utilizing a sediment budget is a viable option for addressing the question at hand. We suggest a seven-tiered framework to assist in the design and construction of a sediment budget (Fig. 10).

1. Decision-making for watershed scale and time period of interest
2. Familiarization with the watershed by conducting a literature review, compiling background information and maps relevant to study questions, conducting a reconnaissance of the watershed, and developing partnerships with landowners and jurisdictions
3. Characterization of watershed geomorphic setting
4. Development of a sediment budget design
5. Data collection
6. Interpretation and construction of the sediment budget
7. Generate products (maps, reports, and presentations) to communicate findings.

This tiered approach proceeds from the early stages of the sediment budget design where determining the important questions and the time and spatial scales that are needed to address the sediment problem are important (Step 1). Compiling existing information on erosion, transport, and deposition of sediment in the watershed and getting to know the constituents of the watershed are important in the early stages of sediment budget design (Step 2).

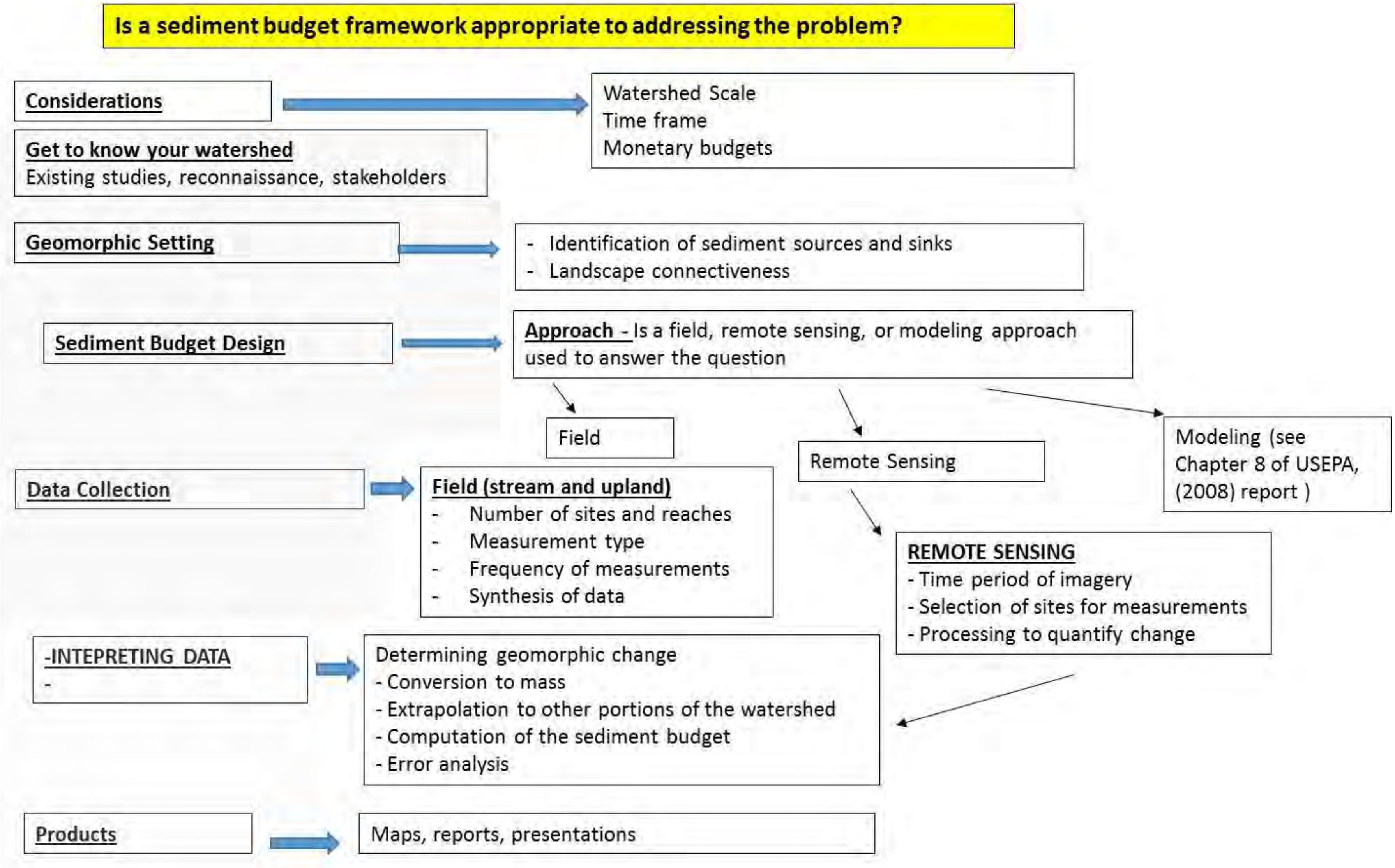

Figure 10. Steps in developing a sediment budget

3.1 Deciding On Sediment Budget Time Frames and Spatial Scales

3.1.1 Time Frame

Deciding on the time frame of the sediment budget is the first step to consider. Sediment budgets can be developed for multi-decadal or century time scales for determining changes in erosion and sedimentation following Euro-American settlement, agriculture, and subsequent soil conservation (Knox, 1972; Trimble and Lund, 1982; Trimble, 1983, Fitzpatrick and Knox, 2000; Knox, 2006) to present-day TMDL applications, which usually involve comparison before and after application of best management practices extending over a period of 5-10 years (USEPA, 2015). For a baseline watershed-based sediment budget related to TMDLs, usually a minimum of 3 years is sufficient to record changes, provided that weather conditions are representative within a longer term range of variability. It should be recognized that most sediment moves episodically during floods; thus, during dry cycles, changes in erosion and deposition in channels and uplands will be low with the opposite true for wet periods. Therefore, for sediment budgets developed for periods of less than a decade, it is important to put the short time period of the sediment budget in a climatic context by comparing rainfall during the study period to a longer rainfall record. Rainfall can also be measured in the study watershed and compared to the historical record. Examination of the nearest Weather Service (NWS) rainfall station will provide current and historical data. A long-term flow record from a USGS gaging station in the watershed is also helpful (http://waterdata.usgs.gov/nwis). Adoption of some of the techniques used for longer time frames also may be useful for giving context to shorter time frames, especially for aspects of sedimentation and sediment storage on floodplains (Fitzpatrick et al., 2009) Regardless of the time span of interest, sediment budget calculations are typically presented and normalized to an annual value.

Monitoring sediment is important in establishing the effectiveness of management actions to reduce sediment, and decisions on when to begin and end sediment monitoring are extremely important. A typical design for a sediment TMDL project in a small watershed (less than about 300 km^2) would be to begin baseline monitoring of sediment transport 3-5 years before management practices are implemented and inventory sediment sources within that 3-5 year period. Sediment transport monitoring is usually done at the watershed outlet but may also be nested in sub-watersheds. Management practices, especially if targeted, are usually implemented over 2-3 years. It is best to continue monitoring for 3-5 years after implementation. This is really a bare minimum of time needed for evaluation of management practices in humid temperate areas of the United States. In semi-arid and arid areas, the time frames need to be expanded to account for year-to-year hydrologic variability. Using a paired watershed approach helps to quantify the effectiveness of management practices. In this approach, a nearby watershed, similar in size, weather patterns, land use, and geologic setting is selected for monitoring. In the paired watershed, land-use management proceeds without any additional management or stream restoration implementation. Both monitoring and inventory results can be compared between the two watersheds.

3.1.2 Spatial Scale

The spatial scale and resolution of the sediment budget are also important in decisions related to time scales and design. Important questions related to spatial scale include:

- What is the size of the watershed where the sediment budget should be performed?
- How many sediment transport monitoring stations can be established?
- A sediment monitoring station should be located at the watershed outlet, but are there other scales in the watershed where monitoring would be of interest?
- Strategically placed sediment-transport monitoring station(s) can help identify sub-watersheds or specific stream reaches that have high sediment loadings compared to the overall loading at the watershed outlet. The spatial scale also affects the design of the measurements (placement and type) and monitoring, where at larger watershed scales, remote sensing and aerial photographic analyses play an important role in selecting reaches for field measurements and monitoring.

3.2 Getting To Know Your Watershed

Usually in the development of a TMDL, partnerships form among Federal, state, and local government agencies as they come together to perform the steps outlined in Figure 1. From this partnership comes a wealth of knowledge about the watershed and the sediment problems encountered as well as the stakeholders involved. Especially knowledgeable for agricultural watersheds are USDA county conservationists usually co-located with the local USDA-NRCS office. The USEPA (2008) handbook for developing watershed plans to improve water quality is an excellent resource to learn how to develop partnerships. This information can be especially useful in the early stages of designing your sediment budget.

For both large and small watersheds, GIS is essential for displaying and analyzing relevant maps and data. This step is also similar to the Reconnaissance Level Assessment (RLA) in the Watershed Assessment of River Stability and Sediment Supply (WARSSS) (Rosgen, 2006). The RLA involves 15 important steps that fit under constructing sediment budgets:

1) Compile existing data
2) Review landscape history
3) Summarize activities that potentially affect sediment supply
4) Identify relations between sediment and geomorphic processes
5) Review the landscape and map the watershed
6) Identify hillslope processes
7) Document surface erosion
8) Document mass erosion
9) Assess hydrological processes
10) Identify streamflow changes
11) Analyze channel processes
12) Detect direct impacts to streambanks and channels
13) Summarize problem verification process – recognition of places, processes, and sources
14) Eliminate sub-watersheds or river reaches that are not sediment problems
15) Select sub-watersheds and reaches for further assessment.

The methods outlined below in more detail are those that we have found particularly helpful in the early stages of designing sediment budgets.

3.2.1 Existing Studies and Expert Knowledge

Many watersheds with sediment problems have been part of state priority watershed programs since the 1980s and 1990s, and many have had soil conservation practices implemented, some going back to the 1930s and 1940s with the Soil Conservation Service efforts. These programs had similar goals of reducing and controlling sediment and nutrients. Other studies were geared toward fish habitat. Sediment deposition, substrate particle size, and bank erosion are typically collected as part of state and Federal habitat assessments and, thus, may be helpful in the early design of the sediment budget (Simonson *et al*., 1993; Fitzpatrick *et al*., 1998; Kaufman *et al*., 1999).

3.2.2 Watershed and Stream Network Delineation

In the sediment budget, an outline of the watershed boundary and rivers draining to the outlet need to be delineated. Most often a GIS or web-based tools will be used for these delineations. A watershed is defined as the area of land that drains water, sediment, and dissolved materials toward a common outlet. The USEPA's Watershed Assessment, Tracking, and Environmental Results System (WATERS) (http://www.epa.gov/waterdata/waters-watershed-assessment-tracking-environmental-results-system) builds a stream network and its watershed based on the National Hydrography Dataset (NHD), the National Elevation Dataset (NED), and the Watershed Boundary Dataset (WBD). The integration of these three national datasets can provide the base layers of watershed boundaries and stream networks needed to design a sediment budget study. For smaller watersheds, additional higher resolution datasets may need to be found for delineating sub-watersheds and topographic relief. The basis for the NHD stream network are streamlines on USGS 1:24,000-scale maps. These streamlines form the framework for much of the watershed geomorphological analyses that have been done in the United States over the past 50 years (Leopold, 2006; Fitzpatrick, 2016). The network of channels is likely more complex than shown by the NHD, especially for ephemeral channels in headwaters. A representative stream network is needed to be able to represent the stream lengths to which sediment sources and sinks are applied.

Some exceptions to be aware of when building a stream network and related watershed boundaries are the following:

- In urban areas, storm sewers often transcend topographic boundaries and additional data on storm-sewer networks are needed.
- In arid areas, water is often artificially routed through pipes or canals across topographic divides into adjacent watersheds for storage or supply for agricultural and industrial uses and drinking water supplies.
- Some watersheds contain depressions or closed basins with no surface water outlet, such as kettle ponds in glaciated terrain, karst landscapes, and playas in the arid western United States. These areas are referred to as noncontributing areas by the USGS, meaning they do not directly contribute to surface water drainage.

3.2.3 Land Cover and Physiographic Setting

Identifying and mapping patterns of land cover and physiographic setting are important for identifying possible areas prone to soil erosion. The patterns can also be used to stratify a sampling design for sampling soils for sediment fingerprinting that will be discussed later. For example, areas of bare ground such as unpaved roads and construction sites are important to identify and map. This information can be found in existing GIS coverages, or examination of aerial photographs.

3.2.4 Hydrologic Alterations

When getting to know your watershed, it is important to be familiar with past and current hydrologic alterations that may affect the erosion, transport, and deposition of sediment directly or indirectly by altering runoff or low flow characteristics. These include inter-basin transfers, stormwater and wastewater discharge, tiling, withdrawals, and dams. In addition, it is important to note any downstream alterations that may affect the vertical base level or lateral constriction of the stream. This can include dams and other impoundments. Downstream features can affect upstream sources and sinks of sediment, and many times they are not included in analyses because they fall outside of the upstream watershed area. An example of this is the upstream aggradation effects of a dam (Fig. 11). In an example of the Balsam Row Dam, an impoundment on the Wolf River in northern Wisconsin (Fig. 11), the impounded section with fine-sediment deposition extends for about 3 km upstream of the dam (Fitzpatrick, 2005). However, sedimentation of the coarser portion of the sediment load is along the next 3 km upstream of the dam. A longitudinal profile of water surface and channel bed help to delineate the extent of sedimentation effects upstream of a dam.

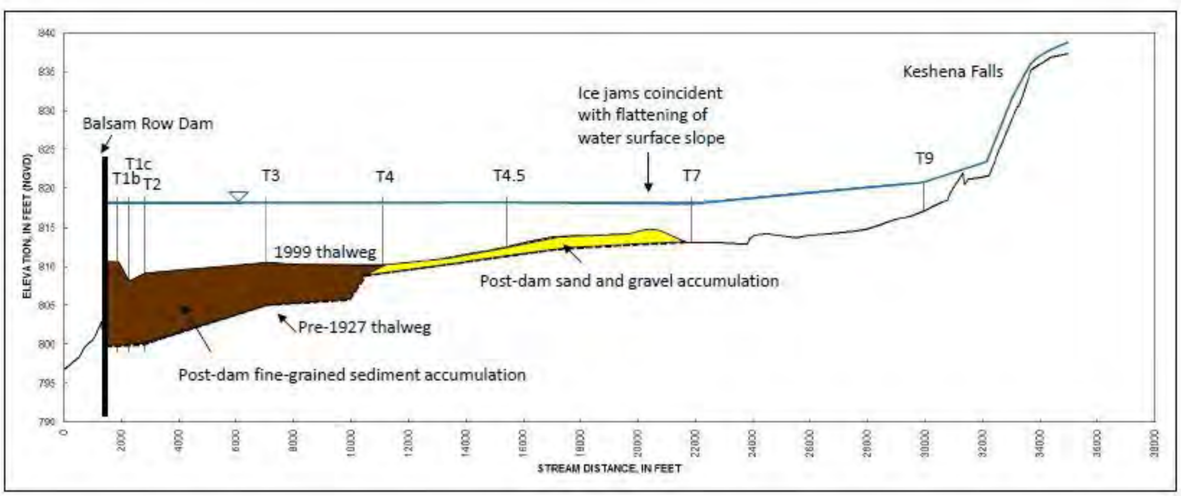

Figure 11. Sedimentation upstream of the Balsam Row Dam on the Wolf River, Wisconsin (from Fitzpatrick, 2005).

3.3. Geomorphic Setting

The next step after becoming familiar with your watershed is developing an understanding of the geomorphic setting of your watershed. This involves how upstream and downstream reaches differ with respect to sediment sources, transport, and delivery.

The fluvial system can be generalized into 3 zones (Schumm, 1977):

- Zone 1 – high up in the watershed, typically an area of erosion;
- Zone 2 – zone of transport; and
- Zone 3 – zone of deposition (Fig. 12).

For the watershed as a whole and in each of the three zones, the geomorphic setting of the stream system can be examined in a planform, longitudinal, and lateral view of geomorphic features and processes. These views of the fluvial system provide important information that is necessary in the construction of a sediment budget.

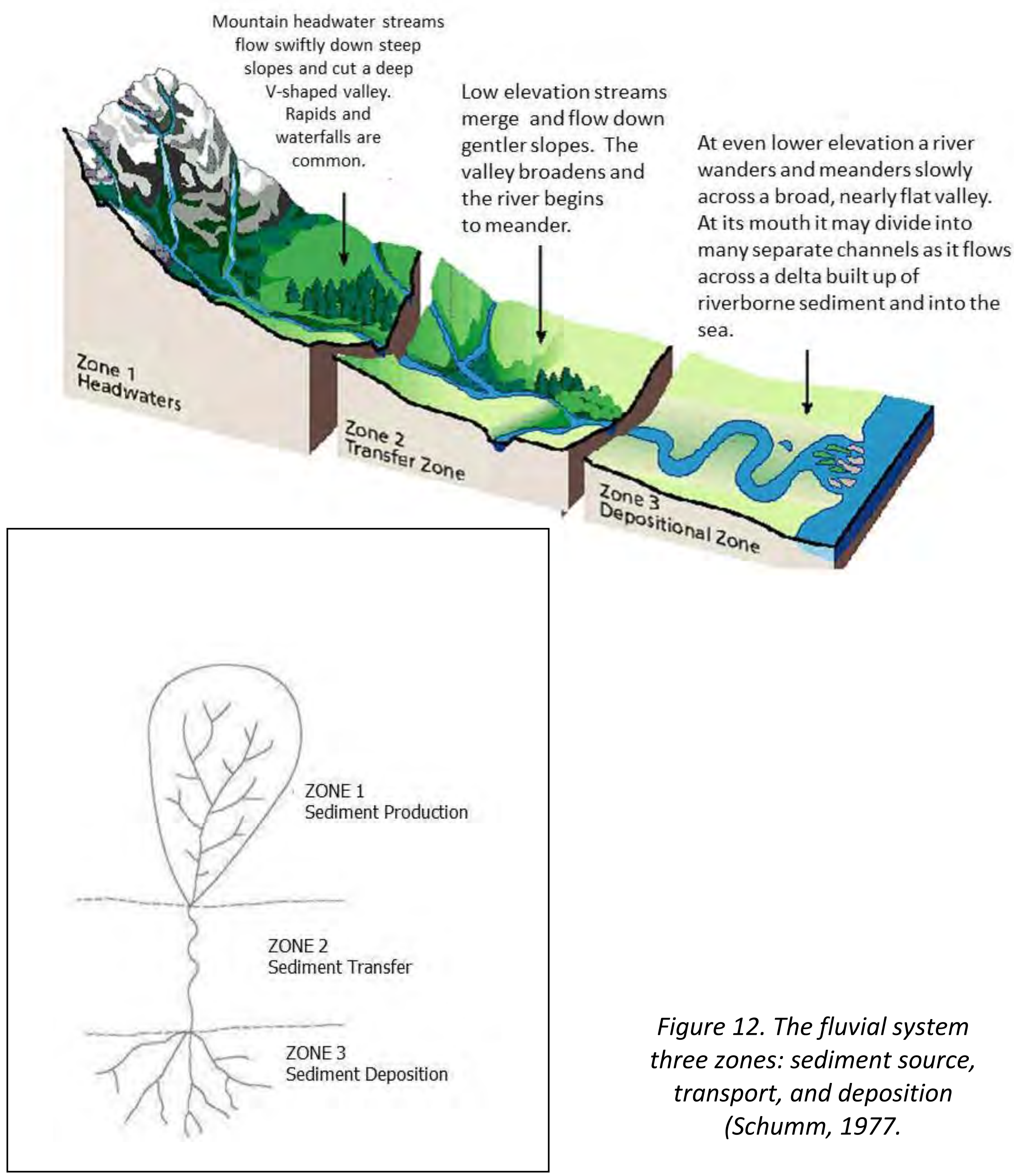

Figure 12. The fluvial system three zones: sediment source, transport, and deposition (Schumm, 1977.

3.3.1 Planform View

The overall setting of the stream planform (looking down from above) relative to the valley is important for describing sediment sources and sinks and how the landscape is connected to the stream (Brierley and Fryirs, 2005). In headwaters (zone 1; Fig. 12), channels are generally in confined valleys where any sediment produced by hillslope erosion or mass wasting is quickly delivered to the stream channels. Headwater channels tend to be steep, allowing for efficient transport and delivery of almost all sediment to downstream areas.

In middle areas of the stream network (zone 2; Fig. 12), stream valleys have widened from zone 1, and it is here that you may see meandering channels with point bars and cutbanks. Channels may still have slopes that efficiently transport sediment from upstream areas. If the meander pattern intersects valley sides (called entrenched valleys), these areas can be major sporadic sources of sediment. Valley confinement or the degree to which the stream impinges on hillslopes and terraces is an important feature of zone 2 that has implications for ecosystem management (Nagel *et al*., 2014). Floodplain areas in zone 2 are irregular but provide information on storage.

Downstream in lowland settings (zone 3; Fig.12), where the meander wavelength is always less than the valley width, streams tend to be more depositional and favor storage of sediment in channels and floodplains. These reaches are usually not sediment sources.

Along the planform view, there may be broad changes in sinuosity and stream planform that reflect sediment dynamics (Schumm, 1977). These are reflective of the relative proportion, particle size, amount of suspended load and bedload, as well as the stream's capacity to transport its load. For example, a stream may switch from a single thread meandering riffle/pool to a straight braided reach, possibly indicating a local source of high sediment supply.

3.3.2 Longitudinal Profile

For a vertical view of channel slope changes that indicate whether the channel is a potential sediment source or sink, it is useful to construct a longitudinal profile along the main stem using the NHD streamlines and topographic contour lines (Fitzpatrick, 2014; Fitzpatrick, 2016). In Fig. 12, most watersheds are described by having steep reaches in the headwaters with slope decreasing downstream. In previously glaciated landscapes with relatively young drainages (less than 14,000 years), the headwaters may be in wetlands with gentle slopes (Fitzpatrick *et al.*, 2015). In either situation, steep reaches may be prone to bank erosion, incision, and direct inputs of sediment from hillslopes and valley sides, whereas gentle reaches may be mostly depositional. In general, a concave-up longitudinal profile reflects steep headwaters and more gentle-sloped mainstem at the watershed outlet. Streams that have concave-up profiles are expected to have consistent increases in discharge and channel size with decreases in slope and bed material size (Gilbert, 1877; Fryirs and Brierley, 2013). In young landscapes, there may be inflections or reaches along the longitudinal profile that are convex. These streams intersect geologically variable terrains and features that may not show up on a surficial geology map. Some common points of inflection are outcrops of erosion resistant bedrock or perhaps an end moraine. Along with the stream planform and valley type, the longitudinal profile helps to form a framework to help guide field inventories and monitoring (Fitzpatrick and Knox, 2000).

