Project Final Report

for

A Grant Awarded Through the
Section 319(h) Nonpoint Source
Implementation Program
Cooperative Agreement
#C9994861-08

under the

Section 319(h) Kentucky
Nonpoint Source Implementation
Grant Workplan "Geomorphic
Assessment of Fine-grained
Sediment Loads in the Bluegrass
Physiographic Region"

Kentucky Division of
Water NPS 08-05
MOA PO2-129-0800020365-1

November 1, 2008 to
March 31, 2013

Geomorphic Assessment of Fine-grained Sediment Loads in the Bluegrass Physiographic Region

Michael A. Croasdaile
Arthur C. Parola, Jr.

of

The Stream Institute
Department of Civil and Environmental Engineering
University of Louisville
Louisville, Kentucky 40292

Funding for this project was provided in part by a grant from the US Environmental Protection Agency (USEPA) through the Kentucky Division of Water, Nonpoint Source Section, to the University of Louisville Research Foundation, Inc., as authorized by the Clean Water Act Amendments of 1987, §319(h) Nonpoint Source Implementation Grant #C9994861-08. Mention of trade names or commercial products, if any, does not constitute endorsement. This document was printed on recycled paper.

Acknowledgments

Michael A. Croasdaile, PhD, Assistant Professor of Civil and Environmental Engineering (CEE) at the University of Louisville, was the principal investigator for this project and directed the collection and analysis of stream geomorphic data.

Arthur C. Parola, Jr., PhD, PE, Professor of CEE and Director of the Stream Institute (ULSI), provided technical advice regarding data collection, analysis, and interpretation.

Deven Carigan, Technical Advisor for the Kentucky Nonpoint Source Pollution Control Program, Kentucky Division of Water (KDOW NPS), reviewed the final report.

Margi Swisher Jones and Elizabeth Finzer, former Technical Advisors for KDOW NPS, provided project oversight and technical guidance.

Clayton Mastin, MEng, ULSI Research Project Engineer, conducted the pond survey data collection, helped maintain field equipment, and supervised the programming of dataloggers.

William S. Vesely, ULSI Research Project Engineer, assisted in field data collection and maintenance of field equipment.

Raja M. Nagisetty, PhD, ULSI Research Project Engineer, contributed to sample processing and data analysis.

CEE students J. Duncan Gatenbee, Hannah Gill, Matthew Holthaus, Michael Page, Donald Helstern, Daniel Warren, and Ian R. Van Lierop assisted with data collection and sample processing and conducted analysis of pond survey data. Danielle V. Dresch contributed to the data analysis.

Chandra Hansen, ULSI Research Technical Writer, edited the final report.

We greatly appreciate the willingness of numerous landowners throughout Harrison Fork, Salt River, Currys Fork, Goose Creek, and UT South Elkhorn Creek watersheds to share their knowledge of their property's land use history and to provide access to their land for sampling or surveys.

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Executive Summary

Stream sedimentation affects aquatic communities by choking spawning gravels, impairing food sources, and reducing habitat complexity. This process of deposition of sediment or other material on the channel bed is one of the most common causes of stream impairment in the Commonwealth, where 69% (2735 miles) of streams are listed as sediment-impaired for warm water aquatic habitat (WAH). Because the water quality in these sediment-impaired streams does not support their designated use, the Commonwealth is required under §303(d) of the Clean Water Act to establish pollution management strategies such as watershed based plans (WBPs) and total maximum daily loads (TMDLs) that will be effective in reducing the impairment.

Monitoring and quantifying sediment loads is important for the development of WBPs and the calculation of TMDLs. Few sediment production and or sediment transport studies have been completed in Kentucky, and available data are biased toward larger streams and rivers, where methods of estimating loads that rely on discharge are more applicable than in small, flashy streams where using a sediment rating curve may lead to large errors in sediment load estimates. The goals of this project were to provide Kentucky Division of Water (KDOW) with a geomorphic assessment procedure to measure sediment loads and characteristics and to provide regional reference rates of sediment production and storage that will inform future sediment TMDLs and other watershed-based sediment assessments within the Bluegrass physiographic region of Kentucky. Because available sediment data are so scarce compared to data for nutrients or pathogens, and because KDOW sediment protocols are not yet available, this project is anticipated to be one step of many along the path to developing a final sediment protocol in Kentucky.

Data collection for this project was designed to support the development of methods and tools that would be useful to KDOW for sediment TMDLs and for other watershed-based sediment assessments in the Bluegrass physiographic region of Kentucky. Sediment production, storage and transport, and yield data were collected in three Bluegrass physiographic region watersheds in 2009, 2010, and 2011. At representative sites in each watershed, sediment production was monitored on hillslopes by measuring sediment deposits in ponds. Because weathering had been identified as an important component of bank erosion processes in two previous §319(h) projects in Currys Fork and Goose Creek watersheds, bank pin measurements from Goose Creek and Currys Fork were used to estimate minimum erosion rates that could be applied to other watersheds. Deposition on floodplains and in riffles was monitored along blue-line stream reaches, and sediment yield was monitored at the mouth of each project watershed. These data were combined with previously collected data from Currys Fork and Goose Creek watersheds to develop regional reference rates of sediment production, storage, and yield.

The methods used to collect those data were also evaluated in the development of a geomorphic assessment procedure for KDOW to use to measure sediment loads and characteristics. Discussions with TMDL regarding the measurement of erosion rates highlighted the need for a method that could (a) be applied during a single field visit (i.e., a method that would not require a long monitoring period), and (b) could mitigate for the variability caused by wet and dry years. Dendrogeomorphology, or the use of tree rings to estimate geomorphic processes, was selected as a the most promising method because of the widespread abundance of exposed tree roots in stream banks in the Bluegrass and the simplicity of the measurements required to calculate the erosion rate.