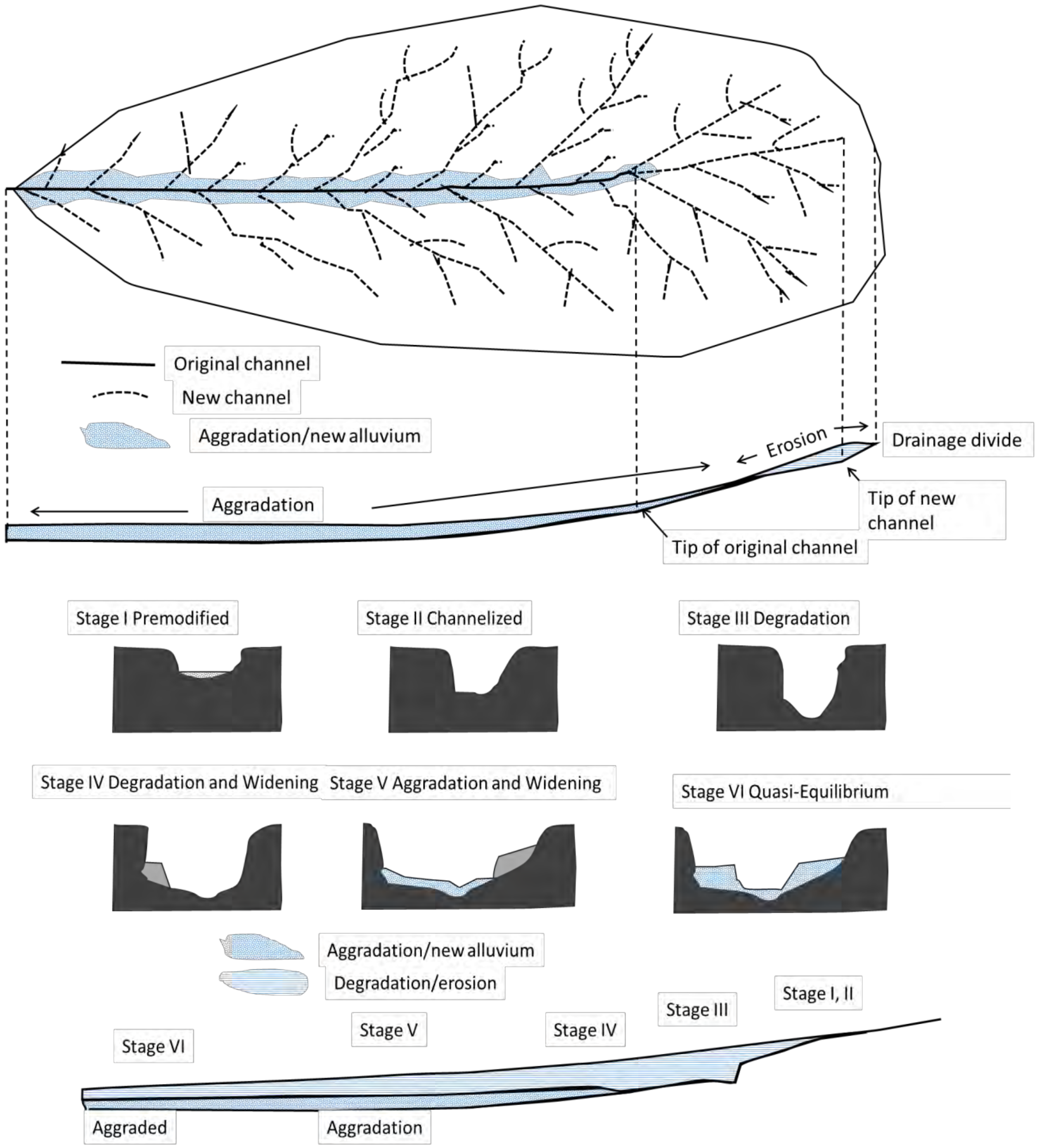

Figure 13. Spatial and temporal changes in stream networks and effects on longitudinal profiles and erosion and deposition: (A) headward expansion of a stream network from land clearing and erosion (modified from Strahler, 1958), (B) Channel Evolution Model, temporal changes due to headward knickpoint migration along channelized streams (from Simon and Hupp, 1986).

The longitudinal profiles can be used to explain the longitudinal continuum of sediment erosion, transport, and deposition over time, especially in situations where there have been changes to the drainage network or widespread channelization (Fig. 13). Channel and floodplain aggradation are common along mainstems that have had drainage network extension (James, 2013) (Fig. 13A). This is typical in agricultural settings with steep uplands where historical gullying has extended the channel network into hillslopes (Happ, 1940; Faulkner, 1988). James (2013) specifically describes how legacy sediment accumulation in river bottoms from anthropogenic-related erosion provides a window into past deposition rates along floodplains and channel margins.

3.3.3 Lateral View

A lateral view of the stream network can provide useful information on the degree of channel incision and channel aggradation. For example, in channelized streams, the channel evolution models (CEM) are helpful for explaining the evolution or trajectory of the vertical and lateral connectivity of sediment-related channel and floodplain processes (Simon and Hupp, 1986) (Fig. 13B). In the CEM, upstream-migrating incision is caused by channelization of downstream reaches. Eventually the incised channels widen and aggrade as incision continues in upstream reaches. Channel and bank erosion are common in Stages III and IV. It is helpful to know the status of stream channels in your watershed along this evolutionary pathway.

3.3.4 Watershed Reconnaissance

After deciding on space and time scales, getting to know your watershed through available data, and identifying broad patterns in geomorphic settings, the next step is to plan a reconnaissance survey of the watershed, stream corridor, and its valley, and further refine knowledge about sediment conditions (Fitzpatrick, 2014). We cannot emphasize enough how one or several reconnaissance surveys of the watershed are needed to better understand sediment conditions and start planning for sediment inventories and monitoring site selection. A car, airplane, or helicopter ride provides a great view of the watershed. A windshield survey can help identify upland features (farms, construction sites, gullies, landslides, etc.) and some channel features (eroding streambanks and incised channels), but car rides often limit you to bridge crossings that may not be indicative of the stream. River walk-throughs are especially valuable in areas of the stream that are harder to get to by roads and, therefore, build upon the watershed reconnaissance.

An example of a form that can be used in a watershed reconnaissance is shown in Fig. 14. Areas of sediment deposition (sinks) may also be noted and included in the reconnaissance (large wide, vegetated floodplains, fans, impoundments) (Fig. 14). Because roads only provide a limited view of the watershed, hiking, boating, or canoeing can provide other ways of viewing the watershed. Examining aerial imagery should be included in the reconnaissance. Speaking to local landowners, county conservationists, and town historians is extremely helpful. You will find that landowners are very knowledgeable of the history of the channel and, if you are fortunate, they may have historical photographs of the channel.

Watershed Name ____________________ Stream Name________________________________

Area Name________________________ Latitude ______________ Longitude ______________Date ______________Time ____________________

Cropland	Pasture	Timber Harvesting	Mining	Unpaved Roads	Active construction	Ditches	Street and parking lot residue	Landslides, mass wasting	Gullies	Burn areas	Lakes and other impoundments	Other

CHANNEL FEATURES

Stream Name ____Reach Name ________________________

Latitude ______________ Longitude ______________________Date _______________Time ____________________

STREAMBANKS					REACH						FLOODPLAIN		FANS
Bank information		Vegetation falling or leaning into channel	Exposed roots	% of reach with Bank slumping, bank erosion	Describe water level (low, medium, high)	Is channel incised?	Dominant sediment on Channel Bed (fines, sand, gravel, cobble, boulders, bedrock	% Presence of soft sediment in reach	% of reach with bars	Average width (left + right)	Type vegetation	Note presence and type of fan
Bankfull Height, m												
Bankfull Width, m												
Terrace Height, m												
Bank Angle, degrees												

Are headcuts present in reach?	% Occurrence of woody debris in reach	Describe human structures present in reach	Is reach transport limited or supply limited?
			______________________________

NOTES

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Figure 14. Example of form used in the reconnaissance of a watershed to assess upland and channel conditions.

3.3.5 Stream Corridor Sediment Sources and Sinks

After the watershed reconnaissance, the next step is to delineate (inventory) sediment sources and sinks along the stream corridor. These can be identified through the approaches suggested above, aerial photographs, maps, reports, and watershed surveys. Stream reconnaissance tools have been developed by many agencies that are very helpful for a rapid evaluation of the stream corridor (for example Thorne, 1993; Kline *et al*., 2004; and Rosgen, 2006). Inventorying sediment sources and sinks along an entire corridor can be done by walking all the drainages in small watersheds (generally less than 10-20 km^2) with overview and supplemental data gathered through aerial photograph and historical map analyses. A short list that helps to remind one who is conducting a river walk of the indicators of geomorphic instability and possible sediment relations is shown in Table 3. An introduction to some of the more common methods used by the authors are described below.

Table 3. Geomorphic Features Identified on a River Walk-Through.

Bank erosion width and height	Bars – length and width
Thickness of soft sediment on the channel bed (length and width)	Recent overbank sedimentation (on surfaces and in bank cuts)
Major changes in substrate texture	Sand deposition on channel bed and floodplain
Bankfull channel width and depth	Channel incision
Overall bank heights	Slope estimate
Bedrock outcrops	Indicators of geomorphic stability
Photographs	Road crossing conditions and slope of road approach
Log jams	Vertical grade controls
Gullies	Mass wasting/valley side failures

3.3.5.1 Aerial Photograph and Historical Map Analyses

Current and historical photogrammetric information (aerial photographs, aerial LIDAR (Light Detection and Ranging) is a useful method to examine your watershed and identify sediment sources and sinks. Geomorphic features and sediment sources such as construction sites, landslides, gullies, etc., can be seen on imagery. These areas can be listed as sites to visit for the watershed reconnaissance.

Depending on the resolution of the aerial photographs and the presence of trees in the river corridor, spatial variations in channel width, along with accounting for valley side and bluff failures, can be assessed. If the river is large enough, the areal extent of non-vegetated bars can also be measured. Field verification is needed for the depth of channel incision.

Quantifying channel location changes over time can be an important component of a sediment budget. Although information on channel changes is not essential in the early stages of reconnaissance, determining where the greatest changes in channels occur can be used to target monitoring sites. This information can also be used in constructing the final sediment budget. Aerial photographs and maps, when overlaid, give a sense of changes in width, length, and location with time. From these changes, estimates of rates of lateral erosion and deposition can be made. Lateral migration rates in meanders can be determined using a comparison of multiple years of aerial photographs. Lateral migration rates are a good indication of the maximum rate of bank erosion. Accompanying field-based ground truthing for heights of erosion or thicknesses of deposition can be added for estimating the total volume of sediment eroded or deposited.

Digital aerial photographs and maps need to be geo-referenced and entered into a GIS using a second-order polynomial transformation, with as many control points as possible. A minimum of 8-12 points are needed to minimize error in geo-referencing (Hughes *et al*., 2006) and keeping track of resolution and accuracy. Combining photogrammetry with maps can also provide a useful method to assess channel change (Donovan *et al*., 2015; Fitzpatrick et al., 1999; Fitzpatrick *et al*., 2009).

Airborne LiDAR is increasingly becoming an important tool to quantify channel morphology and channel change over time (Faux *et al*., 2009; Dietterick *et al*., 2012; Roering *et al*., 2013). LiDAR data can be converted to DEMs, and using a GIS or appropriate software, such as the Forest Service River Bathymetry Toolkit (http://www.fs.fed.us/rm/boise/AWAE/projects/RBT/RBT_lidar_hydro_downloads.shtml), channel morphology can be derived. One powerful application of LiDAR data for erosion prediction is calculating the stream power index for segments along the stream network, using slope and flow accumulation generated from a LiDAR-derived DEM (Nelson, 2010; Danielson, 2013). This index has a major assumption that flow accumulation is proportional to the watershed area (Wilson and Lorang, 1991).

3.3.5.2 River Walk-Throughs

Using the form similar to what is shown in Fig. 14, or a tally in a field note book, the idea is to walk most, if not all, of the stream corridor, accounting for characteristics of the banks, bed, and floodplain (Young *et al*., 2015). A pace of about 10 km a day might be covered, depending on terrain and vegetation. Observations of channel features will assist in identifying reaches of sediment erosion and storage and, again, target sites for monitoring. Photographs and a hand-held GPS are also important. Many of the measurements made in the river walk-through will help in the final construction of the sediment budget.

The general features of eroding banks that are described in a reconnaissance are shown in Figure 15. Figure 16 shows some general guidelines of bank retreat rates. One of the authors has found these rates to be in the ballpark compared to geomorphic monitoring. For example, a small riparian grazed stream in southwest Wisconsin had a bank retreat rate of 4.1 cm/yr, determined through monitoring, which corresponds well with the descriptions of streams in the NRCS category of moderate lateral recession.

River Name: Example River, USA						Date: 5/1/2016		units: (meters) ft		
Field ID	1	2	3	4	5	6	7	8	9	10
General observations, major changes in planform, bedform)	start ds end reach	erosion	log jam	Dep us of log jam	over-bank Sed	bluff erosion	log jam	bar + levee	levee	Soft Sed dep pool
Wetted width	5			7		5				
Channel width	5.6			7		6				
Thalweg water depth	0.2			.5		.3				
Channel depth	1.0			1		1				
Channe bed D50	bo co (gv) sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa (fi)	bo co gv sa fi	bo co (gv) sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi
Soft sediment (L x W x T)	ϕ			100x7 x0.3		ϕ	*			3x2x 0.2
Bar type	(po) ma alt mid trans	po ma alt mid trans	po ma alt mid trans	po ma alt mid trans	po ma alt mid trans	po ma alt mid trans	po ma alt mid trans	po ma alt (mid) trans	po ma alt mid trans	po ma alt mid trans
Bar dimensions (L x W x T)	20x3 x1							20x 5x.5		
Bar D50	bo co gv (sa) fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi
Bank erosion Left or Right (L x H)		15x3 L				500x 20 R				
Bank erosion substrate D50	bo co gv sa fi	bo co gv (sa) fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv (sa) (fi)	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi
Est. Lateral retreat		?				?				
Levee Left (L) or Right (R) (L x W x T)		L 30x2x.3						L 100x 2.5x.4	R 100x 3x 1.0	
Levee D50	bo co gv sa fi	bo co gv (sa) fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv sa fi	bo co gv (sa) fi	bo co gv (sa) fi	bo co gv sa fi
Floodplain overbank sed Left (L) or Right (R) (W x T)					L 40x 0.1					
Floodplain overbank sed D50	gv sa fi	gv sa fi	gv sa fi	gv sa fi	gv sa (fi)	gv sa fi	gv sa fi	gv sa fi	gv sa fi	gv sa fi
Widening										
Lateral migration		X								
Incision										
Knickpoint										
Aggradation				X					X	X
Overbank sed					X					
Impounded										
Log Jam			X				X			
Bedrock outcrop										
Photo	1-5	6-8	7	8	–	9-13	14	15	–	–

Figure 15. River walk-through example field form [D50 abbreviations are: bo = boulders, co=cobbles, gv = gravels, sa = sand, fi = fines; see Table 4 for size breakdown of these sediment categories.

Lateral Recession Rate ft/yr (cm/yr)	Category	Description
0.01-0.05 (0.3 - 1.5)	Slight	Some bare bank but active erosion not readily apparent. Some rills but no vegetative overhang. No exposed tree roots.
0.06-0.2 (1.8 – 6.0)	Moderate	Bank is predominantly bare with some rills and vegetative overhang. Some exposed tree roots but no slumps or slips.
0.3-0.5 (7.0 – 15)	Severe	Bank is bare with rills and severe vegetative overhang. Many exposed tree roots and some fallen trees and slumps or slips. Some changes in cultural features such as fence corners missing and realignment of roads or trails. Channel cross section becomes U-shaped as opposed to V-shaped.
0.5+ (>15)	Very severe	Bank is bare with gullies and severe vegetative overhang. Many fallen trees, drains and culverts eroding out and changes in cultural features as above. Massive slips or washouts common. Channel cross section is U-shaped and stream course may be meandering.

Figure 16. Estimates of lateral recession rates for four degrees of bank erosion (from NRCS, 2003).

Depositional settings that are noted on the reconnaissance form include the floodplain, bars, and in-channel soft sediment accumulation. Soft sediment deposits are defined as sediment that you would sink into and have trouble pulling your boot out from. Fine channel sediment deposits indicate that fine-grained sediment may be important in the system, as it is often these types of fine sediment deposits that cause a river to be listed for impairment. We describe later in the manual how calculating the volume of fine deposits is important. But at this step in the assessment, it is important to identify reaches where fine sediment is present.

Exposed bars of sand or coarser gravel (those with surfaces that are above the low flow water level) can be an important component of sediment transport and aquatic habitat (Pitlick and Wilcock, 2001). Many types of channel bars are recognized in streams (Hooke and Yorke, 2011). Bar area has also been shown to be correlated to sediment flux (O'Connor *et al*., 2014; Fig. 17).

The presence of fine sediment and bars may allow you to make a decision on whether the reach is 'supply limited' or 'transport limited.' A stream is supply limited when it is able to transport all the sediment that is supplied to it; hence, sediment transport is limited by the supply. Transport limited occurs when the sediment supply to the stream is in excess of the ability of the stream to transport it. A channel scoured to bedrock would indicate that it is supply limited, such as might occur below a dam. A channel with abundant bars and soft sediment deposits might indicate that the channel is transport limited.

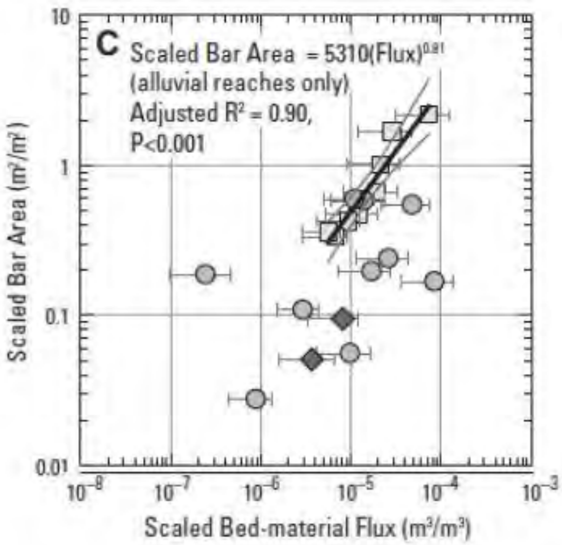


Figure 17. Relation of bed material flux and bar area (O'Connor et al., 2014).

3.3.6 Upland and Hillslope Soil Erosion

Erosion on upland surfaces can occur through sheetwash, rilling, gullying, and mass movements. Many of these features can be observed in a reconnaissance of the watershed and aerial imagery. In the reconnaissance form (Erosion and Storage Factors from Upland Surfaces, Fig. 14), land uses that might be contributing to sediment such as active construction sites, bare fields, logging, mining, dirt roads, and gullies may be worth noting.

Agricultural agencies use a variety of models to estimate soil erosion. The most commonly used model is RUSLE2 (http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm), although there are many others, including tools to help estimate sediment delivery, such as (http://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=76041). Modeling soil erosion can often provide a way to determine the relative contributions of sediment from different subwatersheds. This information can also be used for targeting monitoring sites.

Other features to note in agricultural areas that might not be apparent on GIS land cover or soil maps are dams and irrigation diversions, poor grazing practices, feedlots, and direct drainages to channels. For roads, important features to note are the density, location, number and type of stream crossings, road surfaces, type of drainage along the roads, and any evidence of excessive deposition downstream of a road crossing (Rosgen, 2006).

3.4 Sediment Budget Design and Considerations

At this point in the sediment budget design, the scale of the watershed has been determined, the stream network is defined, and there is an understanding of the geomorphic setting, including hydrology and any hydrologic alterations. The amount of time needed to complete the sediment budget may depend on available funds, available personnel, and how quickly an answer is needed.

Questions that may be asked at this point in the sediment budget design are:

- Is the sediment budget going to be inventory or monitoring based, or both, i.e., is there time to collect data on erosion, transport, and deposition rates?
- What resolution of individual budget components is appropriate, and is it feasible?
- How will the sediment budget results be displayed?
- Is there a need to incorporate management techniques for future projections?

Methods used in sediment budgets are tailored to questions being asked, the time and spatial scales of interest, and available funds and personnel. The steps outlined in Fig. 10 were designed with agricultural watersheds in mind; however, with a little modification and familiarity with the watershed setting, the steps would also work for forested or urban watersheds. Methods for constructing fluvial sediment budgets span disciplines and specialties from soils, geology, hydrology, and engineering. This manual draws from several references and tailors the techniques towards sediment TMDLs. The sediment budget approach is also a watershed approach. Planning and using a watershed approach are summarized in the USEPA (2008) handbook for developing watershed plans. In addition, the following agencies have a history of working with specific aspects of sediment budgets and an inquiry into current references by these agencies on methods may be helpful:

- Upland sources and soil erosion – NRCS (e.g. RUSLE2)
- Landslides – USGS
- Gullies – NRCS
- Bank erosion – NRCS, USDA-ARS, U.S. Forest Service
- Channel bed erosion and deposition, impoundments – USGS, U.S. Forest Service, USACE, Bureau of Land Management
- Floodplain sedimentation – USGS
- Sediment transport (loads, yields) and export – USGS; Forest Service

There are several broad questions that are worth considering at the start of the sediment budget design process. For example, the question ***How detailed should a sediment budget be?*** relates back to the original objective(s) as well as the time frame needed to derive an answer, financial resources, and the scale of the watershed. For example, a sediment budget performed for a large watershed (~2500 km^2) may focus on sediment export measurements from tributaries (Meade, 1994), or involve aerial photograph interpretation of channel erosion and sedimentation. Smaller scale sub-watersheds (<500 km^2) may be identified by geologic setting or land cover (Collins *et al*., 1998) and may involve field measurements and inventories. At any scale, an identification of potential sediment sources is needed, and these may be at different spatial scales along the stream network, in tributaries, and along main stems. Other questions that arise may include: ***Are there particular reaches or a sub-watershed that have high sediment loads?*** and ***Is there a section of stream with intensive grazing?*** These questions are part of the TMDL process.

When working on sediment budgets in Puerto Rico (Gellis *et al*., 2006), the research group noticed termite mounds everywhere. The termites would excavate sediment and place the loose soil on mounds. The research group remarked, "Maybe this is an important sediment source that we overlooked?" When we started our sediment budget analysis, we did a reconnaissance of the study watershed by driving the watershed, conducting an aerial flight, and hiking different sub-watersheds. We were able to qualitatively rank the types of sediment sources, which we decided to be in order of importance from construction, to agriculture (cropland and pasture), to forest. We thus made a decision that termite mounds were probably not an important sediment source.

The Puerto Rico study is a good example of identifying the relative magnitude of importance of various sources and sinks before delving into a detailed monitoring program that only covers a small source or area. We could have spent an enormous amount of time and resources determining how much sediment was supplied from termite mounds, and, in the end, they may have supplied a small percentage to the overall watershed sediment budget. Qualitatively we assumed that because of the small size of a termite mound relative to other sediment sources in the basin (e.g., construction sites), the contributions of termites would be small; a conclusion we could not substantiate. However, if the focus of the study was to budget sediment at the hillslope scale, then quantifying the impact of termites might have been important. Incidentally, termite mounds as a source of sediment has been explored (Dietrich *et al*., 1982). Furthermore, if the termite mounds were a local source of sediment to a sediment transport-limited reach of a channel with important sensitive aquatic habitat, even though contribution to the overall sediment loading is small, the impact to a specific reach may raise its importance in terms of management.

Is there any way to know precisely how important sediment sources are at the start of your assessment? No, not precisely, but qualitatively by getting to know your watershed before you select sampling locations. Know the land cover and get familiar with the local issues, usually concerning upland soil erosion and streambank erosion. Spend as much time as necessary to become familiar with the geomorphic setting of the stream corridor. After conducting a watershed reconnaissance and spending some equally important time looking at the stream corridor, using aerial photograph interpretation, and conducting a field-based river walk-through, you should know if there are key locations of erosion and deposition along the river corridor.

Although no areal or linear coverage of a sediment source is absolute for it to be characterized as an important source, you might choose a threshold of 5 or 10% of the study area or a length of the stream corridor. For upland sources in watersheds with a uniform geologic setting, you might conclude that pastureland covering 10% of the entire watershed area is not worth the effort of monitoring, whereas a construction site or a forest fire that covers 10% of the watershed area may be important. Also, do not only select upland land use sources that are expected to be major contributors of sediment. Land cover types that are not known to be large contributors of sediment may still be of interest, especially if they make up a large percentage of the watershed. For example, it may be important to note that forested areas were measured and erosion rates were low. In Linganore Creek, Maryland, forests covered 27% of the watershed and contributed 3% of the total sediment (Gellis *et a*l., 2015).

Early on in the design of the sediment budget, the sediment size of interest is important. The focus of most TMDLs is fine-grained sediment, which includes clay, silt, and some fine sand (Table 4).These particle sizes are transported as washload in suspension throughout the water column during runoff events (Colby, 1963; Edwards and Glysson, 1999; Rasmussen *et al*., 2009) (Fig. 18). They usually travel at speeds similar to flowing water. The suspended sediment load likely contains mostly washload, usually described as the component that is transported through the stream network rather quickly. In contrast, larger particle sizes usually travel at slower speeds as they bounce along the bottom as bedload (Edwards and Glysson, 1999). Coarse sediment is assumed to be derived mainly from stream bed and bank erosion and mass wasting of valley sides and terrace cuts. However, the stream corridor likely contains fine-grained sediment as well that is eroded from banks, valley sides, and terrace cuts.

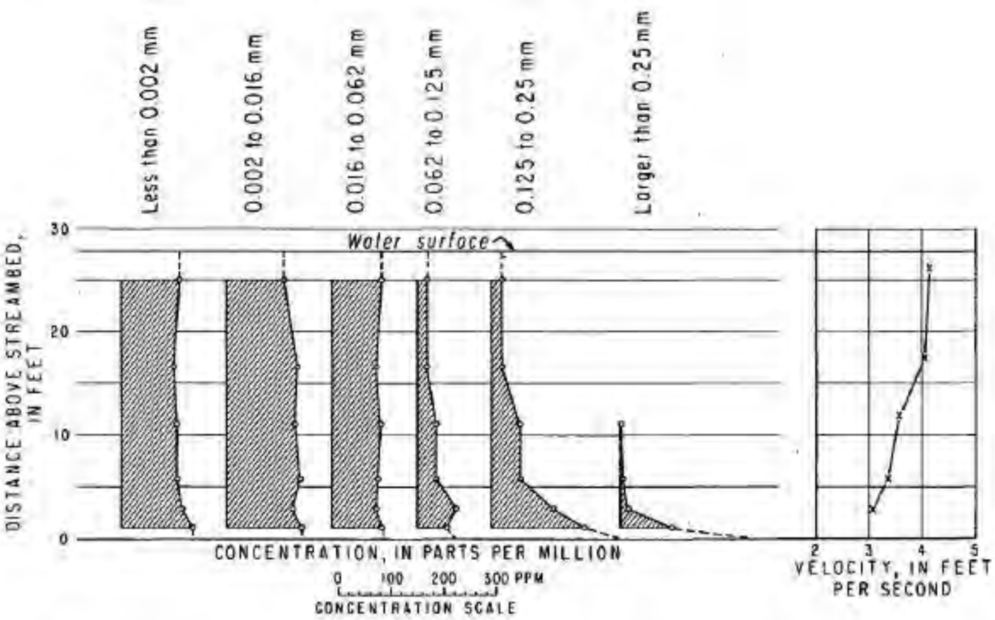


Figure 18. Distribution of the vertical concentration of sediment size classes at the Mississippi River at St. Louis, MO, 1956 (from Colby, 1963).

Sediment classified up to fine sand sizes (0.063 to 0.250 mm) is transported in suspension and as bedload (Colby, 1963) (Fig. 18). These sediment sizes can make up a good proportion of overbank sedimentation from large floods in the form of vertical accretion, alternating with silt and clays; as well as in channel bars. These sand sizes are also in the range of causing burial and scour problems for aquatic life that utilizes gravel and larger stream bed substrates as well as filling scour pools between floods. In areas of the United States with Cambrian- and Ordovician-aged sandstone bedrock, such as the Upper Mississippi watershed, fluvial sediment typically has a large component of fine and medium sand sizes derived from the well sorted uniform fine to medium sands that are common in those bedrock units (Ostrom, 1971; Theil, 1959; Runkel and Steenberg, 2012) as well as silt sizes from extensive loess deposits (Knox, 2006). Lateral accretion deposits, associated with lateral migration in meandering rivers, usually make up a much smaller portion of the post-settlement sediment record than overbank vertical accretion, especially for low gradient floodplains (Bridge, 2003).

Table 4. Standard particle size classes and size ranges used by the U.S. Geological Survey (Lane, 1947; Colby 1963).

Class and subclass	Size range (mm)
Boulder	
Very large boulders	2,048-4,096
Large boulders	1,024-2,048
Medium boulders	512-1,024
Small boulders	256-512
Cobbles	
Large cobble	256-128
Small cobble	128-64
Gravel	
Very coarse gravel	32-64
Coarse gravel	16-32
Medium gravel	8-16
Fine gravel	4-8
Very fine gravel	2-4
Sand	
Very coarse sand	1-2
Coarse sand	0.5-1.0
Medium sand	0.25-0.5
Fine sand	0.125-0.25
Very fine sand	0.062-0.125
Silt	
Coarse silt	0.031-0.062
Medium silt	0.016-0.031
Fine silt	0.008-0.016
Very fine silt	0.004-0.008
Clay	
Coarse clay size	0.002-0.004
Medium clay size	0.001-0.002
Fine clay size	0.0005-0.001
Very fine clay size	0.00024-0.0005

Most TMDL projects concentrate on reducing the suspended sediment load, thus it is important to track the particle size distribution of each component considered in the sediment budget. The focus on the fine-grained component of the sediment load stems from the historical emphasis on soil conservation practices associated with soil erosion from agricultural lands with predominantly fine-grained soils.

Tools and approaches used in a sediment budget can be separated into three categories: 1) sediment inventories, 2) remote sensing, and 3) field measurements (Fig. 10; Table 2). Each of these approaches can be used separately or in conjunction with the other approaches. For this manual, we focus on inventories and field approaches that can be separated into 1) channel and 2) upland measurements (Table 2). Throughout the manual, we provide references related to studies that have used photogrammetry (LiDAR and aerial imagery). Sediment inventories reveal the spatial extents and temporal variability (Fitzpatrick *et al.*, 2009), whereas repeat measurements, such as returning to the channel and upland monitoring sites over a known period, allows for collection of location-specific rates of erosion and sedimentation (Gellis *et al*., 2012,2015). It is helpful to use both repeat field measurements and one time inventorying for a modern sediment budget. Reid and Dunne (1996) provide a text on how to construct a sediment budget quickly using inventorying techniques.

In any approach selected, development of a data-collection plan is one of the most important aspects of a sediment budget. Taylor (1990) defines three types of sampling plans: 1) intuitive based on judgment of the observer, 2) statistical sampling plan of random design to avoid measurement bias, and 3) regulatory that requires data of a given type and frequency. Sediment budgets typically incorporate types 1and 2. For example, intuition may tell you that a large construction site present in a watershed may be an important source of sediment or, as we previously pointed out, that termite mounds may not be important. However, it is understood that without data, whether your intuition is correct cannot be determined. Statistical designs are also important in sediment budgets to assure unbiased measurements over the watershed of interest and that the number of samples collected is adequate. Site selection should be carefully designed to provide reliable assessments of erosion and deposition.

3.4.1 Sample size

An important aspect of any effort to quantify the erosion and deposition of geomorphic features is determining how many samples to collect. Formulas can be used to estimate the sample size needed to produce a confidence interval estimate with a specified margin of error (Schreuder and Ramirez-Maldonado,2004; Singh and Masuku, 2014). For more information on sampling design and sampling size, the reader is encouraged to consult USEPA, 2002, and Artiola *et al*., 2004.

The confidence interval for a given mean (μ) is as follows in a two-sided test:

$$ME = \frac{Z_{\frac{\alpha}{2}}\sigma}{\sqrt{n}} \qquad (4)$$

where ME is the margin of error; σ is the standard deviation; $Z\frac{\alpha}{2}$ is the confidence coefficient and σ is the confidence level (CL). In most cases the CL is 95 or 90%. The confidence coefficient is found by taking (1-CL/100)/2 and finding the appropriate value in a Z Table; found in most standard statistics books. CL values of 95 and 90 have Z values of 1.96 and 1.645, respectively.

By reordering Eq. 1, we can solve for *n*, the number of samples.

$$n = \left(\frac{Z_{\frac{\alpha}{2}}\sigma}{ME}\right)^2 \qquad (5)$$

An assumption made in determining the sample size is that the data are normally distributed. Knowledge of the standard deviation can be obtained from other studies, and the margin of error is decided by the study design. Box 1 provides an example of selecting the number of streambanks to monitor for erosion and deposition.

Box 1. Example of determining the number of sites to monitor in a study.

In this example, the number of banks to monitor for a sediment budget is determined. Based on previous work in Linganore Creek, MD (Gellis *et al*., 2015), the standard deviation of bank change is 6.1 cm. The margin of error selected is +- 2 cm with a 90% confidence level (CL). Using Eq. 3, the number of banks needed is 26. If a margin of error of 1 cm is desired, the number of banks needed is 102, which would demand much greater resources and time.

3.4.2 Use of Sediment Inventories to Construct a Sediment Budget

This section describes the basics for conducting sediment inventories to construct a sediment budget. Sediment inventories usually encompass a one-time visit that covers as much of the stream corridor as possible, whereas monitoring implies repeated measurements at selected representative sites. Inventories involve area or volume measurements of erosion and deposition. Volumes can be converted to mass if the volume-weight conversion or bulk density is measured or referenced (i.e., Chow, 1964) (Table 5). Inventory estimates of erosion and deposition rates are based on literature values or repeat measurements from nearby watersheds with similar physiography and climate. Usually, estimates of erosion and deposition rates are at time scales on the order of decades or centuries where emphasis should be placed on inventorying at spatial scales over several orders of magnitude (Fitzpatrick, 2014).

Table 5. Ranges in dry bulk density for submerged and aerated sediment
[To convert lb/ft^3 to g/cm^3, multiply by 0.016.]

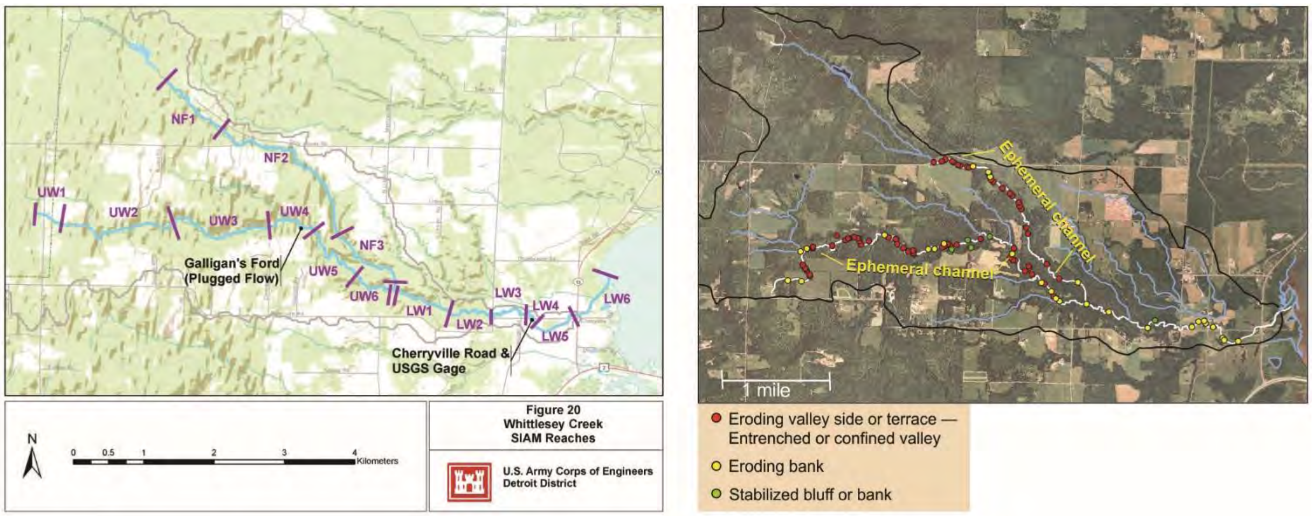
Texture class	**Chow (1954) Permanently submerged (lb/ft^3)**	**Chow (1964) Aerated (lb/ft^3)**	**NRCS (2002) Soils**
Clay	40-60	60-80	65
Silt	55-75	75-85	80
Clay-silt mixtures (equal parts)	40-64	65-85	
Sand-silt mixtures (equal parts)	75-95	95-110	
Clay-silt-sand mixtures (equal parts)	50-80	80-100	
Sand	85-100	85-100	105
Gravel	85-125	85-125	110
Poorly sorted sand and gravel	95-130	95-130	
Fine sandy loam			100
Loamy sand			100
Sandy loam			100
Loam			90
Sandy clay loam			90
Clay loam, silt loam, silty clay, silty clay loam,			85
Organic			22

In typical sediment budget studies, sediment sources and sinks along the stream corridor are often overlooked because management agencies have programs in place that address potentially large upland sources from soil erosion associated with agriculture and urban construction through established conservation and enforcement programs. In many cases, the models that management agencies use to determine sediment sources only include agricultural sources and do not reflect bank erosion processes, such as in the Chesapeake Bay Watershed (Meng *et al*., 2010, Brakebill *et al*., 2010; Shenk and Linker, 2013). Measurements of sediment sources and sinks along the stream corridor are described in detail in previous Section 3.3.5, and Figure 15 shows a field form with a tally that can be kept of the most common sources of 1) banks and bluff erosion and channel incision, and 2) sinks of floodplain and channel bed.

In large watersheds where it is not possible to evaluate the entire stream network, rates estimated in the inventory are applied to processes along specific reaches based on their geomorphic setting and relation to watershed-wide zones of sediment sources, transfer, and accumulation. For stream corridor measurements, the length of stream channel that the rate is applied to is based on the stream inventory. In many instances, the hierarchical order of the stream network, called stream order (Strahler, 1956), is applied (Knox *et al*., 1974; Gellis *et al*., 2015). However, riparian land use, such as grazing, and historical alterations to the channel, such as channelization, can have overriding impacts on channel erosion and deposition that are separate from watershed size and watershed-wide land use. For example, mapping channels in regard to their channel evolution stage (Fig. 13) can be helpful for delineating appropriate stream lengths (Simon *et al*., 2004.)

Whittlesey Creek , a small Lake Superior watershed in Wisconsin with sedimentation problems and important habitat for Coaster Brook Trout rehabilitation, is shown as an example where an inventory style sediment budget was useful for screening potential stream restoration alternatives for a U.S. Fish and Wildlife Service Refuge (Fig.19) (U.S. Army Corps of Engineers, Great Lakes Hydraulics and Hydrology Office, 2010). The study used the U.S. Army Corps of Engineers (USACE) Sediment Impact Analyses Methods (SIAM) model coupled with a HEC-GeoRAS steady state model (Gibson and Little, 2006; Little and Jonas, 2010; U.S. Army Corps of Engineers, Great Lakes Hydraulics and Hydrology Office, 2010) (Fig. 19). The SIAM model tracks sediment transport potential through a stream network by grain size and accounts for the spatial variations in wash load and bedload employing user-defined threshold particle size diameters. The model routes washload continuously through the stream network, but computes differences between bed-material supply and sediment transport capacity. The model is flexible where local sediment sources and sinks can be added on a reach-by-reach basis in addition to loadings from the next upstream reach. For Whittlesey Creek, reach-specified estimates of sediment sources and sinks along the stream corridor were provided by the USGS to USACE by conducting a river-walk-through style inventory. Upland washload from soil erosion was estimated from a drainage-area weighted annual loading from an adjacent stream, North Fish Creek (Fitzpatrick, 1998).

From the inventory, it is immediately apparent that valley side/bluff erosion in upper Whittlesey Creek and the middle section of the North Fork Creek are major sediment contributors, with an order of magnitude higher contribution than upland soil erosion and channel incision. Overbank deposition in lower Whittlesey Creek is an order of magnitude higher than channel deposition, but overall, most of the sediment provided to the stream corridor downstream of the eroding bluffs is transported out of Whittlesey Creek and to Lake Superior. A SIAM model was run for baseline conditions, by which differences in relative sediment transport capacity can be compared on a reach-by-reach basis (Fig.19) or for different management alternatives. For example, reducing peak flows in the upper reaches would reduce erosion and ultimately reduce sediment loads to Lake Superior, but not change sedimentation in lower Whittlesey Creek, where the Refuge and Coaster Brook Trout habitat are located.



		Erosion (tons/yr)				Deposition (tons/yr)		Inventory net erosion minus deposition (tons/yr)	SIAM Potential Local Balance (tons/yr)	SIAM Alternative Reduce peak flows in upper reaches
River	SIAM model reach	upland soil erosion	feeder trib bank/ channel erosion	bank/ bluff/gully erosion	channel incision	overbank sedimentation	channel deposition			
North Fork Creek	NF1	33	22	132	48	0	13	222	-6700	Decrease erosion
	NF2	27	27	717	4	0	3	773	-18000	Decrease erosion
	NF3	11	11	30	0	18	3	32	20000	decrease aggradation
Upper Whittlesey Creek	UW1	52	39	492	58	0	12	629	-3500	decrease erosion
	UW2	11	10	679	29	38	44	647	-400	increase erosion
	UW3	25	6	912	85	112	120	797	-280	No change
	UW4	42	8	586	42	41	45	592	-29000	No change
	UW5	17	12	394	29	81	48	323	23000	No change
	UW6	38	19	196	57	106	54	150	2600	No change
Lower Whittlesey Creek	LW1	47	43	247	0	169	27	141	-52000	No change
	LW2	8	3	14	24	166	15	-132	-2300	No change
	LW3	7	0	6	0	376	34	-397	-2900	No change
	LW4	3	0	21	0	105	21	-102	6000	No change
	LW5	8	0	152	64	230	64	-70	54000	No change
	LW6	4	0	0	0	188	35	-220	6400	No change
Watershed total		333	200	4580	441	1634	537	3383		

SIAM model loads are provided as order of magnitude/relative difference, not actual values
Blue values indicate potential bed aggradation (transport limited)
Red values indicate potential bed degradation (supply limited)

Figure 19. Sediment budget by inventory.

3.4.2.1 Inventorying Upland Sediment Sources for Soil and Gully Erosion

Erosion on upland surfaces can occur through sheetwash, rilling, gullying, and mass movements. Many of these features can be observed in a reconnaissance of the watershed and aerial imagery. Agricultural agencies use a variety of models to estimate soil erosion. The most commonly used model is RUSLE2 (http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm), although there are many others, including tools to help estimate sediment delivery, such as (http://crpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=76041). The RUSLE2 model contains an algorithm to account for some sediment storage, but because the model is applied at a field-by-field scale, it usually overestimates the amount of sediment that is delivered to streams.

Besides modeling, other features to note in agricultural areas that might not be apparent on GIS land cover or soil maps are dams and irrigation diversions, poor grazing practices, feedlots, and direct drainages to channels. For roads, important features to note are the density, location, number and type of stream crossings, road surfaces, type of drainage along the roads, and any evidence of excessive deposition downstream of a road crossing (Rosgen, 2006).

3.4.2.2 Inventorying Channel Corridor Sources

The goals of inventorying channel sediment are to estimate erosion and deposition along the stream network. These sources and sinks are described in the earlier section for river walk-throughs and can be tallied in the field using a form or field book (Fig. 15).

Depositional settings include within channel soft sediment accumulation and bar formation as well as overbanks. For soft sediment and sand deposition that covers the entire channel bed in some reaches, the volume can be calculated by multiplying the thickness by the channel width and length of channel measured during the river walk-through (Fig. 15).

The length and width of eroding banks are measured and the locations are recorded with a GPS. Some general guidelines of bank retreat rates are shown in Fig. 16. One of the authors has found this to be ‘in the ballpark numbers’ compared to geomorphic monitoring. For example, a small riparian grazed stream in southwest Wisconsin had a bank retreat rate of 4.1 cm/yr, which corresponds well with the NRCS category of moderate bank erosion. In contrast, measurements of 13 eroding bluffs along a northern Wisconsin Lake Superior tributary, North Fish Creek, from 1938-1990 had an average retreat rate of 65 cm/yr (Fitzpatrick, 1998). A quick look at bank cuts or measuring the thickness of un-vegetated deposits of sand on a vegetated floodplain surface give some indication of very recent overbank sedimentation following the last flood (Fitzpatrick, 2014). In areas where trees lose their leaves in the fall, new deposition is readily apparent.

3.4.2.3 Valley Cross Sections and Coring

Geological field methods can be employed to construct cross valley and channel diagrams of overbank sedimentation and modern channel elevation compared with historical elevations (Fitzpatrick *et* al., 1999; 2009; Fitzpatrick, 2014). This helps to estimate the volume of overbank sedimentation. If a valley cross section bisects a relict channel and the time of the cutoff is determined, much can be learned about rates of lateral migration and potential bank erosion, as well as rates of incision and aggradation. Cores are collected along the valley transect to determine the thickness and texture of deposition. The valley cross sections are tedious to measure; thus, it is important to know something about the stream network conditions before they are located. It is helpful to locate the valley cross sections throughout the river valley and in different stream orders. These methods are useful for distinguishing modern from historical and natural rates. This technique has been used successfully in Wisconsin for a variety of watersheds where it was determined that post-1830 bank retreat rates were approximately 17 cm/yr compared to 1.4 cm/yr prior to Euro-American settlement (Knox, 1972; Fitzpatrick *et al*., 1999; Fitzpatrick *et al*., 2006).

Helpful guides for collecting and describing terrestrial cores and cuts are the "Soil Survey Field and Laboratory Methods Manual" (Burt, 2009) and the "Field Book for Describing and Sampling Soils" (Schoeneberger *et al*., 2012). The USDA textural triangle and color chart (U.S. Department of Agriculture, Soil Conservation Service, Soil Survey Staff, 1951; Munsell Color, 1975) are used to classify sediment cores for texture and color. Particle size texturing in the field is done using the soil texture classes arranged on a texture triangle (Soil Survey Division Staff, 1993) and grading of texture by rubbing soil between the fingers (Milfred *et al*., 1967). The field descriptions should be as similar as possible to methods used to describe cores collected in liners and brought back to the lab. Of particular importance for sediment budgets is to determine the density of the sediment in order to convert estimated volumes to mass.

Buried soils (paleosols) are commonly found in floodplain deposits and are indicators of past stability in floodplain surfaces (Happ *et al*., 1940; Birkeland, 1984; Retallick, 1985; Fenwick, 1985; Bettis, 1992). Floodplain surfaces are typically subject to local erosion and widespread deposition. Buried floodplain surfaces may be observed as a thin, dark organic-rich zone caused by an accumulation of decomposing organic matter on the floodplain surface. In humid temperate climates, a stable floodplain surface with a relatively slow or negligible sedimentation rate will have a dark organic-rich deposit at the surface, similar to what is found on pre-settlement floodplain surfaces (Knox, 1987). Episodic sedimentation events are noted by deposits of lighter colored sand or sandy loam deposits over dark fine deposits, indicating a change in the rate of fluvial deposition (James, 2013). Besides being lighter in color and sandier, post-settlement alluvium tends to be less compacted compared to its pre-settlement counterpart. Recent fluvial deposits tend to have prominent stratified bedding representative of vertical accretion (settling of suspended sediment) and lack soil development on the floodplain surface compared to presettlement deposits (Knox, 1987). Other landforms that are depositional and represent sediment storage areas are levees, alluvial fans, and crevasse splays (Vanoni, 2006).

Buried channels are notable in cores by the presence of very coarse sand, gravel, cobbles, or boulders that show up in bank exposures as lenses of coarse grained material similar to the width of the modern channel (Bridge, 2003).

3.4.3 Field Measurements in the Construction of a Sediment Budget

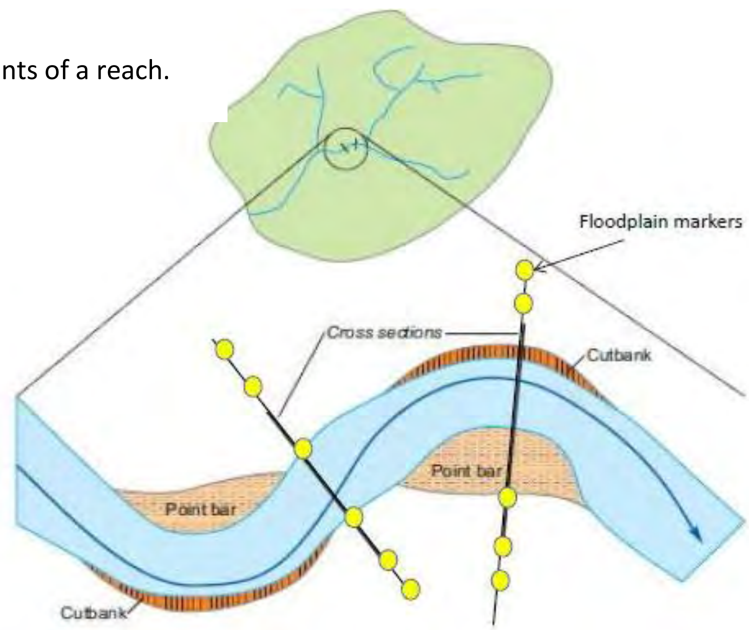
This section describes field measurements used in a sediment budget to quantify the input, storage, and export of sediment (Eq. 1; Table 2).