Analysis of monitoring and geomorphic assessment data indicated that at most sediment-impaired sites, the source of sediment causing embeddedness was from nearby unvegetated banks or small tributaries with unvegetated banks. At all study watersheds, the action of weathering was very important, especially freeze-thaw during winter months. Most banks were composed of cohesive material (silt and clay) and did not appear to erode even during large floods unless weathering had occurred. Only banks with bare soil were observed to weather. To estimate the amount of sediment produced by weathering requires no information on the flow history of a reach but does require that the length of the reach, the height of the banks, and the proportion of exposed soil be determined and combined with a reference rate of erosion due to weathering. A sediment production rate due to weathering can then be calculated that would provide a lower bound estimate of the contribution from bank erosion. The fine sediments derived from weathered bank material are deposited in the channel when flow velocities are low, typically following periods of little or no precipitation. Low flow in the channel is capable of transporting the fine sediments only a short distance, and some of the sediments are deposited along the edge of the water and in other very low-velocity areas of downstream riffles or immediately downstream of a small tributary's confluence with a larger channel.

During floods, the potential for deposition is low because sediment is mobilized and transported through a reach before velocity has slowed sufficiently for deposition to occur. Even though most of the total load is transported during high-flow events, it is also transported out of the reach of interest (i.e., the reach being assessed for siltation impairment); high flows tend to clean the riffles and reduce embeddedness. Prolonged turbidity, which would suggest the potential for sediment deposition as a flood recedes and flow velocities fall, was not observed. Typically, turbidity peaked well before stage for the vast majority of flood events. Turbidity values had declined to near zero when velocities were sufficiently low for sediment deposition to occur. Thus, upland sediments, which are transported primarily during floods, are a negligible component of riffle embeddedness in the Bluegrass, and even a drastic reduction in sediment production from uplands or stream banks far upstream from the reach of interest would be unlikely to affect siltation at a site. One exception to this finding is an embedded reach where an eroding hillside is immediately adjacent to the stream channel. In these instances, decoupling the hillslope from the channel would dramatically reduce the delivery of sediment to the stream. If distal upland sediment production were to be determined to be contributing to embeddedness in a reach of interest, however, a reduction in supply to downstream waters might be more cost effective than reducing the soil loss itself, because upland surface erosion occurs over such a wide area. This could be achieved by implementing BMPs for storing sediment (e.g., those recommended by USDA (2007)) before it enters the small headwater channels and gullies at the upper extents of the drainage network.

Because the closest sources of sediment are probably the most significant to embeddedness in Bluegrass streams, an accurate identification of causes of sedimentation would require delineation of the portion of the channel network and watershed that can supply sediment under the relatively low-velocity conditions that can embed riffles. Focusing on identifying local sediment sources and calculating local sediment loads will be a more efficient way of developing potential solutions for WAH impairment due to siltation/sedimentation than sediment assessments conducted at the watershed scale. Moreover, because embeddedness is primarily caused by local sediment sources, reductions of those sources can be effective in reducing embeddedness in nearby riffles. University of Louisville Stream Institute stream restorations have demonstrated that embeddedness can be reduced within a short sequence of riffles and pools by reducing the local supply and that does not necessarily require the application of watershed-scale BMPs.

Geomorphic Assessment of Fine-grained Sediment Loads in the Bluegrass Physiographic Region

By Michael A. Croasdaile and Arthur C. Parola, Jr.

1. Introduction

Stream sedimentation, the process of deposition of sediment or other material on the channel bed, affects aquatic communities by choking spawning gravels, impairing food sources, and reducing habitat complexity (USEPA 1999). It is one of the most common causes of stream impairment in the United States (USEPA 2000) and in the Commonwealth (KDOW 2010), where “sedimentation/siltation” and other sediment-based pollutants (i.e., solids (suspended/bedload), turbidity, and total suspended solids) and pollution (i.e., particle distribution/embeddedness, physical substrate habitat alterations, and bottom deposits) are cited as the cause of impairment for 69% (2735 mi) of the streams listed as impaired for warm water aquatic habitat (WAH). Because the water quality in these sediment-impaired streams does not support their designated use, the Commonwealth is required under §303(d) of the Clean Water Act to establish pollution management strategies such as watershed based plans (WBPs) and total maximum daily loads (TMDLs) that will be effective in reducing the impairment.

Monitoring and quantifying sediment loads is important for the development of WBPs and the calculation of TMDLs. Estimates of sediment loads and yields at the watershed scale may be developed through the use of fieldwork, reference rates, and/or modeling. Most approaches are based primarily on fieldwork (e.g., Rosgen 2006). The advantages of a field-oriented approach are that real data are calculated, local conditions and variability are incorporated, different sediment sources are identified, and the dominant erosion processes are measured. Collection of field data also allows calibration and verification of watershed-based sediment models.

Few sediment production and/or sediment transport studies have been completed in Kentucky. Some suspended sediment data have been systematically collected (e.g., Crain 2001; Crain 2006; Williamson 2009), and they are useful as reference measurements of suspended sediment concentrations and loads. However, the available data are biased to larger streams and rivers where methods of estimating loads that rely on discharge are more applicable than in small, flashy streams where using a sediment rating curve may lead to large errors in sediment load estimates (e.g., about 900% for monthly loads) (Walling 1977). Furthermore, the data required to address this knowledge gap are becoming less available. A recent inventory of sediment data (Williamson 2009) showed that the number of sites at which sediment data—total suspended solids (TSS) or turbidity and suspended sediment concentrations (SSC)—were being monitored was small and had decreased over the last few decades, from a high of 27 in 1987 to zero during the period 2001–2005. This lack of available information on sediment loads is even more apparent when it comes to estimates of sediment production through bank erosion or surface erosion processes.