3.4.3.1 Stream Corridor Measurements

Elements in the stream corridor that are examined for change over time include: the floodplain, channel banks, channel bars, and the channel bed. Many approaches exist in the literature to measure or estimate channel change (Table 1). Most field approaches involve estimating a change at a point (linear) and interpolating to the next point or to a series of points to obtain a cross-sectional change (Fitzpatrick *et al*., 2005). By extrapolating between cross sections, a volume can be obtained. The process can be automated with a GIS or other computer application tools such as WinXSPRO, a channel cross-section analyzer developed by the U.S. Forest Service Stream Team (http://www.stream.fs.fed.us/publications/winxspro.html).

A watershed is comprised of many kilometers of stream channels of varying stream order (Strahler, 1957). Sites to measure channel changes can be organized around a reach (Fig. 20). Reaches are often defined from one meander loop to the next meander and incorporate floodplain, streambank, streambed, and bars. Although a reach can be heterogeneous, containing a riffle, glide, and pool, other aspects such as riparian land use and land use history, human alteration, and distance from nearest vertical grade control should be similar.

Figure 20. Elements of a reach.



Selection of the number of reaches to measure channel change may depend upon the time frame of the study, budgets, and field reconnaissance (e.g. Fitzpatrick *et al*., 2005). To capture spatial variability, stream channels of varying contributing areas should be monitored. Monitoring by stream order can in part fulfill this objective. In most watersheds, 1st order streams comprise the majority of stream lengths. However, bank heights in 1st and 2nd order channels may be low and the propensity for contributions of streambank sediment limited. Thus, the practitioner has to face a subjective choice of weighting the number of reaches for monitoring based on stream lengths of each order (Box 2) or selectively choosing the number of reaches for each stream order. Although the selection of reaches for monitoring should be as unbiased as possible, it is recognized that other factors may be involved in site selection, such as owner permission or a site of extreme importance or interest. In the example shown in Box 2 for Linganore Creek, MD, the final reach selection was based on the field reconnaissance and not by the length of each stream order. A reconnaissance in Linganore Creek indicated that lower order streams showed little evidence of erosion whereas higher order streams showed higher and steeper banks and thus, more potential for erosion. Although 1st and 2nd order streams had the greater total length of streams, a decision was made to include more streambanks in 3rd to 5th order streams (Box 2).

Once the number of reaches to monitor streambank change is determined, there are two approaches to choose the locations for monitoring: 1) a random design, and 2) a regularly spaced design. In a random design, the stream network is rasterized or gridded and individual cells are selected randomly using a random number generator (Box 3). In a regularly spaced design, reaches are selected on a regular basis, such as every 5 kilometers. Using either approach, after reaches are selected, a reconnaissance of the area will be needed to determine whether this is an acceptable site for monitoring as well as to obtain landowner permission.

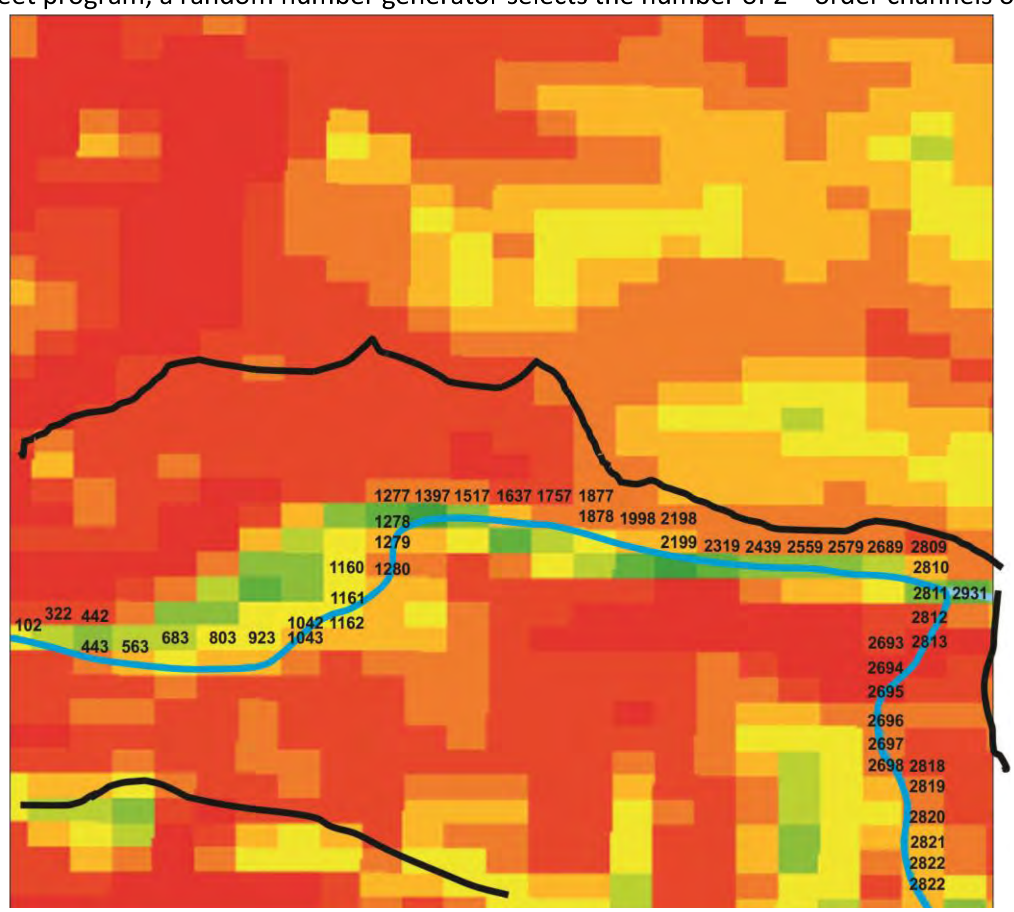
Box 2. Example how reaches were selected for streambank monitoring in Linganore Creek, MD (Gellis et al., 2015).

Linganore Creek is a 5th order stream. The length of each stream order is divided by the total length of rivers to get a weighting factor for each stream order. The weighting factor is multiplied by the total number of reaches that will be used to monitor streambank change (n = 50) to obtain the number of reaches that will be monitored for that stream order. However, based on the field reconnaissance in Linganore Creek, it was decided that the potential for erosion was greater in 3rd to 5th order channels, and the number of reaches selected for the study was increased for these stream orders.

Stream Order	Length (km)	Weighting factor	Number of reaches selected based on a total of 50	Final reaches selected
First	134.4	0.58	29	9
Second	47.6	0.20	10	8
Third	37.7	0.16	8	17
Fourth	7.3	0.03	2	7
Fifth	6.0	0.03	1	9
TOTAL	232.9	1	50	50

Box 3. Example of rasterizing the stream network to choose reaches for monitoring.

In this example, a hypothetical portion of the stream network showing two 2nd order streams is shown. The second order streams are gridded into 10 m by 10 m cells. In the GIS, an ID number is assigned to each cell. All 2nd order cells and their corresponding ID numbers are exported into a spreadsheet program. Within the spreadsheet program, a random number generator selects the number of 2nd order channels of interest.

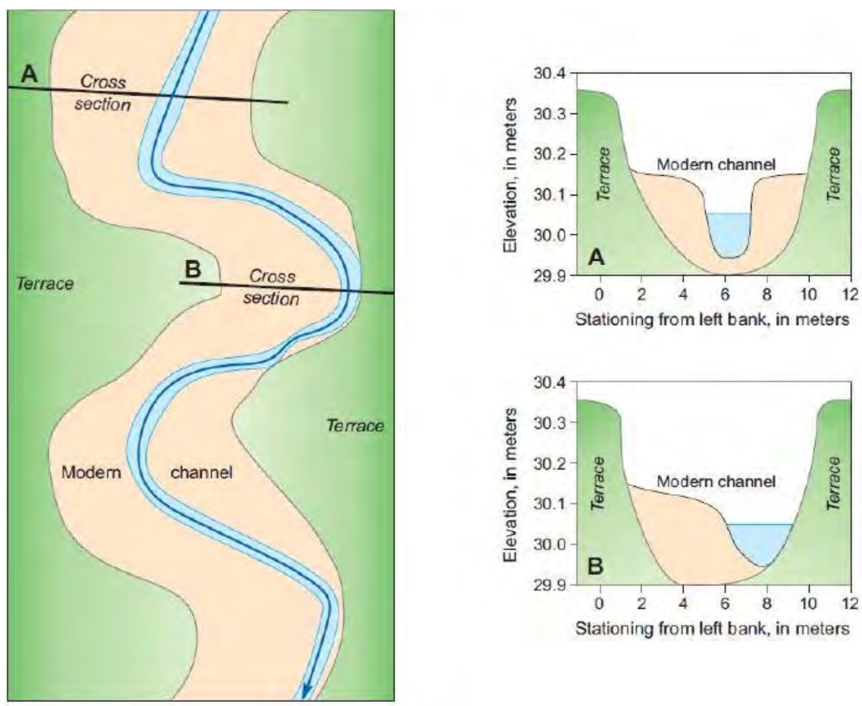


3.5.2.1 Bank, terrace, and valley side erosion

Bank erosion has traditionally been monitored through placement of bank erosion pins. Pins of varying sizes and materials have been used, generally with pins ranging between 50 to 100 cm lengths and 0.5 to 1.0 mm widths on smaller streams (Peppler and Fitzpatrick, 2005; Bartley *et al*., 2008; Gellis *et al*. 2015). The pins are hammered into a bank, and a small portion is left protruding out of the bank (3.0 to 7.0 cm). The number of pins on a streambank is related to the height of the bank. A general rule is to install one pin for every 40 cm of height; for example, a 100-cm high bank would have three pins. Pins can be placed at equal intervals, or if a stratigraphic unit is of interest, pins may be placed at unequal intervals on the bank face.

Pins should be located on both sides of the stream opposite to one another. One side of the stream may contain a steep eroding bank (cutbank), whereas the other side may be a gently sloping bank or contain a bar (Fig. 21). If only the eroding side of streambanks are selected, the sediment budget would be biased towards greater rates of erosion.

Figure 21. Diagram of meandering channel and terrace line. At cross section A, the terrace is not impinging on the channel. At cross section B, the channel left bank has eroded into the terrace.



Pins are measured when installed and at selected times thereafter. The time between measurements may vary depending on the objectives of the study and how the erosion and deposition rates vary over time. For example, if the objective is to understand how storm events affect deposition and erosion, then pins would be measured after individual storms. If the objective is to understand how seasonality affects channel change, such as freeze-thaw activity during winter months, then pins would be measured seasonally. In general, it is common to measure pins annually over the course of the study period. However, if erosion rates are high (~ 1 m/yr), pins may erode out of the banks and be lost. High deposition rates may cause a similar problem where pins are buried and cannot be located. In settings of high erosion and deposition, pins should be read as frequently as every 6 months.

Box 4. Example of how erosion and deposition rates are determined for a bank face.

In this example of a hypothetical bank, pins were installed on the left bank on March 1, 2010 and measured three times thereafter. Pins were placed at equal distances apart (35 cm). The average change for the entire bank face is determined after each measurement. The final change in the streambank is the sum for each measurement, in cm. The total change (net change) for the streambank is multiplied by the bank height (shown here as 1.4 m), resulting in a change in cross–sectional area (cm^2). Average annual change is computed as the total change in the streambank (cm or cm^2) divided by the number of days of monitoring (shown here as 570 days) and multiplied by 365.25.

	Installation reading, cm 3/1/2010	Measurement on 8/14/2010	Reset on 8/14/2010	Change from previous measurement, cm	Measurement on 4/21/2011, cm
Pin 1 at 17 cm	7	21	6	14	21
Pin 1 at 42 cm	6	18	8	12	31
Pin 1 at 79 cm	9	13	no	4	19
Pin 4 at 114 cm	10	6	no	-4	9
Streambank average				6.5	
	Reset 4/21/2011, cm	Change from previous measurement, cm	Final measurement on 9/22/2011, cm	Change from previous measurement, cm	Total change for study period summing changes for each pin, cm
Pin 1 at 17 cm	4	15	18	14	43
Pin 1 at 42 cm	8	23	22	14	49
Pin 1 at 79 cm	7	6	15	8	18
Pin 4 at 114 cm	no	3	12	3	2
Streambank average		11.75		9.75	28
Pin	Number of days of study	Total change for study period for each pin, cm/day	Average annual change for study period by averaging all periods, cm/yr	Average annual change, cm^2/yr	
17 cm	570	0.075			
42 cm	570	0.086			
79 cm	570	0.032			
114 cm	570	0.004			
Streambank average	570	0.049	17.9	2512	

The amount of erosion and deposition on each pin is the difference from the current measurement to the previous measurement (Box 4). Changes for a bank face are estimated by averaging all changes in the pins (Box 4). If the pins are placed at unequal intervals, then weighting the pin readings by the distance each pin represents may be favorable (Box 5).

Box 5. Example of determining streambank change where pins are placed at unequal distances on the bank face.

Example using the same bank in Box 4 but where the pins were placed at unequal divisions on the bank. The pins are weighted by the length of bank represented by each pin. The total bank length is 140 m. Positive values for streambank change indicate erosion.

	Pin location from top bank, cm	Length of bank represented by each pin, cm	Weight	Total change over time, cm	Weighted change	Average annual change, cm/yr
Pin 1 at 10 cm	10	25.5	0.1821	0.075	0.0137	
Pin 1 at 41 cm	41	35.0	0.2500	0.086	0.0215	
Pin 1 at 80 cm	80	36.5	0.2607	0.032	0.0082	
Pin 4 at 114 cm	114	43.0	0.3071	0.004	0.0011	
Streambank average				0.049		16.3

All streambanks in a reach are averaged to get a reach-averaged change. Since dates of streambank measurements may vary from one reach to another, or even for the same reach, measurements are normalized by the amount of days between measurements to obtain a change per day (cm/day) (Box 5). The reach averaged change is multiplied by 365.25 to get an average annual change (cm/yr).

In many studies, streambanks are measured several times during the course of the project. Changes in streambanks between resurveys are termed gross changes, and for the entire study period are termed net changes. Typically, it is the net rate of change (cm/yr) that is of interest (Boxes 4 and 5). In some cases, large storms may occur during the measurement period and interim rates of change (gross change) may be of interest.

In a sediment budget, channels are typically grouped or classified. Classification can include stream order, land use, geology, contributing area, or some other factor that may represent the variability in channels. Box 6 illustrates how changes in streambanks for a given stream order can be converted into a mass change (Mg/yr). It is important to note that because there are streambanks on either side of the channel, the final mass change is multiplied by 2.0.

For large valley side failures and terrace cuts, ground-based LiDAR can be used. This technique is becoming increasingly popular because of the ease of measurement and quantitative results (Collins *et al*., 2008).

Box 6. Example of how to convert streambank measurements at the reach scale (cm) to a mass (Mg) for first order streams.

Rates of streambank change were obtained from Gellis *et al*. (2015) for Linganore Creek, a 147 km^2 agricultural and forested watershed in Central Maryland.

Stream order	Reach ID	Date from	Date to	Total days	Number of banks measured in reach
1	A	3/27/2009	12/23/2010	636	2
1	B	3/27/2009	3/16/2010	354	2
1	C	3/30/2009	11/8/2010	588	1
1	D	6/1/2009	12/21/2010	568	3
1	F	7/22/2009	11/3/2010	469	4
1	G	5/1/2009	11/3/2010	551	4
1	H	3/24/2010	11/8/2010	229	6
1	I	5/8/2009	12/22/2010	593	2
1	J	10/15/2008	12/29/2009	440	3

Why no reach "E" in either of these tables? Why are numerous columns blank in table below?

Reach ID	Average net erosion of bank (cm^2/day) (+ = erosion)	Margin of error 90% confidence level (cm^2/day)	Density of streambanks (g/cm^3)	Length of channels (km)	Mass (kg/day)	Mass (Mg/year)
A	1.67		0.83			
B	-0.14		1.81			
C	-0.32		1.56			
D	-0.08		1.19			
F	-0.03		0.98			
G	0.00		0.96			
H	0.74		1.21			
I	0.48		1.40			
J	-0.22		1.08			
AVERAGE	0.23	0.12	1.22	122	6971	2546

3.5.2.2. Incised Channels

When performing sediment budgets in watersheds containing incised channels, a decision on which streambanks to monitor should be made. If terraces are found to be a distance away from the active channel (Fig. 21), they may not be monitored. In other cases, the active channel meanders into the older deposits and the terrace is in proximity to the active channel (Fig. 21B). In these cases, the terrace deposits may be eroding and supplying sediment to the channel. A decision on whether to monitor banks where terrace deposits may be contributing sediment to the active channel may be made after a reconnaissance. For example, if after a reconnaissance on watershed sediment sources, only 10% of the channels appear to have terraces contributing sediment, terraces may not be monitored. If 50% of the streambanks appear to have contributions from terraces, then these banks might be part of the monitoring program. In other settings where the channel is incised, such as in urban channels, the entire streambanks are usually monitored.

3.5.2.3 Channel Cross Sections

Surveys of the channel cross section can be used to monitor changes in the channel bed, bars, and banks (Harrelson *et al*., 1994; Peppler and Fitzpatrick, 2005; Gellis *et al*., 2012; Moody and Meade, 2013). Similar to bank pins, at least two channel cross-sectional surveys are established in a reach. Steel pins are established on either side of the cross section, vertically into the ground, and a tape is stretched between them. Pins can vary in length from 2 to 4 ft and 1/2 to 1 in. in diameter. The pins also become permanent monument markers to establish elevation control over time. Instruments used to survey the cross sections can include survey levels, total stations, or GPS units.

Each reach contains several cross sections where bank pins are installed. The number of cross sections selected for monitoring may depend on the heterogeneity of the reach. Variability is a factor in channel erosion and deposition, and the more cross sections that are monitored will provide a better understanding of erosion and deposition.. It is recommended that at least two cross sections are installed in a reach.

The distance between cross sections in a reach can be a function of

$$\text{Spacing} = nW$$

where W is bankfull width and n is a number usually between 3 and 20 (Harrelson *et al.,* 1994).

The zero point on the cross section is usually on the left side or left bank of the channel. The left bank is defined looking in the downstream direction on the left side. The channel survey proceeds across the cross section noting the station and elevation. Survey points occur at a regular spacing and at breaks in slope. A simple rule for regular spacing of survey points is to divide the total cross section by 10 and round down. A 42-m channel cross section would have a survey point shot every 4.0 m. The first shot is half this distance (2.0 m) and then every survey point afterwards is 4.0 m. If a break in slope occurs outside of this regular spacing, these points are also surveyed. On resurveys, the tape is stretched to the same width as in the initial survey. The same spacing is used, but the breaks in slope may change. For explanations on how to survey and calculate elevations, see Harrelson *et al*. (2004). Channel changes interpreted from the resurveys include changes in the total cross-sectional area of the channel, changes in top width, depth, channel bed, bars, and streambanks (Fig. 7A).

One choice that arises in channel surveys is how wide the cross-section survey should be. In general, the novice usually ends the cross sections too soon. The cross-section end points are established a distance away from the streambank to avoid them from being lost to erosion. Ideally, a cross section stretches from the edge of the floodplain or terrace on the left bank to the edge of the floodplain or terrace on the right bank. The edge of the floodplain or terrace may be distinguished by a break in slope, change in vegetation, or a change in soils. At a minimum, a channel cross section should extend into the floodplain, two channel widths on either side of the channel in order to incorporate depositional features from overbank flows, such as levees. In larger rivers, the edge of the floodplain on either side of the river may stretch for a considerable distance (100s' meters). In these cases, the width of the cross section may be shorter and floodplain tiles are used to quantify deposition installed away from the cross-section endpoints.

For large rivers that are too deep to wade, bathymetric surveys can be conducted and joined together with topographic surveys (Fitzpatrick, 2014). Acoustics devices are becoming increasingly popular for bathymetric surveys; recent methods are outlined in Lee (2013).

3.5.2.4 Channel Bars

Changes in channel bars can be determined from cross-sectional surveys or by using pins. Cross-sectional surveys measure a cross-sectional change, and pins measure a linear change. Unlike streambanks, bars are intermittent and may not appear throughout the stream network. Therefore, a separate inventory of bars should be made (Box 7).

Box 7. Example of how bar lengths are estimated for a given stream order.

In this example for a hypothetical stream, a tape was laid out at each monitoring reach. The length of bar present within the tape length was noted. The percent of lengths was averaged for each stream order. This example is from Difficult Run, VA, an urban watershed (Gellis et al., In Press).

	Stream order	Length of tape used in bar survey, m	Total bar length, m	Average bar width m	Percent of reach containing bar	Standard deviation
A	1	50	4.0	0.442	8.0	
B	1	50	6.3	0.597	12.6	
C	1	50	12.5	0.641	25.0	
D	1	50	14.4	0.521	28.8	
Average 1st order					**18.6**	9.9
E	2	63	24.8	1.098	39.4	
F	2	200	29	1.162	14.5	
G	2	50	7.7	0.4572	15.4	
Average 2nd order					**23.1**	14.1

If pins are used to record changes in bars, the average change in the pins can be multiplied by the average bar area (m^2) to obtain a volume (m^3). If a survey is used, the cross-sectional change in the bar can be multiplied by the average length of bars to obtain a volumetric change (m^3). The volumetric change (m^3) is multiplied by the bar density (g/cm^3) to obtain a mass (Mg).

3.5.2.5 Floodplains

Floodplains are important areas of sediment storage (Ross *et al*., 2004; Hupp *et al*., 2008). Floodplain deposition can be quantified in a sediment budget using artificial markers (Kleiss, 1993; Hupp *et al*., 2008; Gellis *et al*., 2015), dendrochronology (Hupp, 2000), surveys (Curtis *et al*., 2013) and radionuclides (Kleiss, 1993; Amos *et al*., 2009; Golosov and Walling, 2014).

Artificial marker layers (clay pads, tiles) have been used to monitor floodplain deposition in sediment budgets (Schenk *et al*., 2012; Gellis *et al*., (2015). Markers are laid out on a tape along a cross section that may or may not be surveyed. Clay pads are powdered white feldspar clay laid on the floodplain approximately 20 mm in thickness and placed over an area of ~0.5 m^2. The clay becomes a fixed plastic marker after absorption of soil moisture that permits accurate measurement of short-term net vertical accretion above the clay surface (Ross *et al*., 2004; Gellis *et al*., 2009). Square tiles (8 x 8 cm) made of porcelain or terracotta are used in a similar fashion to clay pads but have the advantage of being a solid surface. A small hole is dug in the floodplain and filled with cement, and the tile is laid in. The number of tile laid out on the floodplain depends on the floodplain width. Sedimentation rates are highest near the channel margin (Simm and Walling, 1998), and markers may not be evenly spaced, where more floodplain ,markers are placed near the edge of the channel.

During or at the end of the study period, the clay pads are examined for depth of burial. Depth of burial for clay pads is measured by coring the ground surface through the clay pads and measuring the vertical depth of sediment above the artificial clay layer. For tiles, a ruler is used to measure the surface of the tile to the ground surface. Cores of the deposited sediment over the clay pads are used to determine floodplain density. For tiles, the entire mass over the tile is sampled and weighed to determine the floodplain density.

Determining a mass of deposition is similar to the method used for streambanks (Boxes 4 and 5). A deposition rate for each floodplain cross section can either be averaged using all markers or weighted by the distances between markers (similar to Box 5) and multiplied by the width of the floodplain (m) to estimate a cross-sectional area of deposition (mm^2). To get a reach average rate of deposition, the cross-sectional area of deposition for all cross sections is averaged and divided by the measurement period (mm^2/d). All reaches in a given classification (e.g., stream order) are averaged and multiplied by the stream lengths to produce a volume (m^3/day). The volume is multiplied by the average floodplain density to arrive at a floodplain deposition mass (Mg/day) and multiplied by 365.25 to get an annual deposition rate (Mg/yr).

3.5.2.6 Measurements of Density

Measurements of sediment density (g/cm^3) are necessary to convert volumetric change (m^3) to a mass (Mg). This should be done for all components that are measured as part of the sediment budget, whether above or below the water surface. Density can be obtained by taking cores of the channel feature with a coring device.