Local measurements of sediment production rates are necessary to link information on sediment loads at the watershed scale to the implementation of BMPs at the local scale to calculate load reductions that might be required as part of a TMDL or WBP. Regional differences in climate, geology, contemporary land cover, historical disturbances, and geomorphic history result in a variety of channel conditions, which in turn have differences in sediment sources, in sediment production rates, and in how sediment is transported through the drainage network. These differences mean that data on source types and loading rates collected in other parts of the USA or Kentucky are unlikely to be applicable to the Bluegrass. In particular, the predominant geology of limestones, dolomites, and shales of Ordovician and Silurian age in the Bluegrass mean that sand-sized sediments comprise a much smaller percentage of the sediment load than in adjacent physiographic regions.

For upland surface erosion, a variety of models can be used to estimate load reductions, but most—especially the widely used universal soil loss equation—were developed for small-scale plots (<0.1 acres), and their applicability to Bluegrass watersheds is unknown. The utility of these models for effective management practices is at best uncertain; at worst, they may produce grossly inaccurate estimates of sediment yield (Trimble and Crosson 2000). For bank erosion, which is often the sediment source closest to the site of impairment, no such models are available.

The goals of this project were to provide Kentucky Division of Water (KDOW) with a geomorphic assessment procedure to measure sediment loads and characteristics and to provide regional reference rates of sediment production and storage that will inform future sediment TMDLs and other watershed-based sediment assessments within the Bluegrass physiographic region of Kentucky. Because available sediment data are so scarce compared to data for nutrients or pathogens, and because KDOW sediment protocols are not yet available, this project is anticipated to be one step of many along the path to developing a final sediment protocol in Kentucky. The data collected in this project will provide initial estimates of these rates and masses that could be used in assessments of other watersheds if time and money were not available for primary data to be collected. These data will also provide a basis for evaluating future modeling methods.

The project goals were accomplished by meeting four objectives. The first objective was the development of consistent, reliable procedures for identifying sediment sources in selected watersheds in the Bluegrass. The second objective was the quantification of sediment production and storage rates, focusing on hillslope, gully, and stream bank components of the watershed. The third objective was the development of a suspended sediment sampling program to provide information on transport rates during individual events and to provide verification data for estimates of sediment production and storage. The fourth objective was the development and dissemination of methods suitable for estimating sediment loads in Bluegrass watersheds. The main activities necessary to achieve the project goals were (1) a geomorphic assessment of four watersheds, one in each physiographic sub-region of the Bluegrass; (2) a sediment production field collection program focusing on supply of sediment from different sources; and (3) a sediment transport monitoring program designed to calculate sediment yields at the mouth of the selected watersheds. The amount of sediment deposited in riffles was estimated and compared to the total sediment loads to provide estimates of the load reductions required to prohibit sediment siltation/sedimentation. In contrast to pathogens, for which surface water standards are available, and nutrients, for which aquatic benchmarks are being developed, no numerical criteria are available to define what sediment loads are detrimental to WAH. The approach developed in this project focused on quantifying reference levels for the amount of sediment that is required to embed riffles. As more data become available regarding both the delivery of sediment and the biological response to the sediment, these reference levels could be revised.

2. Materials and Methods

Data collection for this project was designed to support the development of methods and tools that would be useful to KDOW for the development of sediment TMDLs and for other watershed-based sediment assessments in the Bluegrass physiographic region of Kentucky. Sediment production, storage and transport, and yield data were collected in three Bluegrass physiographic region watersheds in 2009, 2010, and 2011. At representative sites in each watershed, sediment production was monitored on hillslopes by measuring sediment deposits in ponds. Because weathering had been identified as an important component of bank erosion processes in two previous 319(h) projects in Currys Fork and Goose Creek watersheds (Croasdaile and Parola 2011a, 2011b), bank pin measurements from Goose Creek and Currys Fork were used to estimate minimum erosion rates that could be applied to other watersheds. Deposition on floodplains and in riffles was monitored along blue-line stream reaches, and sediment yield was monitored at the mouth of each project watershed. These data were combined with previously collected data from Currys Fork and Goose Creek watersheds (Croasdaile and Parola 2011a, 2011b) to develop regional reference rates of sediment production, storage, and yield.

The methods used to collect those data were also evaluated in the development of a geomorphic assessment procedure for KDOW to use to measure sediment loads and characteristics. Discussions with TMDL regarding the measurement of erosion rates highlighted the need for a method that could (a) be applied during a single field visit (i.e., a method that would not require a long monitoring period), and (b) could mitigate for the variability caused by wet and dry years. Because the bank assessment for non-point source consequences of sediment (BANCS) model utilizing bank erosion hazard index (BEHI) and near bank stress (NBS) assessments (Rosgen 2006) had been found to not reliably predict erosion rates in Currys Fork and Goose Creek watersheds, where weathering is a more significant cause of bank erosion than shear stress is, an alternative method for measuring bank erosion rates was tested. Dendrogeomorphology, or the use of tree rings to estimate geomorphic processes (Shroder 1980), was selected as a the most promising method because of the widespread abundance of exposed tree roots in stream banks in the Bluegrass and the simplicity of the measurements required to calculate the erosion rate.

2.1 PROJECT AREA

Geology and Topography

Structural Geology

The structural geology of central Kentucky is dominated by the Cincinnati Arch (McFarlan 1943:132), the axis of which is oriented in an approximately north-south direction between Cincinnati, Ohio and Lexington, Kentucky. South of Lexington, the structure of the Arch is disrupted somewhat by the east-west alignment of faults and shear zones of the Kentucky River fault system. The general configuration of the Arch is altered in the Jessamine Dome, with limbs descending gently from both sides of the axis. The rock layers dip away from the center of the dome, at an elevation of about 1,000 ft msl, to an elevation of about 850 ft msl at the Ohio River near Cincinnati. The layers dip on average at 20 to 30 ft per mile to the east and west, and at about 10 ft per mile to north and south along the axis.

The Arch formed in a series of episodes of folding and warping that lifted Paleozoic strata far above the elevations at which they had been deposited. Underlying formations were exposed by erosion of the uplifted sedimentary rock layers. Because of the greater uplift at the Jessamine Dome and along the axis of the Arch, the strata exposed in those locations are far older than strata exposed near the outer boundary of the Bluegrass.

Physiographic Sub-Regions

The boundary of the Bluegrass coincides with the exposed Mississippian strata on the flanks of the Arch (Fig. 2.1). Within the region, differences in lithology, soil characteristics, and topography distinguish four separate physiographic sub-regions (Table 2.1): the Inner

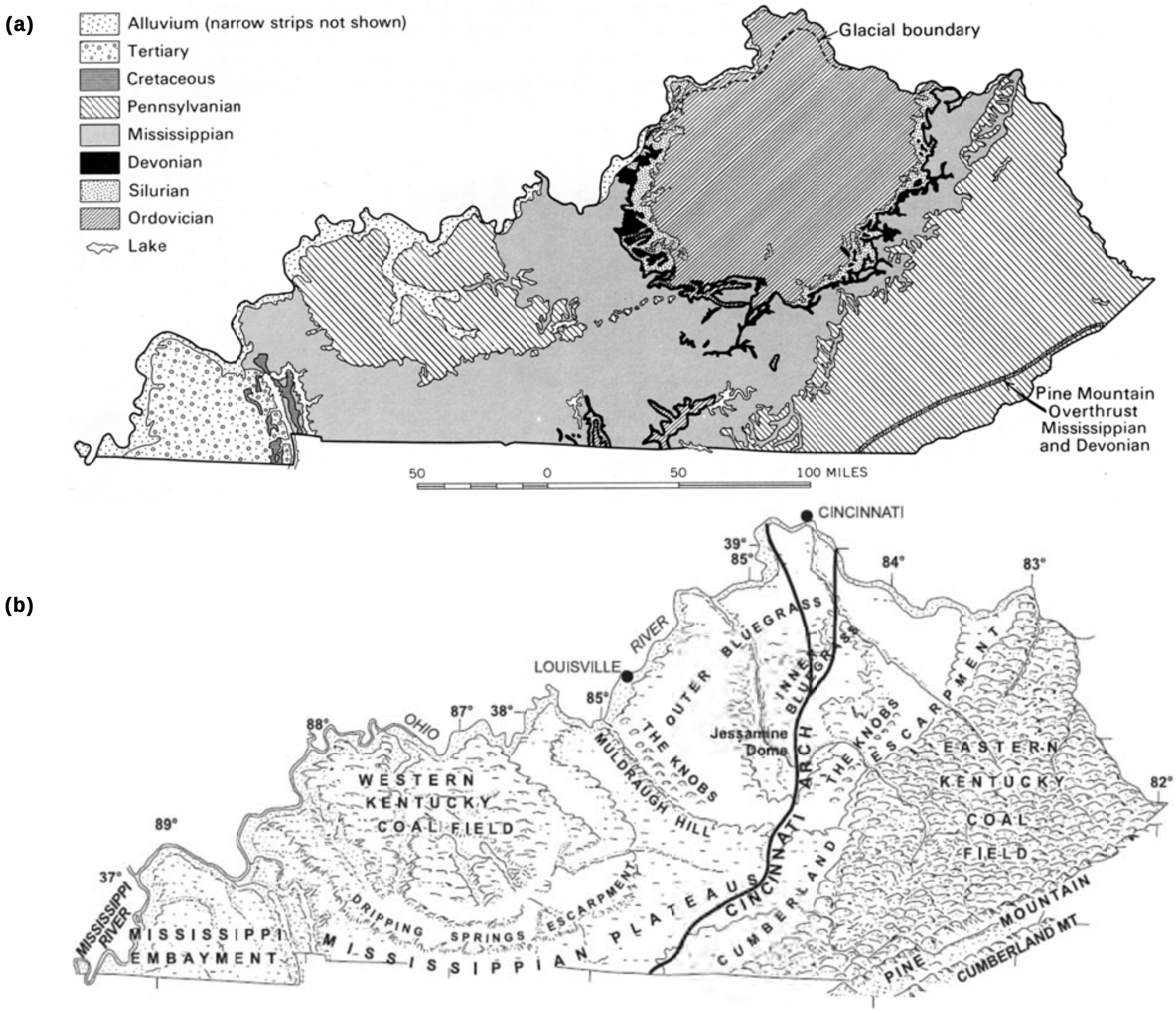

Figure 2.1 (a) Generalized geologic map of Kentucky (after McGrain 1983:12).
(b) Physiographic map of Kentucky (KGS 1980).