For sediment sampling above the water surface, such as for banks or bar deposits, a field core sampling tool is used to drive a cylinder into the ground (Lichter and Costello, 1994; USDA Forest Service, 2005). Cylinder size will vary depending on the material being sampled. Fine-grained to sandy streambanks can be cored using metal cylinders 8 to 12 cm in length and 4 to 6 cm in diameter (Gellis *et al*., 2015). Coarser material, gravel and cobble, require wider cylinders (>10 cm) and varying lengths (>10cm). The cylinders are pushed into the material, and the core is extruded. The core is dried and weighed, and the dry mass of the sediment is divided by the volume of the core cylinder to obtain dry bulk density (mass/volume). Although density is a relatively simple measurement, it is hard to obtain samples without compacting the sediment. Therefore, care must be taken when driving the cylinder into the bank. The USDA Forest Service (2005) describes the impact-driven core sampler that is used to collect a known volume of soil with a minimum of compaction and disturbance. A density measurement should be made for each geomorphic element at each reach. To account for variability, it is useful to take several measurements at the same location.

For submerged sediment in the channel bed, such as soft sediment deposition, a core tube with a known diameter and length is carefully pushed into the deposit. Clear water is poured off the top of the tube and the vertical length of the core recorded before storing the sample in a plastic container. Back at the laboratory, the wet sample volume can be measured and checked against the field measurement of core penetration. The wet and dry samples are weighed to obtain dry bulk density. Density of soft sediment can be quite low because of the high water content. For example, in the Driftless Area of southwest Wisconsin, soft organic rich sediment in a small agricultural stream had a bulk density of 0.8 g/cm^3 or 50 lb/ft^3.

For general inventories and order of magnitude comparisons, general guidelines are provided in Table 5 for volume-to-weight conversions for dry and wet deposits with variable textures (Chow, 1964).

3.5.4 Upland Measurements

This section describes field techniques to measure erosion and deposition on upland land elements, including contributions from roads.

Similar to selecting reaches for stream channels, a random design should be used for the selection of upland sites to determine upland erosion and deposition. Using a GIS, polygons of a given land use type can be rasterized and a random generator used to select pixels (Fig. 22). Dirt roads that are linear features can be treated as stream channels, rasterized, and pixels selected at random. It is understood that in some cases there are upland areas that warrant monitoring as determined from the field reconnaissance or from knowledge of the watershed. For example, perhaps a select land use drains immediately adjacent to an ecologically well-functioning stream reach that needs to be monitored.

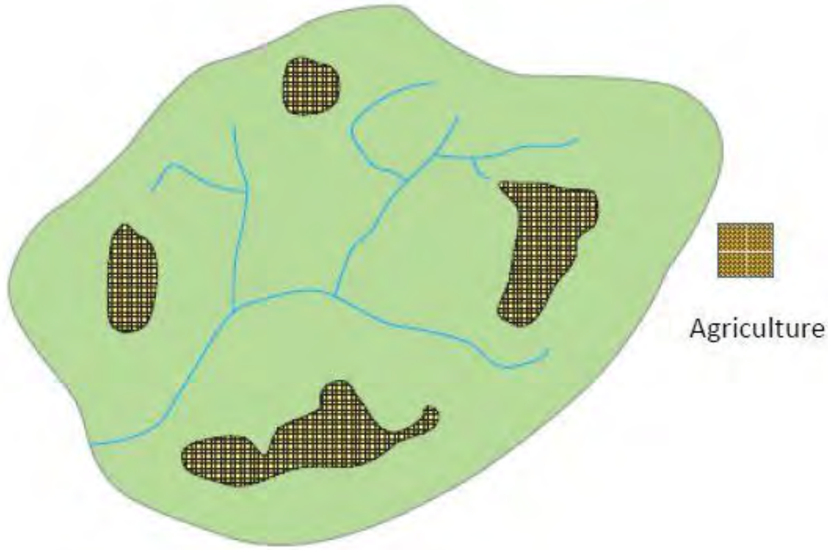


Figure 22. Example of selecting upland areas for monitoring of erosion and deposition. In this hypothetical watershed, areas in agriculture are shown and rasterized. Each cell is numbered and either in a GIS or spreadsheet, cells are selected randomly.

3.5.4.1 Unpaved Roads

Unpaved roads can be important sources of sediment (Reid and Dunne, 1984, Ramos-Scharrón and MacDonald, 2005). Similar to channels, monitoring of unpaved roads is accomplished by selecting reaches throughout the road network to capture the spatial variability. Measurements of unpaved roads over time at each reach can be accomplished with level surveys if erosion is expected to be greater than the precision of level surveying (generally +-0.02 ft). If finer measurements of erosion and deposition are needed, erosion bridges can be used (Ypsilantis, 2011). An erosion bridge is an aluminum or metal board that is placed level across two rebar. The width of the bridge can vary depending on the width of the feature being measured. The rebar should be at least 4 ft in length and hammered into the ground so when the erosion bridge is place across the rebar it is level. The bridge has 10 equally spaced openings across its length where a measuring pin is inserted. The measuring pin is ruled in millimeters and is a length of 2 ft. Because freeze/thaw activity can cause movement of the pins, the elevation of each rebar is surveyed relative to a stationary benchmark monument. The benchmark can be a plate cemented into the ground. If infrastructure is nearby, such as the corner of a bridge, this can be used as a benchmark.

The average erosion or deposition rate of unpaved roads at a reach (cm) is multiplied by the road width (m) to calculate a cross-sectional area change (m^2). This value is multiplied by the unpaved road length (m) to determine a volume. The volume is multiplied by the density (g/cm^3) of unpaved road material to get the final mass (kg). Dividing the mass by the number of days of measurement (kg/day) and multiplying by 365.25 produces an annual mass determination (kg/yr).

3.5.4.2 Upland and Hillslope Measurements

Various approaches ranging from field collection to fallout radionuclides have been used to estimate hillslope erosion and deposition. A common field approach is to capture eroded material in pits or traps. Silt fences, 3 to 15 m across the hillslope, can be installed to capture eroded sediment (Robichaud and

Brown, 2002). The amount of mass deposited behind the silt fences is determined and related to the contributing area on the hillslope to estimate a yield (Robichaud and Brown, 2002).

Traps installed on hillslopes, often called Gerlach Troughs (Gerlach, 1967), can be used to capture eroded sediment (Gellis *et al*., 2012; Larsen *et al*., 2012) (Fig. 23A). Gellis *et al*., (1999, 2012) installed plastic rain gutters, ranging from 52 to 85 cm long and 8.5 to 13 cm deep, with each end capped off on hillslopes to capture runoff and sediment. Holes drilled into the sides of the rain gutter were attached to collection buckets with plastic hosing. The contributing area to each trap was bounded with metal edging (Gellis *et al*., 2012). After rainfall events, the sediment water mixture was taken to the laboratory and dried to determine the mass of sediment (Gellis *et al*., 1999; 2012). The traps were helpful in quantifying erosion for individual storm events but required a great deal of labor.

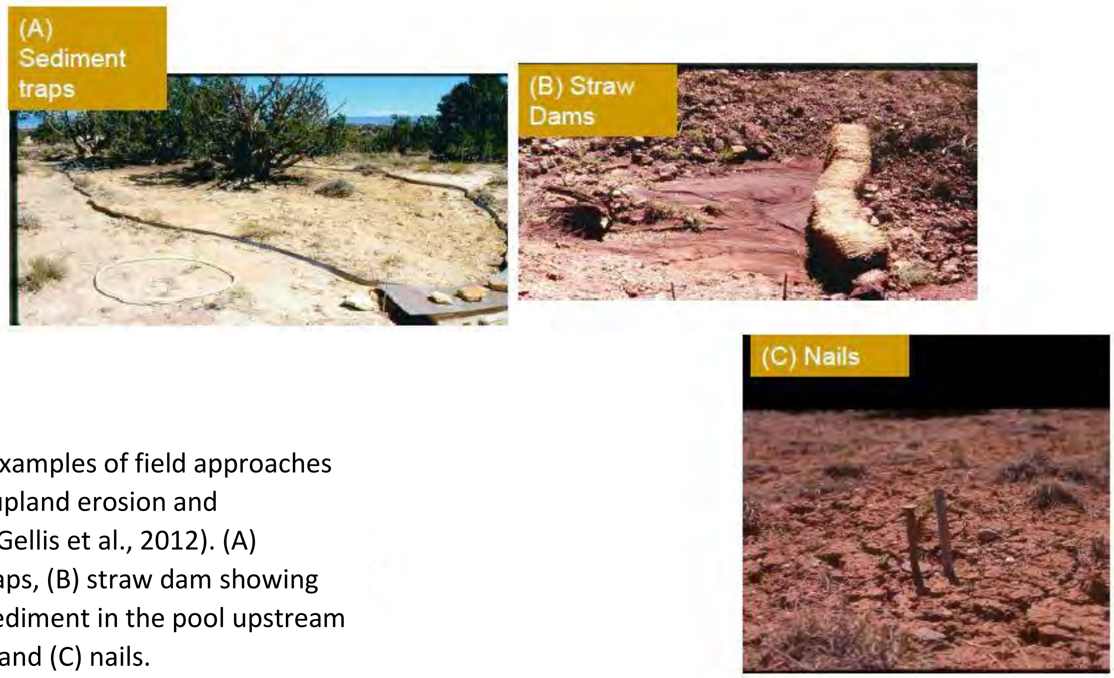


Figure 23. Examples of field approaches to monitor upland erosion and deposition (Gellis et al., 2012). (A) sediment traps, (B) straw dam showing deposited sediment in the pool upstream of the dam, and (C) nails.

Small impoundments and ponds have also been used to determine the sediment yield. Gellis *et al*., (2012) placed straw in zero-order channels, i.e., channels that are of too fine a scale to be delineated as first-order channels, in New Mexico to create a sediment pool (Fig. 23B). The sediment pool was surveyed periodically to determine the volume of deposited sediment. Taking cores to determine the density of the deposited sediment allows the volume to be converted to a mass. The contributing areas to the dams were surveyed as a total station. Quantifying the contributing area to the dams enabled a sediment yield (kg/m2/yr) to be determined. Repeat surveys in small ponds can also be used to determine the amount of deposited sediment (Renwick *et al*., 2005).

Small pins or nails can also be used to quantify hillslope erosion and deposition (Leopold *et al*., 1966; Gellis *et* al., 2012) (Fig. 23C). On grazed areas of New Mexico, Gellis *et al*. (2010) used a 15-cm-long nail put through a washer and driven into the ground to measure erosion and deposition. Nails were arrayed in lines, 4 to 163 m long and measured periodically.

Field measurements of erosion and deposition have their advantages and disadvantages. Advantages include direct on-the-ground measurements. Disadvantages include investment in time and labor, and some of the measurements may only quantify erosion and deposition at small spatial scales (10's of square meters).

3.5.4.3 Upland Erosion and Deposition Using Cesium-137

The cesium-137 (^{137}Cs) technique has been used worldwide to estimate soil loss and gain (Sutherland, 1989; Ritchie and McHenry, 1990; Gellis *et al*., 2009). ^{137}Cs is a by-product of above ground thermonuclear bomb testing and was released globally as fallout from the testing in the 1950s and 1970s (Carter and Moghissi, 1977). Deposited primarily through precipitation, ^{137}Cs strongly adsorbed to soil, especially to fine particles (less than 2 mm) (He and Walling, 1996). By comparing the amount of ^{137}Cs bound to soil in a non-eroded or reference area to the amount in an eroded or depositional area, the rate in which soil has been redistributed (erosion/deposition) can be estimated (Walling and He, 1997). In the Chesapeake Bay watershed, the ^{137}Cs technique has been used to estimate erosion and deposition on agricultural and forested land in selected watersheds of the Chesapeake Bay (Gellis *et al*., 2009; Clune *et al*., 2010; Gellis *et al*., 2015).

At select hillslopes, 5 to 15 composite samples are collected along a slope (Fig. 24). At each sampling point on the slope, composite samples are taken from three locations about 15 m apart along a contour (Fig. 24). In agricultural fields, soil is cored manually down to the tillage depth using a coring device. The tillage depth can be determined on the basis of textural and color differences in the soil. Finding reference areas where little to no erosion has occurred is critical to the ^{137}Cs approach. Reference sites have a typical profile of ^{137}Cs with depth, where most of the cesium is found in the uppermost portion of the profile (Mabit *et al*., 2008). Therefore, it is important to verify that the reference site matches this profile. Rather than using one core at reference sites, it is recommended that coring be done at smaller centimeter increments to determine if the ^{137}Cs profile matches that of a reference site. The models developed to quantify soil erosion and deposition using ^{137}Cs found in Walling and He (1997) are in the units of kg/ha/yr.

Figure 24. *Illustration of the cesium-137 sampling technique used in agricultural and forested areas in the Linganore Creek watershed (Gellis et al., 2015). A composite sample was taken from three locations (represented by white dots in the photograph) that were approximately at the same elevation on the slope (contour) and 15 meters apart. At each slope, 6–12 composite samples were collected and analyzed separately for cesium-137. [Photograph of Linganore Creek watershed from Clune et al., 2010.]*

3.5.5 Age Determinations of Sediment Collected in the Field

Sediment budgets that have the objectives of determining sediment budgets for different time periods rely on age determinations of sediment. Sediment budget rates often are examined over different time periods to understand natural versus human-influenced rates or changing land use conditions (Trimble. 1983; Kesel *et al*., 1992).

Several approaches can be used to determine the age of sediment deposits ranging from historical maps, artifacts, anthropogenic markers (i.e., old road surfaces and dating cores). A brief review of some of the most common methods for dating sediment are in Fitzpatrick (2014). Berglund (1986) is a standard reference for many of the terrestrial methods for Quaternary studies. For aquatic environments, methods employed by paleolimnology and lake sedimentation studies are helpful (Hakanson and Jansson, 2002).

Radiometric techniques based on the uranium decay series, such as lead-210 (Schelske *et al*., 1986; Olsson, 1986; Cohen, 2003) or ^{137}Cs derived from atmospheric fallout from above-ground nuclear bomb testing that occurred between 1953 to 1973 (Van Metre *et al*., 2004), are best done with profiles of fine-grained sediment that have had no erosion, chemical or physical remobilization, bioturbation, pedogenesis, decomposition, or diagenesis. This technique is most often used for aquatic sediment profiles but can also be used carefully for fine-grained vertical accretion deposits in terrestrial floodplain settings.

Radiocarbon (carbon-14) dating (Libby *et al.,* 1949) has a resolution back to about 50,000 years where wood and organic matter as well as carbonate precipitates can be dated. Radiocarbon dating has been especially useful for dating wood and charcoal in buried abandoned channels and can be used in both terrestrial and aquatic environments where organic matter is present.

For floodplain sediment, optically stimulated luminescence (OSL) dating has been used that has a resolution back to about 800,000 years (Lundstrom *et al*., 2008). This technique calculates the time since the sediment was last exposed to sunlight or intense heat and uses quartz or potassium feldspar that are commonly found in sand. This technique is helpful for determining the age of coarse-grained fluvial deposits.

3.5.6 Measuring Sediment Transport and Export

The inputs and storage of sediment should hypothetically equal the output or export of sediment from the watershed of interest. The output of sediment is typically expressed as a suspended sediment or total sediment load (kg). In some studies, the output is measured as the volume of sediment in an impoundment (m^3). The measurement of suspended sediment loads has less error than the input and storage measurements, making this an important aspect of a sediment budget. Sediment transport may be monitored at the watershed outlet and potentially at multiple sub-basins of interest. The collection and computation of fluvial sediment transport (suspended and bedload) can be found in (Edwards and Glysson, 1999; Rasmussen *et al*, 2009). The details of this exercise are quite involved, and, thus, it is best to consult these USGS techniques manuals. A short video illustrates a setup on the Patapsco River in Maryland (https://vimeo.com/29783454). Suspended sediment concentrations and bedload are collected along with continuous discharge so that a rating curve can be established between concentration and discharge for computation of event-specific or annual loads. Automated samplers are usually best to use for suspended sediment because runoff inconveniently happens in the evening hours of a Saturday night. Some examples of automated samplers are in Anderson and Rounds (2010). Less expensive siphon samplers for suspended sediment and nutrient sampling can be strategically located upstream (Graczyk *et al*., 2000).

3.5.6.1 Impoundment Surveys

Impoundments along stream corridors, whether on main stems or tributaries, consist of small sediment detention basins that contain important sedimentation records that can be used as sediment budgets as the storage or output terms in Eq. 1. Field methods for determining the volume and mass of sediment stored in impoundments are described in Bureau of Reclamation (2006). The techniques are a combination of high-level surveying to identify the spatial distribution and thickness of post-construction sediment accumulation and cores to calculate the volume-to-weight conversion factor. These techniques can be applied to either inundated or dry sediment accumulations. General guidelines of volume-weight conversion factors for a variety of sediment sizes are given in Table 4. An important aspect of using impoundments is estimating the trap efficiency, the ratio of sediment inflow to outflow, of the impoundment (Renwick *et al*., 2005). Results of impoundment surveys are documented as a volume (m^3) or mass (kg).

3.5.7 Budget Calculations

A sediment budget is an accounting of the sources (erosion), storage (deposition), and delivery (transport) of sediment in a watershed (Eq. 1). The field measurements and estimates of areas are used to determine a sediment budget. The final sediment budget is the summation of all measurements of streambanks, channel beds, bars, floodplains, upland areas, ponds, etc., computed using the following equations:

$$T_s = S_k + S_b + F_p + A_g + F_r + P_d \qquad (6)$$

where:

T_s = total sediment export to the watershed outlet, in megagrams per year ('+' = erosion, '-' = deposition);

S_k = erosion or deposition from streambanks, in megagrams per year;

S_b = erosion or deposition from streambed, in megagrams per year;

F_p = deposition from floodplain, in megagrams per year;

A_g = erosion or deposition from agricultural areas, in megagrams per year;

Fr = erosion or deposition from forested areas, in megagrams per year;

P_d = the total mass of sediment deposited in ponds, in kilograms per year, and

where:

$$Sk = \sum_{s=1}^{s=5}\left[\frac{K_{r(s)} * K_{\mu} * (L_s * 100) * (M_k / 100)}{1,000}\right] \qquad (7)$$

Sk = erosion or deposition from streambanks in kilograms per year;

$K_{r(s)}$ = net change in streambanks for stream order (*s*), in square centimeters per year (Eq. 13);

K_{μ} = streambank sediment density, in grams per cubic centimeter;

L_s = length of streams for stream order (*s*), in meters; and

M_k = percent silt and clay in streambanks of stream order (*s*).

and:

$$S_b = \sum_{s=1}^{s=5}\left[\frac{B_{r(s)} * B_{\mu} * (L_s * 100) * (M_b / 100)}{1,000}\right] \quad (8)$$

S_b = erosion or deposition from streambed, in kilograms per year;

$B_{r(s)}$ = net change in channel bed for stream order (*s*), in square centimeters per year (Eq. 10);

B_{μ} = channel bed density, in grams per cubic centimeter; and

M_b = percent of silt and clay in channel bed of stream order (*s*).

and:

$$F_p = \sum_{s=1}^{s=5}\left[\frac{F_{r(s)} * F_{\mu} * (L_s * 100) * (M_f / 100)}{1,000}\right] \quad (9)$$

where:

F_p = deposition from floodplain, in kilograms per year;

$F_{r(s)}$ = net change in floodplain for stream order (*s*), in square centimeters per year (Eq. 17);

F_{μ} = floodplain sediment density, in grams per cubic centimeter; and

M_f = percent silt and clay in floodplain of stream order (*s*).

and:

$$A_g = \left[A_{Cs} * (S_a / 100) * A_t\right] * 1,000 \quad (10)$$

$$F_r = \left[F_{Cs} * (S_o / 100) * A_f)\right] * 1,000 \quad (11)$$

where:

A_g = total erosion or deposition from agricultural areas, in megagrams per hectare per year;

A_{Cs} = agricultural erosion estimated using ^{137}Cs, in megagrams per hectare per year;

S_a = percent silt and clay in agriculture areas;

A_t = total area in agriculture, in hectares;

F_r = total erosion or deposition from forested areas, in megagrams per hectare per year;

F_{Cs} = forest erosion estimated using ^{137}Cs, in megagrams per hectare per year;

S_o = percent silt and clay in forest; and

A_f = total area in forest, in hectares.

All sediment inputs and storage terms should balance to the output (Eq. 1), but this rarely happens (Kondolf and Matthews, 1991). Kondolf and Matthews (1991) reported imbalances as high as 104% of the total sediment output. Errors involved in developing sediment budgets include limited spatial and temporal measurements, inaccurate field techniques, natural data variability, overly simplified models, and extrapolation of measurements to unmeasured areas. It is recommended that in the final dissemination of the sediment budget the range of values be shown as confidence intervals (i.e., 10th and 90th percentiles).

3.5.7.1 Error Analysis

Construction of the sediment budget relied on averaging and summing field measurements. A confidence interval is a range that encloses the true average of the measurement with a specified confidence interval (i.e., 10th and 90th percentiles). Any standard statistics package can provide examples on how to determine confidence intervals. In the computation of the sediment budget, measurement averages are multiplied and added (Eqs. 4-8). The propagation of uncertainty (i.e., 10th and 90th confidence intervals) has defined rules for multiplication, addition, and subtraction (Bevington and Robinson, 2003) (Table 6).

An example of how a sediment budget is computed is shown in Box 8.

Box 8. Computation of the Sediment Budget

The example shown here is from a sediment budget study conducted by Gellis *et al*. (2015) for Linganore Creek, MD from 2008 through 2010. Land use in 2006 in the 147-km^2 watershed was 27% forest, 62% agriculture (pasture and cropland, 8% developed, and 3% other). The watershed is listed on Maryland's 303D list for sediment impairments, and the cooperator, Frederick County, was interested in targeting the sources of sediment.

Channels (streambanks, channel bed, and floodplain), uplands (agriculture and forest), and storage areas (ponds) were measured in the sediment budget. Streambanks were monitored with pins (n = 50 reaches), the channel bed through level surveys (n = 22 reaches), the floodplain using clay pads (n = 20 reaches), agricultural fields (n = 18) using ^{137}Cs, forested slopes (n =13) using ^{137}Cs , and an estimate of pond storage (n = 195) using photogrammetric, GIS analysis, and literature values (Gellis *et al*., 2015). The output of sediment was computed as suspended sediment loads at the mouth of the watershed where a USGS station was located (Linganore Creek near Libertytown, MD - Station ID 01642438). The sediment grain size of interest was <0.063 mm (silts and clays), and samples from all sources were sieved. Confidence intervals (CIs) (10th and 90th percentiles) were used to assess the uncertainty about the mean of the field measurement.

The following is a summary of the computation of the sediment budget (negative numbers indicate erosion and positive numbers indicate deposition).

A) Summary of Channel Measurements

Stream order	Length (m)	Streambank change (cm2/yr)	Channel bed change (cm2/yr)	Floodplain Deposition (cm2/yr)
		Mean(10%CI, 90%CI)		
1	12200	85.1 (-23.8, 216)	-25.6 (-135, 80.8)	59 (35.7, 81.8)
2	6428	-360 (-552, -166)	-25.6 (-135, 80.8)	59 (35.7, 81.8)
3	4341	-628 (-772, -483)	195 (-954, 490)	508 (296, 722)
4	1805	-1410 (-2620, -609)	2408 (317, 5274)	1572 (887, 2293)
5	641	-562 (-796, -330)	2408 (317, 5274)	1572 (887, 2293)

B) Density Measurements

Stream 0rder `	Streambank density (g/cm3)	Channel bed density (g/cm3)	Floodplain density (g/cm3)
	Mean(10% CI, 90% CI)		
1	1.22 (1.01, 1.42)	1.85 (1.34, 2.33)	0.80 (0.57, 1.0)
2	1.11 (1.00, 1,21)	1.85 (1.34, 2.33)	0.70 (0.50, 0.89)
3	1.10 (0.98, 1.22)	1.40 (0.50, 2.4)	0.76 (0.58, 0.95)
4	1.06 (0.94, 1.18)		0.70 (0.52, 0.90)
5	1.10 (1.03, 1.16)		0.72 (0.48, 0.96)

Box 8. Continued.

C) Percent Silt and Clay

Stream order	Streambank	Channel bed	Floodplain
	Mean(10%CI, 90%CI)		
1	40.9 (35.3, 47.3)	2.3(0.4, 0.5)	44.2(34.5, 55.0)
2	30.4 23.2, 39.1)	13.8(2.5, 28.0)	50.0(39.2, 61.9)
3	38.7 (33.2, 44.6)	1.4(0.5, 2.4)	47.6(40.1, 54.9)
4	40.9 (28.7, 53.2)	6.3(0.3, 12.4)	50.4(39.0, 61.7)
5	44.9 (40.0,50.0)	6.3(0.3, 12.4)	55.6(46.3, 65.1)

D) Final Contribution From Channel Elements.

Stream Order	Net contribution from streambanks (Mg/yr)	Net contribution from the channel bed (Mg/yr)	Net deposition on floodplains (Mg/yr)
	Mean(10%CI, 90%CI)		
1	1040(-309; 6,720)	-11.8(-63.6,40.4)	508(2.36,787)
2	1560(-2490; -746)	-41.6(-224,137)	262(124,414)
3	-2330(-3000,-1660)	-25.2(-124,66.4)	1600(790,2420)
4	-2200(-4210,-1000)	577(-279,1530)	2000(888,3170)
5	-356(-511,-241)	205(-99.1,545)	803(345,1280)
Total from all channel elements	-5400(-8090,501)	703(-790.2320)	5180(2380,8070)

E) Upland Erosion

Land use	Average erosion (t/ha)	Percent fines	Erosion (Mg/yr)
Agriculture	-19.0 (-22.3, 16.0)	38.2 (35.4, 41.2)	-54,800 (-65,100; -45,300)
Forest	-1.45 (-2.38, -0.65)	40.2 (32.3, 48.0)	-2030 (-2033 ,-2027)
Total upland	-56,800 (-67,100; - 47,300)		-56,800 (-67,100; -47,300)

F) Pond Storage

Ponds	Total sediment storage (Mg/yr)
	932 (901, 956)

G) Final Sediment Budget

FINAL SEDIMENT BUDGET (Mg/yr)
47,000 (-49,800; -41,000)

H) Fine-Grained Suspended Sediment Computed at the Watershed Outlet = 5,450 Mg/yr.

Box 8. Continued.

Combining all erosion and deposition (storage) measurements equaled 47,000 Mg/yr. This indicated that the sediment budget did not balance the fine-grained sediment mass leaving the watershed measured at the streamflow-gaging station (5,450 Mg/yr). The difference in sediment (41,500 Mg/yr) was attributed to measurement error and to sediment that went into unmeasured storage elements.

Overestimation of erosion may also be related to the period in which the ^{137}Cs method estimates erosion and deposition, which is a period of over 50 years. The channel and floodplain measurements in the sediment budget were taken over a 3-year period. Large storms such as hurricanes, which cause significant amounts of erosion that would have occurred over the 50 years, would be reflected in the ^{137}Cs estimates. Another factor that would lead to higher erosion rates in agricultural areas over the historical period compared to the period of study would be the recent implementation of agricultural conservation practices to reduce erosion such as no-till, contour plowing, and vegetated buffers. If these practices were recently established on agricultural lands, the reduction in erosion may not be reflected in the ^{137}Cs-derived estimates of long-term erosion.

Table 6. Rules of how uncertainties are propagated.

Addition/Subtraction	$z = x \pm y$	$\Delta z = \sqrt{(\Delta x)^2 + (\Delta y)^2}$
Multiplication	$z = xy$	$\Delta z = \lvert xy \rvert \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2}$
Division	$z = \frac{x}{y}$	$\Delta z = \left\lvert \frac{x}{y} \right\rvert \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2}$
Power	$z = x^n$	$\Delta z = \lvert n \rvert x^{n-1} \Delta x$
Multiplication by a Constant	$z = cx$	$\Delta z = \lvert c \rvert \Delta x$
Function	$z = f(x,y)$	$\Delta z = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 (\Delta x)^2 + \left(\frac{\partial f}{\partial y}\right)^2 (\Delta y)^2}$

3.5.7.2 Displaying Budget Results

Diagrams of sediment budgets are usually the most useful for managers to help understand the magnitude and inputs of sediment. Some simple examples were given in Figures 5 and 6. Depending on the level of detail of the budget, data can be displayed along a longitudinal continuum with the width of the arrows representative of the amount of loading associated with each source and sink.

3.5.7.3 Incorporating Management Practices

Once the initial sediment inventory is completed, what-if scenarios can be developed for various management techniques spanning uplands to channels, assuming that the hydrology has not been altered. This can be expanded to particulate-bound phosphorus sources and sinks as well. For example, if bank erosion or valley side failures were stopped, the potential reduction in loading can be calculated. Likewise, if a section of stream would lose its floodplain connection, it can be determined how much sediment would continue to be transported downstream.

4.0 Sediment Fingerprinting

Recent advances have been made in developing field-based approaches to identify sediment sources in watersheds using the sediment-fingerprinting approach (Williamson *et al*., 2014). This part of the manual discusses how to develop a sediment fingerprinting study, including collection, laboratory analysis, sediment source apportionment, and error analysis.

The sediment-fingerprinting approach provides a direct method for quantifying watershed sources of fine-grained suspended sediment (Gellis and Walling, 2012) (Fig. 25). This approach entails the identification of specific sources of sediment 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 properties that allows them to be traced back to their respective sources. Tracers that have been used in sediment fingerprinting studies are shown in Tables 7A and 7B.

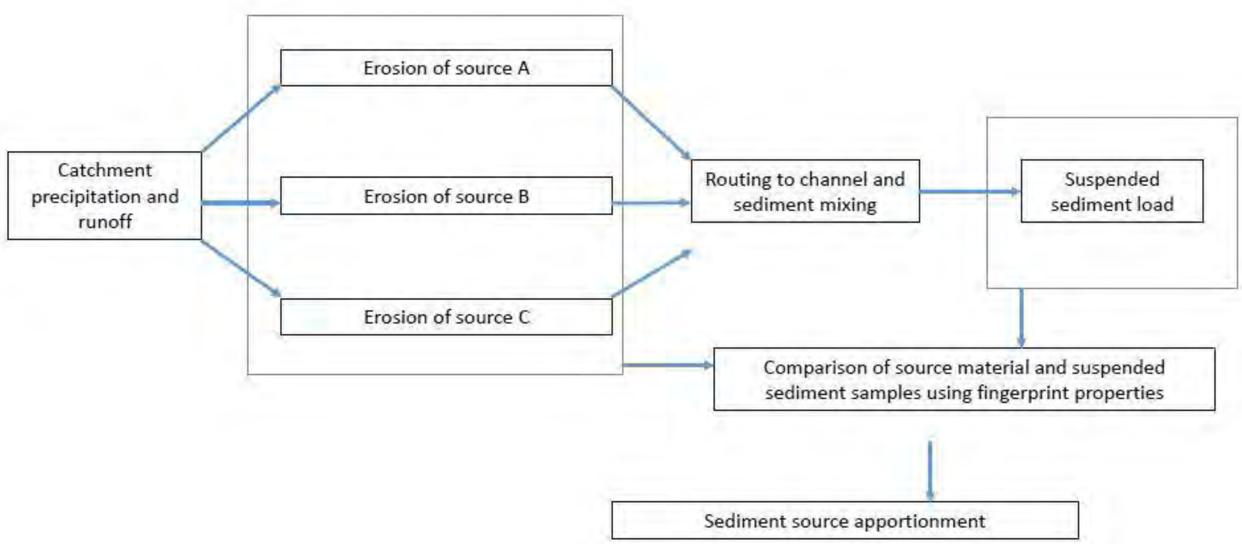


Figure 25. Outline of the sediment fingerprinting approach (from Walling and Collins, 2000).

Table 7A. Example of tracers that have been used in sediment fingerprinting studies. (See Miller et al., 2015, Table 2.1 for a more extensive list of tracers used.)

Tracers used	Reference
Mineralogy	Motha *et al.*, 2003; Gingele and De Deckker, 2005
Radionuclides	Walling and Woodward 1992; Collins *et al.*, 1997; Nagle *et al.*, 2007; Evrard *et al.*, 2011
Trace elements	Devereux *et al.*, 2010; Mukundan *et al.*, 2012; Gellis *et al.*, 2015
Stable isotope ratios	Papanicolaou *et al.*, 2003; Fox and Papanicolaou, 2008; Stewart *et al.*, 2014
Magnetic properties	Foster *et al.*, 1998; Slattery *et al.*, 2000; Hatfield and Maher, 2009
Color	Krein *et al.*, 2003; Barthod *et al.*, 2015

Table 7B. Example of 38 elemental metals used in elemental analysis for fingerprinting sediment (Gellis et al., 2015).

Silver (Ag)	Cadmium (Cd)	Potassium (K)	Phosphorus (P)	Selenium (Se)	Vanadium (V)
Aluminum (Al)	Cerium (Ce)	Lanthanum (La)	Lead (Pb)	Strontium (Sr)	Yttrium (Y)
Arsenic (As)	Cobalt (Co)	Lithium (Li)	Rubidium (Rb)	Sodium (Na)	Zinc (Zn)
Barium (Ba)	Chromium (Cr)	Magnesium (Mg)	Antimony (Sb)	Niobium (Nb)	
Beryllium (Be)	Cesium (Cs)	Manganese (Mn)	Gallium (Ga)	Titanium (Ti)	
Bismuth (Bi)	Copper (Cu)	Molybdenum (Mo)	Thorium (Th)	Thallium (Tl)	
Calcium (Ca)	Iron (Fe)	Nickel (Ni)	Scandium (Sc)	Uranium (U)	

The steps in sediment fingerprinting are shown in Fig. 26. Potential sediment sources in the watershed are identified in the same procedure as was used in the sediment-budget analysis (Sections 3.2; 3.4). Sediment sources include but are not limited to agriculture, forest, construction sites, urban sources, channel banks and beds, drainage ditches, and floodplains. Target sediment includes suspended-sediment, bed sediment, floodplain sediment, and reservoir or lake sediment (Miller *et al*., 2015).

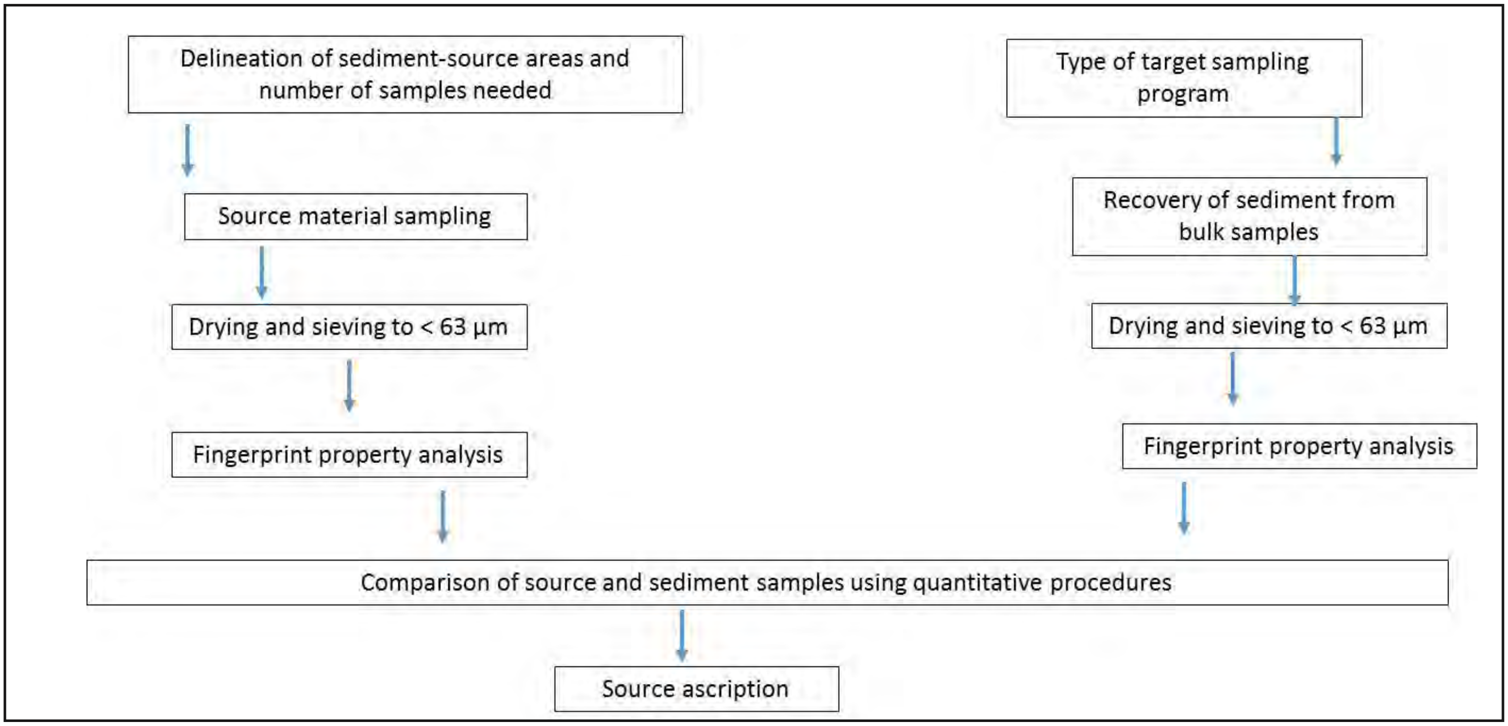


Figure 26. Outline of the sediment fingerprinting sampling procedure

4.1 Tracer Selection

The tracers used in sediment fingerprinting are numerous (Tables 7A and 7B) (Miller *et al*., 2015). It is rare to know *a priori* which tracers will be able to discriminate between watershed sources. Most sediment fingerprinting studies use elemental analysis, where for a relatively small cost, 20 or more elemental results are provided. Several studies have used stable isotope analysis that reflects the organic content of the sediment. Fallout radionuclides (^{137}Cs, $^{210}Pbex$, ^{7}Be) have been shown to discriminate between channel and upland sources (Matisoff *et al*., 2005). Other properties that have been used to distinguish sediment sources include color (Krein *et al*., 2003), magnetic properties (Slattery *et al*., 2000), and mineralogy (Motha *et al*., 2003). Miller *et al.* (2015) provide a review of the tracers used in sediment fingerprinting studies.

Elemental analysis involves inductively coupled plasma combined with mass spectrometry (ICP-MS) and/or inductively coupled plasma optical emission spectrometry (ICP-OES). These methods are described online at http://www.epa.gov/sam/pdfs/EPA-200.7.pdf and http://www.epa.gov/sam/pdfs/EPA-200.8.pdf. Stable isotope analysis determines the ratio of $\delta(^{15}N/^{14}N)$, abbreviated as $\delta^{15}N$, and $\delta(^{13}C/^{12}C)$, abbreviated as $\delta^{13}C$. Laboratory procedures for stable isotope analysis can be found at Révész *et al*. (2012). Information on the analysis of radionuclides can be found at http://www2.epa.gov/radiation/marlap-manual-and-supporting-documents.

4.2 Target Sample Collection

The choice of the type of target sediment used to apportion sediment depends on the objectives of the study. If understanding how sediment sources change through storm events or between events is of interest, then storm samples of suspended sediment should be collected (Mukundan *et al*., 2012; Gellis *et al*., 2015. In many studies, the objective is to obtain a target sample that is representative of long-term conditions, on the order of years. Suspended sediment can be sampled over the course of one or more years. Bed sediment can be a surrogate for watershed derived fine-grained sediment (Miller and Miller, 2007) and has been used in several studies to source sediment (Collins and Walling, 2007A, B). Bed sediment reflects sediment that is eroded and deposited over several events and can be used to source sediment over time periods of weeks to months (Collins and Walling, 2007A, B). Because flow and sediment conditions change seasonally, bed sediment should be sampled several times during the year. Floodplain sediment, which has been used in sediment fingerprinting, is deposited during larger flow events that may occur at a frequency of years (Owens *et al*., 1999; Miller *et al*., 2015). Lake cores have been used for understanding sediment sources even further back in time (Foster *et al*., 1998; Pittam *et al*., 2009). In the collection of suspended, bed, floodplain, and lake sediment, it is assumed that the sediment is representative of conditions for the entire watershed.

Prior to planning for the target-sediment sampling design, the tracers that will be analyzed should be known. Therefore, it is important to contact the laboratory where the analyses will be performed to ask questions pertaining to sample mass and holding requirements, such as should the samples be refrigerated? In each of the target-sediment collection schemes, it is necessary to obtain enough mass for tracer analysis. Different types of tracers have different mass requirements. Elemental analysis and stable isotopes, for example, require sediment on the order of 1 to 5 grams. Radionuclides may require up to 30 grams. Therefore, it is important that the sediment sampling technique employed provide the needed mass. In addition, one should consider the materials used in constructing the samplers. For example, if the sediment is to be analyzed for metals, the samples should not contain metal. Holding times of the sediment samples are also important as certain elements, such as short-lived radionuclides (i.e., ^{7}Be), may lose activity over time.

Commonly, suspended sediment is chosen as the target sediment. Suspended sediment can be collected using several approaches: manual samples (Edwards and Glysson, 1999), automatic samplers (Gellis *et al*., 2015), and passive samplers (Phillips *et al*., 2000) (Fig. 27). Manual samplers can be used during storm events to collect suspended sediment for source analysis. Automatic samplers consist of a peristaltic pump and 24 1-liter (L) clean, plastic storage containers. Intakes for these samplers are placed mid-stream and at mid-depth. The placement of the intake is based on a site-by-site inspection of the stream to ensure that the intake is placed in a good transport reach. Backwater areas, or placing the intake too close to the bed or near obstructions (boulders, bridge piers, trees, etc.), should be avoided. Automatic samplers are triggered to sample at a preset river stage and will sample at preset times.

Since most sediment is transported on the rising limb of the hydrograph, it may be useful to have the first samples collected relatively close together. Storm durations vary, and it may be helpful to have the last samples further out in time. If historical streamflow records exist at the study site or at nearby watersheds, storm hydrographs should be examined to develop a sample timing scheme.

(A) (B)

Figure 27. (A) Photo of automatic sampler intake at Linganore Creek, Maryland. (B) Example of passive samplers used in Big Soos Creek, Washington. Four tubes were installed, each in pairs. [Photos taken by A. Gellis, 2009]

At selected sites, passive samplers, as described in Phillips (2000), can be used to collect suspended sediment over time. The passive sampler is secured to two posts that are firmly hammered into the channel bed. To adjust for changing flow conditions, the passive sampler can be moved up and down on the posts using hose clamps and other fasteners that can be removed. The passive sampler should be placed in the channel cross section where the sampler will obtain a representative sample. The sampler can be placed at an elevation between baseflow and bankfull flow or installed submerged. Because baseflow is subject to seasonal changes, the passive sampler may be moved accordingly. Samples are collected after storm events, and the contents of the sampler (approximately 8 L of sediment and water) should be emptied into a clean plastic bottle (~20 L).

Another consideration in the sampling design is the expected suspended sediment concentration of the stream during high flows. Low suspended sediment concentration streams (~100 mg/L and lower) may require additional samples to obtain the necessary amount of mass. When using manual and automatic samplers, it is common to combine samples that were collected over the storm hydrograph, or separate the samples based on position on the hydrograph (e.g., rising versus falling limb). If passive samplers are used, several tubes should be placed in the stream to obtain the necessary mass as well as to provide a backup should some samplers be destroyed during high flows (Fig. 27B). In streams with low suspended sediment concentrations, the passive samplers may have to be deployed over several events to obtain the necessary mass.

Bed material for sediment source analysis is typically found in two portions of the channel: 1) fine-grained channel deposits that may drape coarser bed material, and 2) within the interstitial spaces of coarse-grained bed material. Fine-grained channel deposits are often found in pools and backwater areas of the stream and can be sampled with a coring device. Because the fine-grained sediment has high plasticity, using a coring device that creates a vacuum is necessary to hold the fine material intact. Sometimes simply capping the coring device will create enough suction to retrieve the sample. Generally, the top few centimeters of the fine-grained sediment are sampled. Care should be taken not to sample channel material immediately below an eroding bank.

Bed material is scoured and deposited during storm events with the depth of scour proportional to the velocity and water depth. Bed material is mobilized during high flows. During the recessional portion of the hydrograph, fine-grained sediment becomes deposited in the interstitial spaces between the course material. The fine-grained sediment found in the coarse-grained material can be sampled by isolating the bed with a cylinder and sampling the bed material in the cylinder (Fig. 27C). Collins and Walling (2007b) sampled the fine-grained sediment in the channel bed by isolating the channel bed with a cylinder, stirring the bed inside the cylinder, and collecting the slurry. Only the bed material on the surface is stirred. The stirring rod made of PVC can be 1 m in length and 1-2 cm in diameter. Sediment for sourcing in lakes and other impoundments, as well as floodplains, can be sampled with coring devices (Pulley *et al*., 2015).

4.2.1 Target Sample Preparation

Typically, the samples obtained from the automated sampler are processed for suspended-sediment concentrations to determine suspended sediment loads, although this does not have to be a necessary objective of sediment source analysis. A decision is made whether to combine bottles or analyze them separately. This decision is based on the objectives of the study and the mass needed for analysis. If bottles are combined, this should be performed as soon as they return from the field. Processing of suspended sediment may include centrifuging or filtering the water-sediment mixture. Centrifuging is preferable because the lab will return the dried fraction of sediment (< 0.063 mm) from each bottle in a vial.

If the lab uses filters for suspended sediment concentrations, the sediment is scraped or rinsed off the filters with de-ionized water to remove the dried sediment that is collected in a glass bowl(s). The glass bowl(s) is dried at 65°C for 24-48 hours. In some circumstances, the automatic samplers are installed for the sole purpose of obtaining suspended sediment for sediment source analysis. Bottles from the automatic sampler are composited, refrigerated, and the water allowed to settle 72 hours. When the water is clear to the bottom of the container, the clear water is pumped out, and the slurry is transferred to a non-metal drying bowl using de-ionized water. The slurry is then wet-sieved (see below).

After drying, a sufficient mass needed for analysis is weighed, ground with a ceramic mortar and pestle, and wet-sieved through a 63-micron polyester sieve using de-ionized water. ASTM D3977-97 (2002) Method C, wet-sieving filtration, is used to separate sand and coarser material from finer material. The water-sediment mixture is captured in a glass bowl(s) and dried at 60°C for 24-48 hours. After drying, the sediment in the bowl is scraped with a plastic blade, weighed, and placed in a plastic vial for shipping. The coarse material is saved, dried, and weighed to obtain the percentage of fines (<0.063 mm) and coarser material.

The sediment-water mixture from a passive sampler is placed in a cooled area and left for several days in order to let the sediment settle to the bottom. The samples are ready to be decanted when you can see the bottom of the container. This may occur when the water is still a little cloudy. The water from the passive sampler is decanted until only a slurry is present. The slurry is emptied into a glass bowl(s) and dried at 65°C for 24+ hours until dry. After drying, a sufficient mass needed for analysis is weighed, ground with a ceramic mortar and pestle, and wet-sieved through a 63-micron polyester sieve using de-ionized water. The water-sediment mixture is captured in a glass bowl(s) and dried at 65° C for 24+ hours until dry. After drying, the sediment in the bowl is scraped with a plastic blade, weighed, and placed in a plastic vial for shipping. The coarse material is saved, dried, and weighed to obtain the percentage of fines (<0.063 mm) and coarser material.

Bed, floodplain, and lake sediment may have less water in the sampled sediment and can either be stored in a refrigerated area or immediately wet-sieved. Since these samples have greater mass, depending on the final mass needed, a subsample is combined with deionized water to create a slurry. Sample preparation for the slurry follows the same procedure for other slurry samples as described above.

4.3 Source Sample Collection

Soil samples for source analysis collected from upland areas are taken from the top 1 to 2 cm of the soil surface with a plastic hand shovel. To account for variability in the tracer properties at upland sites, sediment is collected across transects and composited into one sample. A 10-L plastic container can be used to hold the composited sample. The composite sample is mixed well with a plastic shovel, and a subsample is placed in a plastic bag. Roots, leaves, twigs, and other organic debris can be removed. The total mass sampled from an upland site should be a minimum of 50 to 100 g.