Table 2.1 Soil Characteristics and Topography of Bluegrass Physiographic Sub-Regions

Physiographic Sub-Region	Lithology	Major Soil Units	Soil Thickness*	Topography
Inner Bluegrass	Lexington Limestone (Ol) of Ordovician age	McAfee-Maury (M-M) association, McAfee-Maury-Fairmount (M-M-F) association, and Nicholson-Lowell-Faywood (N-L-F) association	Undulating deep and moderately deep soils high in phosphate (M-M) found on broad gently sloping ridges and somewhat steeper slopes along drainage ways and around sinkholes. Sinkholes are common in this soil unit. Rolling uplands and moderately steep slopes along drainage ways (M-M-F); this soil is well drained and has many sinkholes. Typically deep, gently sloping to sloping, well drained, and moderately well drained soils found on broad upland ridges (N-L-F).	Very low relief with broad gently sloping ridges and steeper areas around abundant shallow sinkholes. Highest elevation is 1070 ft above sea level and the lowest elevation occurs at the normal pool depth of the Kentucky River at 550 ft above sea level.
Eden Shale Belt	Ordovician limestone and shales interbedded with some siltstone (Kope, Okc, and Clays Ferry, Ocf, Formations)	Faywood-Eden-Lowell (F-E-L), Eden-Lowell (E-L) association	Shallow to moderate soil depths on steep slopes (F-E-L) and variable on ridgetops (E-L). Soils generally well drained with dominantly clay subsoil. Soils may be moderately deep on floodplains and terraces of larger rivers.	Highly dissected area with steep convex hillsides, long narrow v-shaped valleys and rounded ridgetops. The highest elevation is found in Bath County at approximately 1000 ft. Ridge tops of 900 ft are typical elsewhere with valleys commonly 150 to 300 ft below.
Outer Bluegrass	Limestones, dolomites, and shales of Late Ordovician and Silurian age (primarily Oaf, Ob, Od, Odc)	Nicholson-Lowell-Faywood (N-L-F) association, Shelbyville-Lowell-Faywood (S-L-F) association	Deep to moderately deep, well drained soils with clayey subsoil (N-L-F) over limestones, and shallow to moderately deep, somewhat excessively drained soils (S-L-F) over shales. Soils developed on some Silurian carbonate rocks are nearly as rich as those of the Inner Bluegrass.	Rolling, undulating hills of low to moderate relief, with elevations typically between 800 and 900 ft above sea level. Jeptha Knob in Shelby County is an exception and the highest elevation at 1188 ft.
Knobs	Thick shales (with thin siltstone and sandstone inclusions) of Devonian age (New Albany shale, MDnb) or Mississippian age (New Providence shale, MDbb) and the edges of thick layers of Mississippian limestone strata (Msh)	McGary-Markland-Lawrence (M-M-L) association, Huntingdon-Lawrence-Newark (H-L-N) association and Rockcastle-Colyer-Trappist (R-C-T) association.	On stream terraces, soils are deep, somewhat poorly drained to well-drained, and nearly level to gently sloping (M-M-L). Similar soils found along Rolling Fork (H-L-N). In the upland portion of the Knobs, the soils are shallow, excessively drained, and gently sloping to steep (R-C-T).	Individual knobs are characterized by symmetrical concave-upward slopes which rise gently out of the bottomlands or surrounding plains. The slopes steepen upward into cliffs on knobs with resistant caprocks. Knobs that have lost their protective caps have rounded crests. Well-developed knobs may be nearly circular or elliptical in plan view. Elevations from 520 to 1575 ft above sea level.

* Depth of soils over bedrock, as determined by USDA soil surveys. Very deep = >60 in over bedrock; Deep = 40-60 in; Moderately deep = 20-40 in; Shallow = 10-20 in; Very shallow = <10 in.

Sources: Hall et al. 1980; McDonald et al. 1983; McDonald et al. 1985; Odor et al. 1968; Preston et al. 1961; Richardson et al. 1982; Sims et al. 1968;Weisenberger and Isgrig 1977; Weisenberger et al. 1963; Zimmerman 1966.

Bluegrass, a gently rolling lowland underlain by Middle Ordovician rocks; the Eden Shale Belt, a rugged transitional region of Kope and Clays Ferry formations; the Outer Bluegrass, subdued hills and lowlands on Late Ordovician, Silurian, and Devonian rocks; and the Knobs, a narrow band of hills bounded by the Muldraughs Hill and Pottsville escarpments of the Mississippian Plateaus physiographic region.

The Inner Bluegrass is characterized by gently rolling topography developed in thick layers of residual soils formed from in-place weathering of limestones, dolomites, and shales (Sims et al. 1968). Deeply entrenched streams such as the Kentucky River flow through gorges carved in resistant rock units like Lexington Limestone and the massive limestones of the High Bridge Group. The Lexington Limestone consists mostly of very fossiliferous and fossil-fragmental limestone with minor amounts of shale (Cressman 1973); in contrast, the High Bridge Group consists of sparingly fossiliferous and micrite-rich limestone (Cressman and Noger 1976). These units are among the most karst-prone in the Bluegrass, and sinkholes, formed by dissolution in carbonate rock layers, are concentrated primarily in this sub-region (Fig. 2.2). Subsurface channels are present where joints or solution cavities form in soluble limestone or dolomite, but outside the Inner Bluegrass the development of karst topography or extensive subsurface channel networks tends to be limited by interbedded shale. This is especially the case in the Eden Shale Belt, where the prevalence of impermeable shale strata ensure that sub-surface drainage does not develop.

The boundaries of the Eden Shale Belt (also known as the Eden Hills or Hills of the Bluegrass) have been varyingly defined according to numerous criteria including geology, topography, soils, vegetation, and others (e.g., W. Andrews, pers. comm.; Davis 1927; Woods and Omernik 2002). For the purposes of this report, the region has been defined as that underlain by the Okc and Oc members of the Kope and Clays Ferry formations (see Fig. 2.3). These strata are of Ordovician age, but they are significantly different in lithology from the strata of the Inner Bluegrass. The rock layers of the Eden Shale Belt consist mostly of interbedded shales and limestones. These strata are both thinner and more erodible than the layers of limestone and dolomite in the Inner Bluegrass. Dissection by streams has occurred to a high degree in the Eden Shale Belt, with little flat land present in the sub-region. The residual soils developed from the interbedded shales and limestones are cut by steep-sided narrow valleys that contrast sharply with the more subdued landscape of the Inner Bluegrass with its gentler rolling hills.