At a channel reach, three to six eroding banks are sampled, each spaced a minimum of 10 m apart. If streambanks are eroding on both sides of the channel, samples are taken on both sides of the river. An eroding bank face is typically oriented at a high angle (>45 degrees) with a large portion of the bank faces (>50%) exposed and not covered with vegetation. Each streambank is sampled from the bottom to the top of the bank face with a plastic (non-metal) hand shovel. All samples are composited into one sample. A 10-L plastic container can be used to hold the composited sample. The composite sample is mixed well with a plastic shovel, and a subsample is loaded into a plastic bag. Roots, leaves, twigs, and other organic debris can be removed. The total mass sampled from an eroding bank should be a minimum of 50 to 100 g.

4.3.1 Source Sample Preparation

Upland and bank samples should be refrigerated or put on ice after sampling. The samples are wet-sieved following the same procedure for slurries of fluvial sediment. Further quantification on sediment samples and cores involves particle size determinations and organic matter content. These methods are discussed in detail in Guy (1969) and Burt (2009).

4.3.2 Grain Size – Laboratory Analysis

Either grain size or surface area can be used to correct for grain size. It is common to analyze for grain sizes less than 63 microns (Collins et al., 2010; Lamba et al, 2015); however several researchers suggest that analyzing sediment to a narrow range of particle sizes (Hatfield and Maher; 2009) or only to <10 microns (Wilkinson et al, 2013; Laceby et al., 2015) may improve results and reduce error.

After the sample is wet-sieved to the preferred grain size, the surface area or grain size of the sediment is determined for the portion of sediment that is less than 0.063 mm. Universities and private laboratories have equipment that can analyze fine-grained sediment for surface area and grain size. Pipette analysis is considered the standard for determining grain size (ASTM D422-63, 2007), but laser and optical methods are acceptable (Konert and Vandenberghe, 1997). The facilities that will conduct the size analysis should be contacted to determine what type of preparation is needed for the sediment prior to size analysis. For example, prior to size analysis using a laser diffraction (LISST-100X with mixing chamber) (Pedocchi and Garcıa, 2006), Gellis (2014) prepared the sediment samples for size distribution analysis by disaggregating the sample in a sodium hexametaphosphate solution that was sonicated for 5 minutes, shaken for 16 hours, and then analyzed on the LISST-100X to determine the median particle size (D_{50}) (Wolf *et al*., 2011). Typically, the median surface area and median grain size of the sediment are used in the grain size correction procedure and can be reported by size-analysis outputs and laboratory reports.

4.3.3 Organic Content

Enrichment of loss of organic matter during the erosion cycle can also affect the tracer property, and correcting for differences in organic content between the source and target samples should be performed. Organic content of the sediment can be determined using loss-on-ignition (ASTM D7348-13, 2013).

4.3.4. Field and Laboratory Quality Assurance

4.3.4.1 Precision and Accuracy

Precision is the degree of agreement among repeated measurements of the same characteristic, or parameter, and gives information about the consistency of methods. Accuracy is a measure of confidence that describes how close a measurement is to its "true" value. Duplicate measurements will be performed for sediment source and fluvial samples.

Field analytical precision will be evaluated by the relative percent differences (RPDs) between field duplicate samples and/or duplicate readings using the following formula:

$$RPD = [(R1 - R2)/\{(R1 + R2)/2\}] \times 100 \qquad (12)$$

where: R1 = the larger of the two duplicate values

R2 = the smaller of the two duplicate values

The values of the RPD are intended to provide information on the variability of field samples. Differences that are greater than 10% are flagged but not discarded. Replicate analyses for the two samples are averaged for the final sediment sourcing analysis.

4.3.4.2 Data Representativeness

Representativeness is the extent to which measurements actually represent the true environmental condition. It is the degree to which data from the sampling accurately represent a particular characteristic of the watershed that is being tested. Representativeness of samples is ensured by adherence to standard field sampling, measurement, and laboratory protocols. The design of the sampling scheme and number of samples for this plan provide representativeness of the part of the watershed being monitored. The representativeness of the data is dependent on: 1) the sampling locations, 2) the number of samples collected, and 3) the sampling procedures. Site selection and use of only approved analytical methods will ensure that the measurement data represents the conditions at the site. The goal for meeting total representation of the targeted drainage area is tempered by the availability of time and funding. Representativeness will be measured with the completion of sample collection in accordance with the approved Quality Assurance Project Plan (QAPP) (USEPA, 2001).

4.3.4.3 Data Comparability

Comparability is the degree to which data can be compared directly to data from similar studies. The comparability of the data produced is predetermined by the commitment of the staff to use only approved procedures as described in this manual. Comparability is also guaranteed by reporting data in standard units, by using accepted rules for rounding figures, and by reporting data in a standard format. The methods used to determine sediment sources are methods that are established in the literature.

By its very nature, soil is highly heterogeneous and variability among samples is expected (ITRC, 2012). Comparability will be checked by collecting replicate samples (about 10% of sediment source samples). Replicate samples are collected by sequentially taking two field samples for each analysis from the same source. Comparability goals for field replicate samples are to have results within 10% of each other. Samples that exceed this are not discarded but are flagged. The replicate sample is not used in the analysis and the two samples, the field and replicate, should not be averaged (ITRC, 2012). Unless there is clear evidence that the sample has been compromised, the laboratory value should be used.

4.3.4.4 Statistical Methods

Several analytical and statistical steps are used to determine which tracers are most significant in defining sediment sources (Fig. 28) as follows:

- Determine if there are outliers for each tracer in each source type.
- Test if tracers in each source group need to be corrected for size differences between the source samples and the fluvial sample.
- Test if tracers in each source group need to be corrected for organic content differences between the source samples and the fluvial sample.
- Perform a bracket test of size- and organic-corrected fluvial and source samples for each tracer.
- Determine the optimum number of tracers that discriminate among the sources using stepwise discriminant function analysis (DFA).
- Identify source percentages using a mixing model on the final set of tracers.
- Perform error analysis using Monte Carlo and other designs.

To assist the user in the statistical steps outlined above for sediment fingerprinting, the USGS has designed the Sediment Source Assessment Tool (Sed_SAT) (Gorman-Sanisaca *et al*., In Preparation).

Statistical methods to allocate sediment sources

- Imputing non-detects
- Outlier removal
- Size and organic corrections
- Bracket test
- Stepwise Discriminant Function Analysis
- Multivariate *unmixing* model
- Error Analysis

Figure 28. Summary of statistical operations used in sediment fingerprinting to apportion sediment sources.

4.4.1 Outlier Test

The presence of outliers can lead to errors in data analysis and statistical conclusions (Helsel and Hirsch, 1992). The first step in the statistical procedure is to remove outliers. In each source group, each tracer is tested to determine if it has a normal distribution using the Shapiro-Wilk test at a 95% confidence interval (H_o = samples that are random and come from a normal distribution). All variables that were not normally distributed are tested again for normality after transformation using a log, power, square root, cube root, inverse, and inverse square root function (Helsel and Hirsch, 1992). The best transformation for normality is selected (if necessary aided by visual analysis of histograms), and the tracers are transformed. The average and standard deviation within each source group for each transformed tracer are determined. If the tracer value for a given source sample exceeds three times the standard deviation more or less than the average value, this sample is considered an outlier and the entire sample is removed from further analysis (Wainer, 1976).

4.4.2 Correcting Source Tracers for Sediment Size and Organic Content Variability

The property of a sediment tracer not only depends on source material but also on grain size and organic content (Collins *et al*., 2010; Horowitz, 1991). As sediment is eroded and transported through the watershed over time, grain size may change. Generally, sediment delivered out of a watershed has a finer grain size compared to the source areas (Walling, 2005). The finer grain sizes have potentially greater surface area to sorb constituents and consequently have a higher tracer concentration. Conversely, iron oxides that develop on coarser sediment in the silt range may also contain more sites for constituents to sorb onto resulting in higher concentrations. Organic matter on sediment can also result in additional sites for sorption of tracers or include tracer elements within organic molecules.

A correction procedure using loss on ignition (LOI) values or total organic carbon (TOC) concentration of the sediment can be applied to account this effect. It is worth noting that while some researchers agree that sediment should be corrected for organic content differences, others report that this results in ‘overcorrecting’ of sediment tracer concentrations (Koiter *et al*., 2013; Smith and Blake, 2014).

To assure that tracer concentrations from sediment sources are comparable to concentrations in target sediment based on grain size and organic content, the source samples need to be corrected for grain size and organic content. Gellis *et al*. (2015) applied a regression approach to correct for grain size differences between the target and source samples.

For each source group, linear regression was used to determine if the relation of median grain size (D_{50}) or TOC to a given tracer's concentration was significant. Tracer concentrations are corrected first for grain size and then for organic content. An example of how tracer concentrations are corrected using D_{50} is shown in Figure 29. Corrections of organic content follow the same approach.

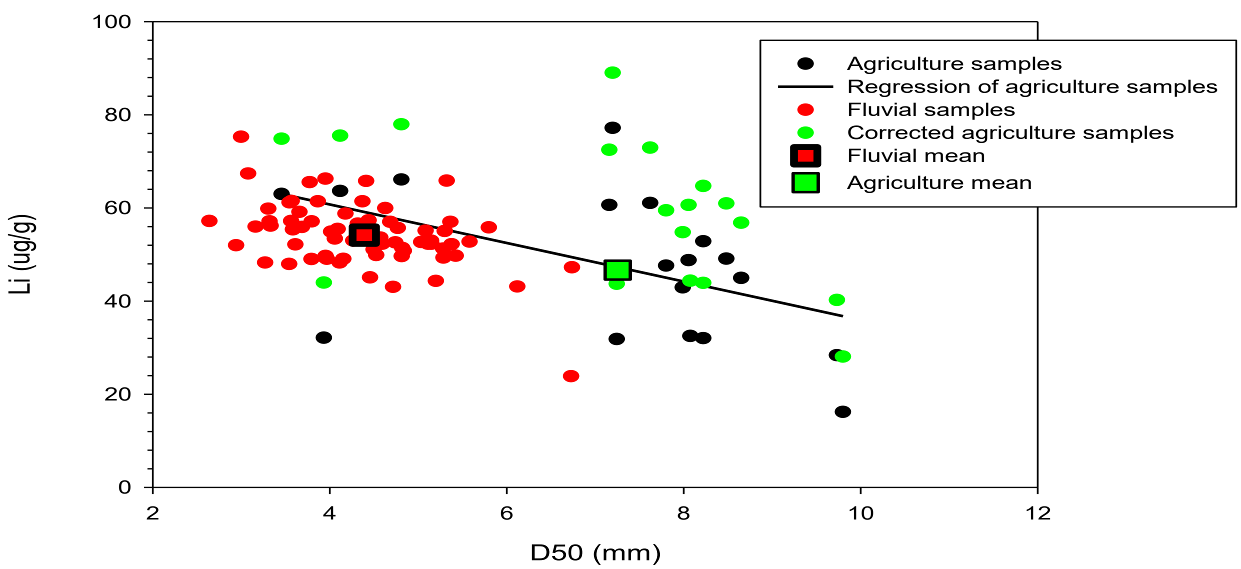


Figure 29. Example of how the size-correction factor is applied to a source group. In this example, the D_{50} from agriculture samples was regressed against the tracer lithium (Li). The line of best fit of agriculture D_{50} and agriculture lithium is negative, showing the concentration of lithium in the agriculture samples decreases as D_{50} increases. The average of D_{50} of fluvial samples is finer than the average D_{50} of agriculture samples. To correct for the differences in size, lithium should be adjusted to be higher. [mg, milligrams; g, grams; D_{50}, median grain size of fine sediment; µm, microns] (Gellis et al., 2015).

Guidelines used to determine if the relation of D_{50} or TOC to a given tracer's concentration is significant include determining that the slope of the regression line is significant ($p<0.05$) and the residuals area normally distributed. The Shapiro-Wilk test (H_o (null hypothesis)= samples are not random and do not come from a normal distribution) is used to determine that the residuals follow a normal distribution. Plots of residuals compared to predicted values as well as histograms and QQplots of the residuals are also used to determine if the regression model is reasonable. In a plot of residuals compared to predicted values, a regression model is considered to be reasonable where the residuals show no curvature or changing variance (Helsel and Hirsch, 1992).

The steps used to determine the best regression model are: 1) determine if the relation of untransformed D_{50} and TOC compared to each source group's tracer concentration is significant; 2) if no significant relation is found, then D_{50} and TOC are transformed using the Tukey Ladder of Powers transformations. The transformed D_{50} and TOC are then regressed for each source group's tracer concentrations to find the best regression model; 3) if after (2) is completed, no significant relations are found, then the tracer concentration values are transformed using the same transformations applied to D_{50} and TOC . The transformed tracer concentration values for each source group are regressed with all possible combinations of transformed D_{50} and TOC (including untransformed), and the optimum regression model is selected. If no significant relation is found with D_{50} or TOC in (1), (2), or (3), a correction factor is not applied. It should be noted that the tracers $\delta^{13}C$, $\delta^{15}N$, and %N are affected by the relative proportions of different kinds of organic matter in the sample, not the total organic matter content. These tracers, $\delta^{13}C$, $\delta^{15}N$, and N should not be corrected by TOC.

If the regression model of a source group's tracer compared to D_{50} is determined to be significant, then a correction factor is applied to the tracer as follows:

$$C_n = \{Ti_{i(n)} - [(D50_n - FD50)*m]\}^{\wedge} \quad (13)$$

where:

Cn = untransformed tracer after size correction;
$Ti_{i(n)}$ = value of tracer (i) (if transformed in source group (n);
$D50_n$ = the mean D_{50} of samples in source (n) (if necessary the values of D_{50} are transformed and a mean of the transformed D_{50} is determined);
$FD50$ = the mean D_{50} of target samples (if necessary, the target samples are transformed as the $D50$ samples in source (n) and a mean of the transformed variables is determined);
m = slope of regression line of tracers in source group (n) (if necessary, tracer is transformed) versus D_{50} of source group (n) (if necessary, D_{50} is transformed); and
^ = if the tracer is transformed, the final corrected tracer is untransformed.

If the regression model of a source group's tracer concentration values compared to TOC was determined to be significant, then a correction factor is applied to the tracer as follows:

$$C_o = \left\{Ti_{i(n)} - [(CS_n - CF) * m]\right\}^{\wedge} \quad (14)$$

where:

C_O = untransformed tracer after organic correction;
$Ti_{i(n)}$ = original value of tracer (i) (if necessary,) in source group (n);
CS_n = average TOC of source group (n) (if necessary, the values of TOC are transformed and a mean of the transformed TOC is determined);
CF = average carbon content of target samples (if necessary, the target samples are transformed by the same transformation as the TOC samples in source (n) and a mean of the transformed variables is determined);
m = slope of the regression line of tracers in source group (n) (if necessary, tracers are transformed) versus TOC of source group (n) (if necessary, TOC is transformed); and
^ = if the tracer is normalized by a transform, the final corrected tracer is untransformed.

Equations 13-14 are used with the mean of a source group's D_{50} as well as the mean D_{50} of all target samples. Corrections can also be made using an individual target sample, where the difference of each target sample's D_{50} or TOC and the mean source D_{50} or TOC (for a given source group) is determined and a correction is applied to each source sample. If an individual target sample is used the mean in equations 13-14 are replaced with the individual target sample's D_{50} and TOC.

When determining the size-correction factor, it is important that the results be unbiased. If a non-linear model is used, a bias in the estimation can occur (Koch and Smillie, 1986). The bias occurs when tracers that are transformed are then corrected using Eq's. 13-14 and then untransformed. Bias correction factors ($\hat{B}$) should be applied to the corrected, untransformed tracer concentrations only for those tracers that are transformed prior to correction. If D_{50} or TOC are transformed in the determination of correction factors but the tracer concentration is not transformed, no bias correction is required. Bias correction factors ($\hat{B}$) are determined by using the transformed tracer concentration per the equations given in Table 8 (Stuart and Ort, 1991). The size- or organic-corrected tracer concentration is divided by $\hat{B}$ to calculate the final untransformed tracer value.

Table 8. Equations used to correct for bias in untransforming the tracers (Gellis et al., 2015).
[B, the bias correction factor; *f(y), the* transformed value of the tracer; D_{50}, the median grain size of the sediment; $\overline{x}_s$, the mean value of all transformed D_{50} or total organic carbon (TOC) for a given sediment source; $\overline{x}_f$, the mean value of the transformed D_{50} for the target samples; $\hat{b}$, is the slope of the line of best fit; $\hat{\sigma}_b^2$, is the standard error of the regression of D_{50} of TOC compared to tracer concentration; exp, exponential]

Transformation	$\hat{B}$
Squared	$1+\frac{1}{8}[f(y)-(\overline{x}_S-\overline{x}_F)\hat{b}]^{-2}(\overline{x}_S-\overline{x}_F)^2\hat{\sigma}_{\hat{b}}^2$
Square root	$1+[f(y)-(\overline{x}_S-\overline{x}_F)\hat{b}]^{-2}(\overline{x}_S-\overline{x}_F)^2\hat{\sigma}_{\hat{b}}^2$
Cube root	$1+3[f(y)-(\overline{x}_S-\overline{x}_F)\hat{b}]^{-2}(\overline{x}_S-\overline{x}_F)^2\hat{\sigma}_{\hat{b}}^2$
Inverse	$1+[f(y)-(\overline{x}_S-\overline{x}_F)\hat{b}]^{-2}(\overline{x}_S-\overline{x}_F)^2\hat{\sigma}_{\hat{b}}^2$
Inverse square root	$1+3[f(y)-(\overline{x}_S-\overline{x}_F)\hat{b}]^{-2}(\overline{x}_S-\overline{x}_F)^2\hat{\sigma}_{\hat{b}}^2$
Log	$10\hat{}[(\overline{x}_S-\overline{x}_F)^2\hat{\sigma}_{\hat{b}}^2/2]$

4.4.3 Bracket Test

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, the next step in a statistical analysis is determining that for a given tracer, the fluvial samples are within the range of the equivalent values obtained for the potential sources (Gellis and Walling, 2011) (Fig. 3). The bracket test is an important prerequisite before further statistical analyses are performed. Any tracers that do not satisfy this constraint within the measurement error (10% of each fluvial sample's tracer value) are considered to be non-conservative and are removed from further consideration. The bracketing test is performed on tracers after the particle size and organic correction factors are applied.

4.4.4. Stepwise Discriminant Function Analysis

Collins and Walling (2002) and Collins *et al.* (1997) have suggested that a composite of several tracers provides greater ability to discriminate between sources than a single tracer. To create the optimal group of tracers, a stepwise DFA was used to select tracers after size and organic corrections were applied (Fig. 28). This procedure assumes normality among the variables being analyzed; thus, all variables used in the DFA were tested for normality using the Shapiro-Wilk test (H_o = samples are random and come from a normal distribution). All variables that are not normally distributed at a 95% CI should be tested again for normality after transformation using a log, power, square root, cube root, inverse, and inverse square root function (Helsel and Hirsch, 1992).

The best transformation for normality is selected (if necessary), and stepwise DFA is performed on the normalized data. Stepwise DFA incrementally identifies which tracers significantly contribute to correctly differentiating the sediment sources and rejects variables that do not contribute based on the minimization of the computed value of the variable Wilks' lambda (Collins *et al.*, 1997). A lambda close to 1.0 indicates that the means of all tracers selected are equal and cannot be distinguished among groups. A lambda close to zero occurs when any two groups are well separated (within group variability is small compared to overall variability). Thus, the model selects a combination of tracers that provide optimal separation, meaning that no better separation can be achieved using fewer or more tracers. The statistical program Statistical Analysis System (SAS) was used in stepwise DFA (SAS Institute, 2004). A probability value of 0.01 was used to determine significance in the stepwise DFA.

4.4.5 Computation of Source Percentages

The final step in the statistical analysis is determining the significant sources of sediment using an unmixing model (Fig. 3; Eqs. 3, 4, and 5; all modified from Collins *et al.*, 2010). The set of tracer values that are determined from the stepwise DFA are used in the mixing model but with the particle size and organic correction factors applied. The mixing model does not use data transformed for normality, but it does use the values that have been adjusted for D_{50} and TOC.

$$\sum_{i=1}^{n}\left\{\left[C_i - \left(\sum_{s=1}^{m} P_s S_{si}\right)\right] / C_i\right\}^2 W_i \quad (15)$$

and

$$\sum_{s=1}^{n} P_s = 1 \quad (16)$$

where:

C_i = concentration of tracer property (i) in the suspended sediment collected during storm events;

P_s = the optimized percentage contribution from source category (s);

S_{si} = mean concentration of tracer property (i) in source category (s) after size and TOC correction factors are applied in source category (s);

W_i = tracer discriminatory weighting;

n = number of fingerprint properties comprising the optimum composite fingerprint; and

m = number of sediment source categories.

Collins *et al.* (2010) applied the particle size and organic corrections factors directly in the mixing model. In this modified version (Eq. 3), the set of tracer values that were determined from the stepwise DFA were used in the mixing model with the particle size and organic correction factors applied.

The mixing model iteratively tests for the lowest error value using all possible source percentage combinations. A P_s step of 0.01 is used in the source computations. The tracer discriminatory weighting value, *Wi*, is a weighting used to reflect tracer discriminatory power in Eq. 3 (Collins *et al.*, 2010). This weighting is based on the relative discriminatory power of each individual tracer provided by the results of the stepwise DFA and ensures that tracers that have a greater discriminatory power are optimized in the mixing model solutions. The weighting for each tracer that passed the stepwise DFA test is determined as follows:

$$Wi = \frac{P_i}{P_{opt}} \quad (17)$$

where:

W_i = tracer discriminatory weighting for tracer (i);

P_i = percent of source type samples classified correctly using tracer (i). The percent of source type samples classified correctly is a standard output from the DFA statistical results; and

P_{opt} = the tracer that has the lowest percent of sample classified correctly. Thus, a value of 1.0 has a low power of discriminating samples.

4.4.6 Limitations and Uncertainty in Sediment Fingerprinting

A Monte Carlo approach is used to quantify the uncertainty in sediment fingerprinting results produced by the mixing model (Collins and Walling, 2007). The Monte Carlo simulation randomly removes one sample from each of the source type groups, and the mixing model is run without these samples. The Monte Carlo simulation is conducted 1,000 times on each target sample. For each of the 1,000 iterations, the average, minimum, and maximum sediment-source percentage for each source are determined.

Another estimate-of-error assessment available uses the source samples and runs them through the mixing model. Ideally, putting source samples through the model should result in the output indicating 100% of that source. For example, using a bank sample should result in the mixing model showing 100% bank-derived sediment. However, because of variability in source tracer properties and possible deposition from other sources, the results may not always be 100% accurate. For example, the top portions of a streambank may be an active floodplain that is still receiving sediment from upstream sources. If a sample reveals a small percentage of its designated source (i.e., <50%), the history of the sample, i.e., collection and laboratory results, should be examined and a decision made whether the sample was contaminated and whether it should be kept in the analysis.

4.5 Analyzing Results

4.5.1 Weighting Sediment Apportionment

Suspended-sediment samples collected using automatic or manual samplers may be collected at several times during an event as well as for several events. The practitioner has the option of averaging source apportionment results for each sample or weighting the results by sediment load. It is reasonable to weight samples by the sediment load for each sample or for each storm (Box 9). In addition, results for each storm could be weighted by the total sediment mass transport during the study period (Box 10).

The concept of weighting sediment-fingerprinting results can be demonstrated by using an example of sediment coring. For example, if a target sample for sediment sourcing was obtained by coring a reservoir that was constructed 20 years ago; the thickness of the deposited sediment in the reservoir would vary with the transported load of each event over the 20-year period. The larger sediment loading events would have thicker sediment deposits. Coring the entire sediment package would weight each event because the higher loading events would have greater sediment thicknesses compared to other events. The same logic may apply to weighting samples by the sediment transported for that sample or that event. The larger events transported more sediment and should be weighted (if sediment records exist) by loadings. If sediment records do not exist, peak flow or some other hydrologic factor may be used.

Box 9. Example of weighting sediment fingerprinting results by the load computed for each sample.

Each sample represents an interval of time. Suspended-sediment load computations for each time interval are computed following Porterfield (1977) using the USGS program GCLAS (Graphical Constituent Loading Analysis System) (Koltun et al., 2006). Each interval suspended sediment load is divided by the total load of the event to compute the weighted total load (Col B). Fingerprinting results for each sample are found in columns C to E. These results can be averaged for each sample in the event. The weight of each sample (Col B) is multiplied by each sample's result (columns F, G, and H). The sums of each column F, G, and H, is the weighted source percentages.