The topography of the Outer Bluegrass, where underlain by Ordovician rocks, is similar to the Inner Bluegrass, typically with low-to-moderate relief and soil depths ranging from thick over limestones to thin over shales. Where Silurian and Devonian carbonate rocks are exposed, the terrain is very similar but with fewer hills and more flat land. The Silurian strata consist of dolomites, limestones, and shales (minor components, in general) that are significantly different in properties from the younger Devonian fossiliferous limestones and thick shales that crop out farther away from the Inner Bluegrass. The soils developed on some Silurian carbonate rocks may be nearly as rich as those of the Inner Bluegrass. Unstable hillslopes, with small, low-angle landslides, are a characteristic of areas underlain by Silurian shales, which contain abundant swelling clays. The outer edges of the Outer Bluegrass typically consist of lowlands or gently rounded low hills.

Bordering the Outer Bluegrass is the Knobs sub-region, formed by erosional outliers developed in thick, silty Devonian shales with thin sandstone inclusions (New Albany Shale) or Mississippian-age shales (New Providence Shale) and the edges of thick layers of Mississippian limestone strata. The Knobs contain hundreds of isolated hills formed from the New Albany and New Providence shales. Where the shales are capped by thin, resistant layers of siltstone or sandstone, the hills are almost flat-topped. When erosion and weathering undermine the cap-rock layers, the hills become conical; without the cap-rock layers, the hills become more rounded.

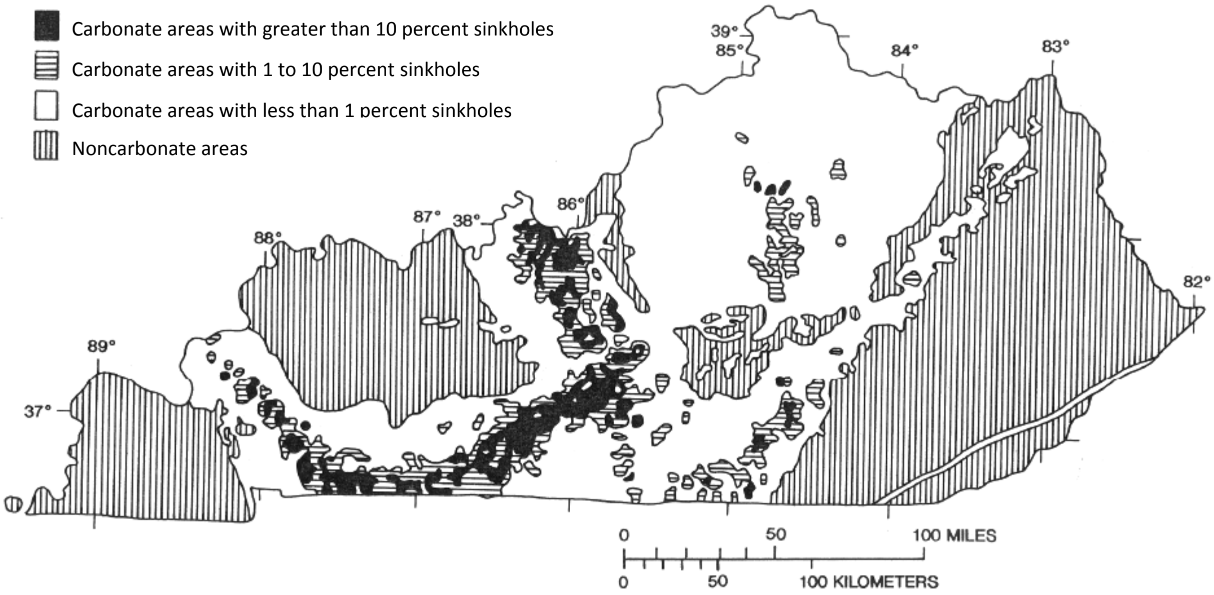

Figure 2.2 Generalized carbonate areas and surficial karst development in Kentucky (from Crawford and Webster 1986).

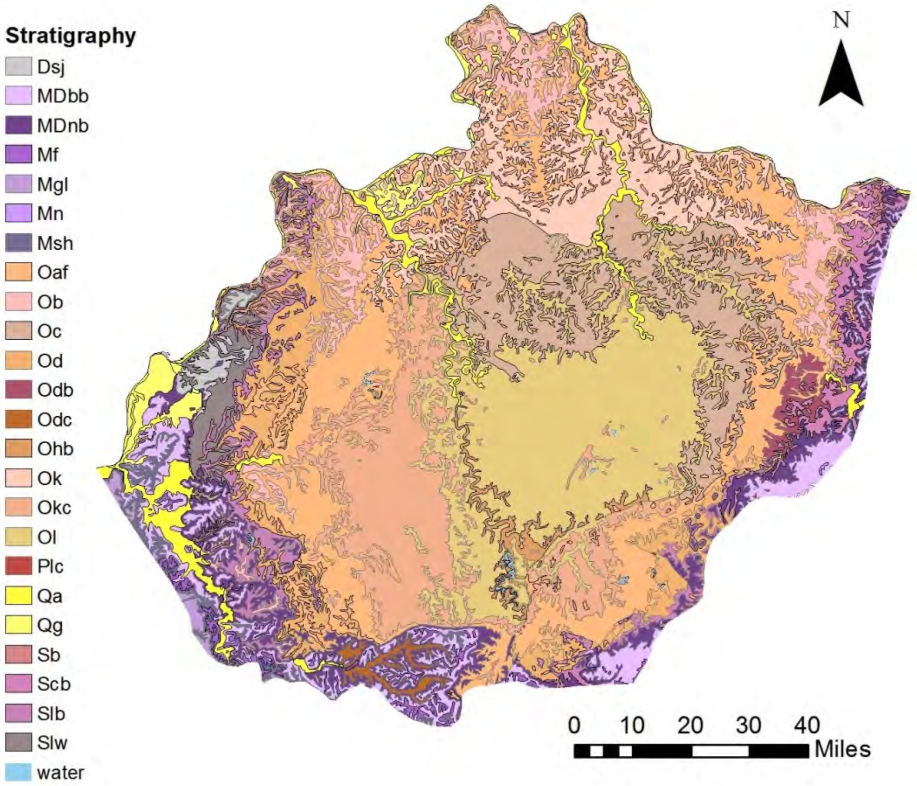

Figure 2.3 Lithostratigraphy of the Bluegrass region. The strata exposed near the middle of the region are far older than strata exposed near the outer boundary (KGS 2002; Noger 2002).

Climate

Kentucky has a moist-continental climate with distinct seasonal differences and variable weather patterns. Winter temperatures are moderate, rarely below 0°F; typical summer temperatures are warm and rarely above 100°F. Average annual snowfall is about 20 in., but the snow cover rarely remains longer than three days at a time.

Weather patterns in Kentucky are affected variably by the meeting of cold, continental air masses arriving from the northwest and warm, moist air masses moving up the Mississippi and Ohio River Valleys from the southwest (Conner 1982). The rainfall pattern in the Bluegrass is bimodal (Hodgkins and Martin 2003). Precipitation in winter months generally results from frontal storm systems. Precipitation in summer is characterized by convective storm activity, typically in the form of afternoon thunderstorms. The intensity of precipitation is generally higher in summer than during other seasons, but the number of days having precipitation is similar in winter and summer.

2.2 WATERSHED SELECTION

Remote Watershed Assessment

A list of watersheds to be considered for selection was created from the KDOW (2006) *Integrated Report*. The list included the watersheds of all Bluegrass physiographic region stream reaches that were listed as impaired for WAH due to sedimentation/siltation or other sediment pollutants. Geospatial datasets were reviewed to screen each watershed and its subwatersheds according to two additional preliminary selection criteria prior to field reconnaissance:

1. Drainage area. HUC-14 boundaries defined in the National Hydrologic Dataset (NHD) (USGS 2008a) were used to delineate each watershed and its subwatersheds and to estimate their surface drainage areas. Field reconnaissance was limited to watersheds draining less than 50 mi^2 to enable monitoring within the project timeframe and budget.
2. Physiographic sub-region. The physiographic sub-region(s)—the Inner Bluegrass, Eden Shale Belt, Outer Bluegrass, and/or Knobs—drained by each watershed were identified (KGS 2002). Field reconnaissance was limited to watersheds in which at least 80% of the drainage area was within a single physiographic sub-region.

Geospatial data were then reviewed to identify characteristics that could be relevant to field evaluation of the watersheds that had not been eliminated from consideration. The following tasks were completed in the review:

1. The watersheds were located on US Geological Survey (USGS) 7.5-minute topographic maps and their surface drainage areas were estimated.
2. Watershed geomorphic characteristics were recorded from the USGS quadrangle map: locations of major tributaries, changes in topography, and evidence of channel straightening, realignment, or other modifications such as excavation for old mill races.

3. Geology and karst hydrology of the watersheds were examined:
   a. The bedrock strata underlying the watershed were identified from KGS 7.5-minute geologic quadrangle maps.
   b. Maps indicating karst-prone areas (KGS 2006) at scales of 1:500,000 and Kentucky Geological Survey (KGS) 7.5-minute geologic quadrangle maps (1:24,000) were checked for karst-prone strata.

Two watersheds in the Knobs physiographic subregion were eliminated based on this preliminary review. Mill Creek (NHD reach code 5140101003369) was rejected because it drains directly into the Ohio River, which exerts an atypically large backwater influence on the channel. Salt Lick Creek (NHD reach code 5100101000199) was rejected because it drains some of the Eastern Kentucky Coal Field physiographic region and a previous field visit revealed it has a significant sand load, which is atypical of watersheds in the Bluegrass region.

Field Reconnaissance and Final Watershed Selection

Field reconnaissance visits were made to finalize the selection of at least two Bluegrass watersheds. In the Eden Shale Belt physiographic sub-region, Clear Creek in the Guist Creek watershed and Salt River into Sixmile Creek (hereafter referred to as Salt River) were evaluated for selection during field visits with KDOW TMDL and NPS sections. Clear Creek was rejected due to the presence of a large reservoir which is trapping a large proportion of fine sediment. Salt River watershed was selected.