				Col (A)	Col (B)	Col (C)	Col (D)	Col (E)	Col (F)	Col (G)	Col (H)
Sample #	Date	Sample time	Time interval sample covers	Suspended sediment load for time interval, megagrams	Weighted-total load	Sediment Fingerprinting Results			Samples Weighted by Sediment Load		
						Agriculture	Banks	Forest	Agriculture	Banks	Forest
1	12/11/2008	16:24	15:00-18:48	25	0.01	13	87	0	0	1	0
2	12/11/2008	19:15	18:48-19:48	55	0.03	22	76	2	1	2	0
3	12/11/2008	20:15	19:48-20:48	67	0.03	27	64	9	1	2	0
4	12/11/2008	21:15	20:48-21:48	146	0.07	52	36	12	4	3	1
5	12/11/2008	22:15	21:48-22:48	454	0.23	40	42	18	9	10	4
6	12/11-12/2008	23:48	22:48-00:48	545	0.27	27	61	12	7	17	3
7	12/12/2008	1:48	00:48-02:48	304	0.15	40	60	0	6	9	0
8	12/12/2008	5:51	02:48-08:54	353	0.18	59	33	8	10	6	1
9	12/12/2008	10:00	08:54-12:04	35	0.02	72	25	3	1	0	0
10	12/12-13/2008	14:17	12:04-04:30	10	0.01	51	49	0	0	0	0
						Average sources (%)			Weighted source (%)		
			Total load	1684		40	53	6	40	50	10

Box 10. Example of weighing sediment fingerprinting results by the sediment load for each sampled storm event.

			Fingerprinting source results					
Date event	Suspended sediment load, megagrams	Weight	Agriculture	Banks	Forest	Agriculture	Banks	Forest
10/31/2009	112	0.02	42	56	2	1	1	0
11/12-13/2009	202	0.04	33	66	1	1	3	0
12/11-13/2008	1684	0.36	13	87	0	5	31	0
1/15/2009	45	0.01	59	36	5	1	0	0
2/3/2009	88	0.02	51	42	7	1	1	0
2/14-16/2009	987	0.21	12	79	9	3	17	2
4/15/2009	54	0.01	40	60	0	0	1	0
5/2-3/2009	455	0.10	33	66	1	3	6	0
5/25-26/2009	376	0.08	16	76	8	1	6	1
6/3/2009	41	0.01	41	55	4	0	0	0
6/5/2009	36	0.01	35	62	3	0	0	0
6/13-14/2009	344	0.07	20	80	0	1	6	0
7/12/2009	69	0.01	9	91	0	0	1	0
7/22/2009	88	0.02	12	88	0	0	2	0
9/12-13/2009	109	0.02	6	93	1	0	2	0
			Averaging			Weighted		
Sum	4690		28	69	3	19	78	3

To include the importance of samples collected during periods of high sediment loading, the sediment sources determined for each sample should be weighted by the total amount of sediment transported for that event (storm weighted) using the following equation:

(18)

where:

S_{vj} = storm-weighted source allocation for sediment source (v) (e.g., streambanks, agriculture, or forest) (in percent) and event (j);

SA_{vi} = sediment source allocation (in percent) for source (v) and storm sample (i);

SL_i = sediment load for storm sample (i), in megagrams;

SL_{tj} = total sediment load for event (j), in megagrams, determined using the program Graphical Constituent Loading Analysis System (GCLAS) (Koltun *et al.*, 2006); and

n = number of samples (i) collected during storm event.

As previously discussed, because of mass constraints, a storm sample represents one instantaneous time or several times on the storm hydrograph. To determine a sediment load for a given sample (SL_i), a time interval is assigned for each sample. Discharge is usually computed at 15-minute intervals but can vary. The time interval for each sample is midway between the previous and next samples. The first sample is assigned a time to the nearest measured interval (e.g., 15- minute intervals) before that sample and midway to the next sample time. The last sample is assigned a time midway to the previous sample time and the nearest measured interval (e.g., 15-minute intervals) after that sample. Each sample's time interval is input into programs that compute sediment. For the USGS, this is the program GCLAS (Koltun *et al*., 2006; available at *http://water.usgs.gov/software/GCLAS/*) and a sediment load (mg) was determined for that time interval. The sum of sediment loads for each time interval is the total sediment load for the event (Box 10). If sediment sources are determined for several events, the source percentages for each event can be weighted by the sediment load of that event compared to the total sediment load of all events (Box 10).

The sediment source weighting for the entire study period (total load-weighted percentage) is determined using the equation:

$$TS_{vj} = \sum_{j=1}^{m} \left[S_{vj} * \left(\frac{SL_{tj}}{SL_p} \right) \right] \tag{19}$$

where:

TS_{vj} = total load-weighted sediment-source allocation for sediment source (v);

S_{vj} = sediment source allocation for source (v) for event (j);

SL_{tj} = total sediment load for event (j), in megagrams (Eq. 6);

m = number of events during the study period = 36; and

SL_p = total sediment load for 36 events, in megagrams.

A similar approach for representing sediment sources for an entire study period was used by Walling *et al*., (1999) and Gellis *et al*. (2009).

5.0 Summary

Sediment is one of the leading pollutants in the United States degrading aquatic habitats. In order to effectively manage sediment and reduce sediment loads, it is necessary to identify the sources of sediment. In general, watershed sediment sources can be separated into two broad categories: 1) upland areas of various land cover, and 2) the stream corridor (channel bed, banks, and floodplain). Differentiating between upland and channel sources is important because management strategies to reduce sediment differ by source and require very different approaches. Reducing agricultural sources may involve soil conservation and tilling practices, whereas channel sources of sediment may involve bank stabilization and channel restoration to arrest downcutting. The manual provides information on using a sediment budget approach to understand the erosion, deposition, and delivery of watershed-derived sediment. We also highlight the sediment fingerprinting approach in apportioning sediment sources. These approaches can be used to assist in management strategies concerned with sediment TMDLs, assessing the contributions from various land uses, and contrasting this to the stream channel, as well as monitoring the effectiveness of management actions to reduce sediment.

A sediment budget is an accounting of the inputs (erosion) and storage (deposition) of sediment that in theory match the output or sediment transported out of the watershed. The available tools and approaches used to construct a sediment budget are considerable, and selection will depend on many factors, such as financial resources and temporal and spatial aspects of the study. Determining upland erosion and deposition can involve pins, nets, impoundment surveys, the Cesium-137 approach, GIS analysis, and modeling. Determining stream-corridor erosion and deposition involves monumented channel surveys, bank pins, floodplain markers, ground-based and airborne LiDAR, aerial photographs, and modeling.

The first step in any sediment budget program is to decide on the watershed scale and the time frame of the study. Before measurements are made, it is important to 'get to know your watershed' by reading published literature, local reports, local maps, and GIS analyses, all of which help to understand historical and current sediment problems, land cover in the watershed, and any hydrologic alterations that may be present. Map and GIS interpretations can create longitudinal profiles of the channel that are used to classify steep (incisional) and shallow (depositional) reaches. Aerial photographic surveys can identify upland sediment sources and channel planform width and depth, which may target areas of erosion and deposition. Meeting with stakeholders and local management authorities is important in understanding management problems in the watershed, and lines of communication should be established in the early stages of sediment budget development.

A car or aerial reconnaissance of the watershed is important in understanding the geomorphic setting of the watershed. Filling out geomorphic assessment forms during the reconnaissance can aid in developing qualitative assessments of watershed features, such as: incised reaches, location of steep banks, depositional reaches with bar occurrence, upland sites of bare ground (e.g., construction sites), riparian canopy density, etc. The information gleaned from the reconnaissance can help in site selection for monitoring.

The approaches and tools used to construct a sediment budget generally fall under three categories: 1) field approach, 2) remote sensing, and 3) modeling. Site selection can be: 1) judgement based, such as selectively choosing incised reaches, or 2) a random design, where sediment sources are rasterized in a GIS and chosen randomly, such as agricultural areas, or 3) based on regulatory requirements, such as monitoring restoration activities. Site selection should be carefully designed to provide reliable assessments of erosion and deposition.

Elements in the channel corridor that are examined for change over time include the floodplain, channel banks, channel bars, and the channel bed. Sites for measuring channel elements can be organized around a reach that is typically of a length to incorporate channel variability in width, depth, and sinuosity. This is often achieved with a reach that is one meander length. Establishing two or more cross sections in a reach can capture the form variability. To capture spatial variability, reaches of varying contributing areas should be monitored. Monitoring by stream order can in part fulfill this objective.

Field approaches to quantify channel corridor changes include pins, surveys, and ground-based LiDAR. Some measurements are linear (cm) (i.e. pins), some are cross sectional (m^2) (i.e. channel resurveys), and others can be volumetric (m^3) (i.e. a pond survey). Accounting of erosion and deposition in a sediment budget is displayed as either a volume (m^3) or a mass (kg). Linear changes are converted to cross-sectional area (m^2) by multiplying the linear change (cm) by the width, length, or height of the channel feature (i.e. height of the channel bank). All cross-sectional area changes (cm^2) are averaged for a reach and then averaged for all reaches in that stream order. The average change in channel features for each stream order (m^2) is multiplied by the length of that stream order (m) to obtain a volume (m^3). Multiplying this volume by the average density (g/cm^3) of the channel feature for the selected stream order provides an estimate of mass (kg). Dividing the mass by the number of days of the study period (kg/day) and multiplying by 365.25 provides an annual mass (kg/yr) for that land use type.

Current and historical photogrammetric information (aerial photographs and airborne LiDAR) can be used to quantify channel widening (width, m). The digital photographs need to be georeferenced into a GIS and changes over time in the distance between bank streambank edges can be used to calculate streambanks retreat. Airborne LiDAR can be used to quantify changes in cross-sectional area (width and depth, m^2) and volumetric changes (m^3) over time. Digital elevation models created from the LiDAR data are used with appropriate software to quantify cross-sectional and volumetric changes in channel morphology.

Floodplain deposition can be monitored using permanent markers installed on the floodplain (e.g., clay pads and tiles) placed along a cross-sectional transect. All measurements of deposition (mm) are averaged for the floodplain portion of the cross section to compute a change in cross-sectional area (m^2). The cross-sectional area change for each cross section is averaged for the reach and then averaged by stream order (m^2). The length of each stream order (m) is multiplied by the average cross-sectional area change for each stream order to obtain a volume of deposition (m^3), which is multiplied by the average floodplain density for that stream order

(g/cm^3) to obtain a mass (kg). Dividing the mass by the number of days of the study period (kg/day) and multiplying by 365.25 provides an annual mass estimate (kg/yr).

In the early stages of sediment budget development, upland areas for source analysis are mapped out. Upland areas can be classified by land use or soil type. Unpaved roads also fall under the classification of upland erosion. Upland erosion can be measured using traps and nets to capture the mass of eroded sediment (g). The mass is normalized by the contributing area to compute a yield (kg/m^2). Pins can also measure ground surface lowering and deposition (cm) and are arrayed in grids or along transects. The pin measurements are averaged for the plot area (m^2) to obtain a volume (m^3) and then multiplied by the average soil density (g/cm^3) in the measurement area to obtain a mass (kg). The mass is divided by the measurement area to obtain a yield (kg/m^2). Yields (kg/m^2) are multiplied by the upland areas they represent (i.e., pasture) to obtain a total mass of change (kg). Dividing the mass by the number of days in the study period (kg/day) and multiplying by 365.25 provides an annual mass (kg/yr) for that land use type.

For unpaved roads, at each transect the linear changes in the unpaved road surface (cm) are multiplied by the width of the road (m) to obtain a cross-sectional area (m^2). At each reach, all measurements on unpaved road surface are averaged and multiplied by the total length of roads to obtain a volume (m^3). This volume is multiplied by the average density of roads (g/cm^3) to obtain a mass estimate (kg).

The cesium-137 technique can be used to estimate soil erosion and deposition. It is based on the principle that non-eroding areas (i.e. the summit of a stable forested slope) reflect the reference condition of cesium-137. By comparing the inventory of cesium-137 for several reference sites to other slopes of varying land use, estimates of erosion and deposition can be made using appropriate models. Hillslopes of selected land covers are cored for soil samples at several locations along a transect that extends from the summit to the toe. Samples from each location are analyzed for cesium-137. Cesium-137 displays a characteristic profile with depth on stable surfaces. For the reference site, it is important to sample at several cm incremental depths to establish the site as a reference. To assess variability in reference inventories, it is important to sample several reference sites.

The output or export of sediment from the watershed of interest is important in closing the sediment budget. The output of sediment is typically measured as sediment loads or sediment volumes. Suspended-sediment collection and load computation are standard practices for agencies such as the USGS, and methods to collect and compute sediment can be downloaded at their websites. Computation of sediment loads has less error than the measurement of inputs and storage and, therefore, is an important aspect of the sediment budget. Volumetric measurements are often based on bathymetric surveys of impoundments (ponds and lakes).

The final step in computing a sediment budget is the summation of all measurements on inputs and storage terms. All sediment inputs and storage terms should balance to the output, but this seldom happens. Causes for the discrepancy include measurement error, the natural variability of channel and upland erosion and deposition, and the number of measurements. It is recommended that in the final calculation of the sediment budget, error estimates are presented for the input and storage measurements. This way, the sediment budget can be represented as a range. Often the range of values are shown as confidence intervals (i.e. 10^{th} and 90^{th} percentiles).

Sediment fingerprinting is a technique that apportions the sources of fine-grained sediment in a watershed using tracers or fingerprints. The sediment fingerprinting procedure establishes a minimal set of physical and/or chemical properties (tracers) based on samples collected in upland or channel locations identified as potential sources of sediment. Due to different geologic and anthropogenic histories, the chemical and physical properties of sediment in a watershed may vary and often represent a unique signature (or fingerprint) for each source within the watershed. Fluvial sediment samples (the target sediment) also are collected and exhibit a composite of the source properties that can be apportioned through various statistical techniques.

There are a number of steps involved in the sediment fingerprinting approach including source sampling, lab analysis, statistical operations, and results. Potential sediment sources in the watershed are identified using the same procedure that was used in the sediment budget analysis. Target sediment can include suspended sediment, bed sediment, floodplain sediment, and reservoir or lake sediment, and each has its own sampling procedure.

The choice of tracers is broad and can include elemental analysis, stable isotopes, magnetic properties, color, mineralogy, and radionuclides. Collection of appropriate mass is a consideration in tracer type analysis. It is important to contact the laboratory where the analyses will be performed to ask questions pertaining to sample mass and holding requirements.

Soil samples for source analysis collected from upland areas are taken from the top 1 to 2 cm. To account for variability in the tracer properties, sediment is collected across transects and composited into one sample. At a channel reach, three to six eroding banks are sampled, each spaced a minimum of 10 m apart. Streambanks are sampled from the bottom to the top of the bank face and composited into one sample.

All source and target samples are wet-sieved though a 63-micron polyester sieve. The slurry is dried at 65°C, and the dried material is collected for laboratory analysis. Fluvial sediment, because it has been eroded and transported through the watershed, often has a smaller grain size diameter and greater surface area than the source samples. Grain size differences between the target and source samples can cause differences in tracer activity. Grain size or surface area analyses are performed on each sample.

Several statistical steps are used to determine which tracers are most significant in defining sediment sources. This includes: 1) testing for outliers, 2) testing and correcting tracers for differences in grain size and organic content between the source and target samples, 3) testing for the conservativeness of the tracer by confirming that target samples are bracketed by the source samples where target samples that are not bracketed are not used, 4) determining the optimum number of tracers that discriminate among the sources using stepwise discriminant function analysis, 5) identifying source percentages using a mixing model, 6) performing error analysis using a Monte Carlo and other designs, and 7) analyzing results and applying sediment weighting factors.

Combining the sediment budget and sediment fingerprinting results can provide resource managers with information on where to target measures to reduce erosion, sediment delivery, and the net transport of sediment (Gellis and Walling, 2011). Areas where sediment is stored can also be determined by combining the sediment fingerprinting and sediment budget approaches. Box 11 provides an example from Linganore Creek, MD, where the two approaches were combined.

Box 11. Combining Sediment Budget and Sediment Fingerprinting Results

Combining sediment budget and sediment fingerprinting results can provide resource managers with information on where to target measures to reduce erosion, sediment delivery, and the net transport of sediment (Gellis and Walling, 2011). Areas where sediment is stored can also be determined by combining the sediment fingerprinting and sediment budget approaches.

Here the sediment budget results from Linganore Creek are combined with the sediment fingerprinting results (Gellis *et al*., 2015). Sediment budget results provided estimates of gross erosion from upland and erosion from streambanks (Table A). Sediment budget results show the delivered percentages from each source (Table A). The sediment delivery ratio is computed as the delivered sediment divided by the gross input of sediment multiplied by 100 (Table A). Subtracting the delivered sediment from the gross erosion from each source type computes the mass of sediment in storage (Table A).

Table A. Sediment budget and sediment fingerprinting results from Linganore Creek, MD (Gellis *et al*., 2015). Why are some cells blank? Should you indicate?

	Linganore Creek	Gross erosion	Gross erosion	Erosion
	Watershed	Agriculture	Forest	Streambanks
Export of suspended sediment out of the watershed, Mg	5450			
Sediment budget results, Mg		54800	2030	6440
Sediment fingerprinting source apportioning results, %		45	3	52
Delivered sediment, Mg		2453	164	2834
Sediment in storage, Mg		52348	1867	3606
Sediment Delivery Ratio (SDR), %		4	8	44

Box 11. Continued.

According to the sediment budget for Linganore Creek, the total gross input of sediment was 63,270 Mg (Table A). Storage elements measured in the sediment budget (Table B) showed a total storage of 16,240 Mg. The inputs minus the storage measurements yield an output of sediment of 47,030 Mg. The suspended sediment export at the watershed outlet was 5,450 Mg (Table A), indicating that the sediment budget did not account for 41,600 Mg. The errors in the sediment budget could be due to an overestimation of erosion using the Cesium-137 method and/ or not adequately measuring storage areas in the watershed (Gellis *et al*., 2015).

Table B. Summary of storage measurements from the sediment budget conducted for Linganore Creek, MD (Gellis *et al*., 2015)

	Storage (Mg)
Ponds	9320
Floodplain	5180
Streambanks	1040
Channel bed	700

The final diagram of the sediment budget and sediment fingerprinting results is shown in Figure. A.

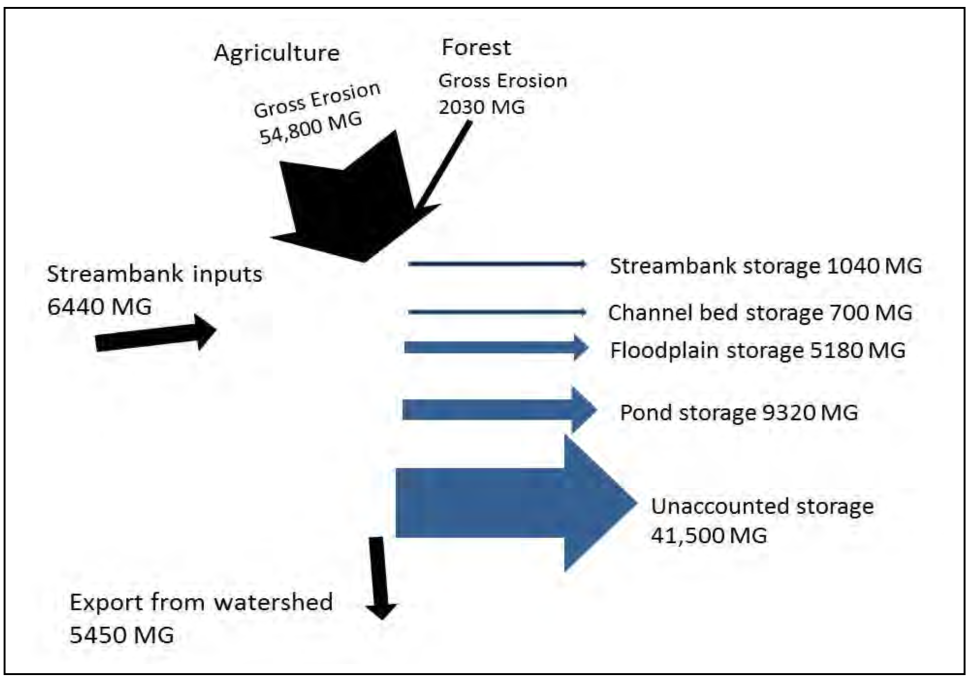


Figure A. Sediment budget and sediment fingerprinting results for Linganore Creek, MD shown as a flow diagram.

Box 11. Continued.

Combining the sediment budget and sediment fingerprinting approaches has implications for land management agencies interested in reducing sediment. The sediment fingerprinting results (total load-weighted percentage) indicate that the two main sources of fine-grained sediment delivered out of the watershed were streambanks (52%) and agriculture (45%). Because streambanks have a higher sediment delivery ratio than agriculture (44% compared to 4%), management actions to reduce sediment may be more effective in reducing the net export of fine-grained sediment if directed toward stabilizing streambank erosion. In addition, streambank sediment is directly delivered to a stream channel and can have an immediate negative effect on aquatic habitat. The sediment budget was able to identify and target areas of high bank erosion (Fig. B).

Ponds and floodplains are important sites of sediment storage. There were numerous ponds in the Linganore Creek watershed (n = 195) constructed on farms and urban areas that drain 16% of the Linganore Creek drainage area. The ponds were estimated to store 9,320Mg, which is 15% of the total eroded sediment. The estimated amount of sediment deposited on floodplains was 5,180 Mg, or 8% of the total eroded sediment.

TOP TEXT IN GRAPHIC IS CUT OFF; CHECK FINAL VERSION (“Sampling Site Numbers”)

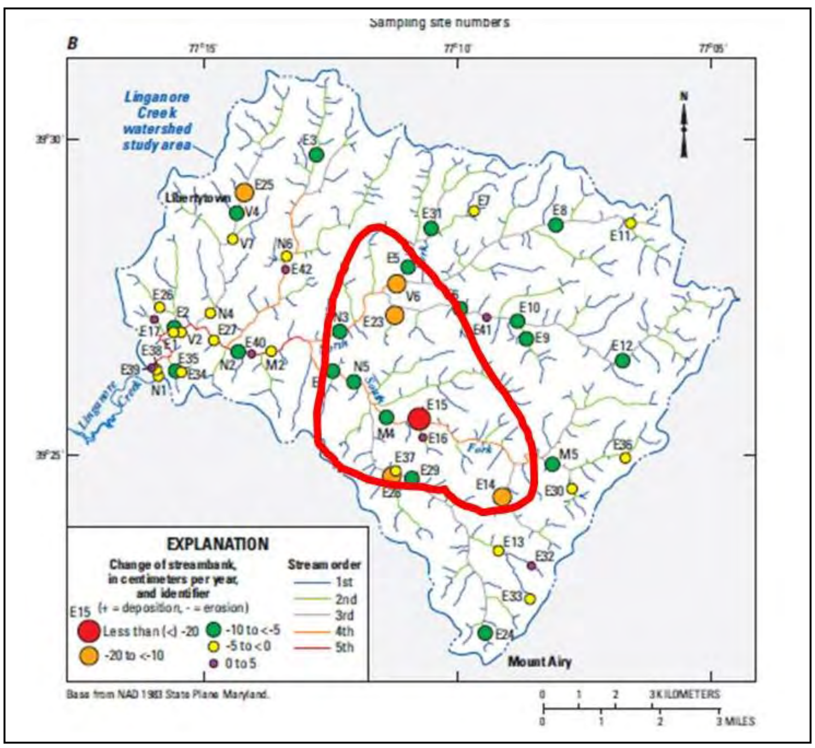


Figure B. Reach averaged streambank changes determined through bank pin measurements (cm per year), Linganore Creek watershed study area, Frederick County, MD, August 11, 2008 through December 24, 2010 (Gellis *et al*., 2015). Areas of high bank erosion are shown in the red circled area.

Box 11. Continued.

The final sediment budget product including sediment fingerprinting may be a report with diagrams. Diagrams of sediment budgets are usually most useful for managers to help understand the magnitude and inputs of sediment inventories and transport. A useful diagram is to display the inputs and storage of sediment along a longitudinal continuum with the width of the arrows representative of the amount of loading associated with each source and sink.

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