All other watershed evaluations and selections were completed in consultation with the project’s KDOW NPS technical advisor. In the Inner Bluegrass sub-region, an unnamed tributary (UT) watershed in South Elkhorn Creek watershed was selected because it drains into 303(d)-listed South Elkhorn Creek and its small drainage area would facilitate data collection. In the Knobs sub-region, two watersheds were evaluated during field visits. The impaired reach of Long Lick Creek (NHD reach code 5140102000328) was found to have silt-bed reaches that crossed the floodplain of the Salt River (drainage area of 1240 mi^2); away from the influence of the larger river, the channel bed was primarily bedrock with cobble and gravel riffles. Although the influence of large river floodplains on the sedimentation and siltation of smaller tributaries is a potentially useful area for study, it was not the focus of this project, so Long Lick was rejected. The other watershed, Harrison Fork, was selected. Harrison Fork flows into Wilson Creek, which is listed as non-supporting for WAH due to sedimentation/siltation and other pollutants (KDOW 2006). The HUC-14 for Harrison Fork watershed is 40 mi^2, and the lower end of the watershed (western part) is geologically and topographically different from the upper portion (eastern part). Only the upper 12.2 mi^2 of the watershed, which is the area upstream of the confluence between Harrison Fork and Wilson Creek, was selected. The area upstream of this confluence is relatively homogenous geologically.

Data from two other 319(h) projects (Croasdaile and Parola 2011a, 2011b) were also used in this project. The two watersheds from those previous 319(h) projects and the three watersheds selected for this project’s data collection all had drainage areas of less than 30 mi^2 (Table 2.2) and collectively represented the four Bluegrass physiographic sub-regions (Fig. 2.4).

Table 2.2 Assessed Watersheds in the Bluegrass Region

Watershed	Drainage Area (mi^2)	Physiographic Sub-region
Harrison Fork	12.2	Knobs
Salt River	12.0	Eden Shale Belt
UT South Elkhorn	0.37	Inner Bluegrass
Currys Fork*	28.5	Outer Bluegrass
Goose Creek†	10.3	Eden Shale Belt

* Currys Fork data were collected in 2007–2010 for a previous 319(h) project (Croasdaile and Parola 2011a).

† Goose Creek data were collected in 2007 and 2008 for a previous 319(h) project (Croasdaile and Parola 2011b).

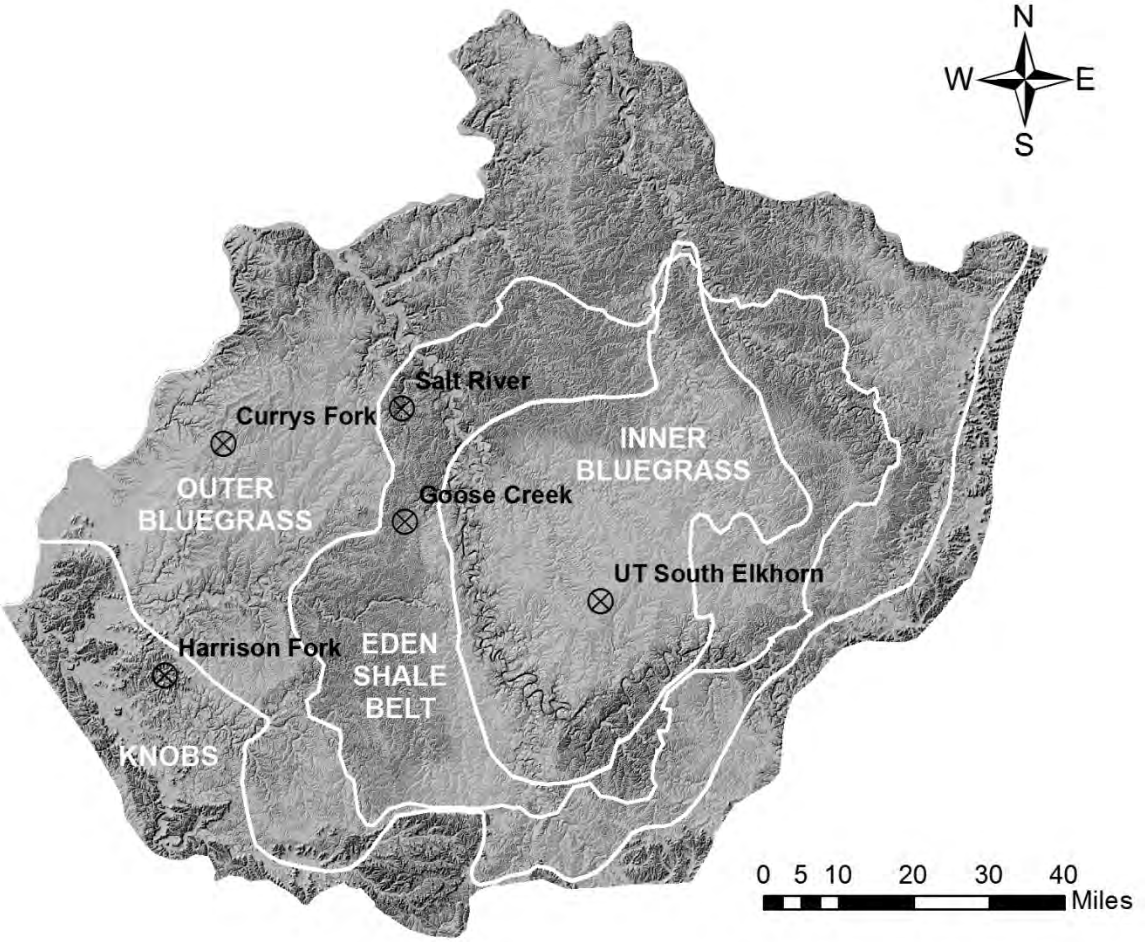

Figure 2.4 Selected subwatersheds and Bluegrass physiographic sub-regions.

2.3 SITE SELECTION

Blue-Line Stream Sediment Production Sites

Blue-Line Bank Geometry

The selection of blue-line reaches for field assessment was finalized during an initial field evaluation. Nine blue-line channels in the three project watersheds were selected for documentation of bank geometry and sediment characteristics. Only those reaches that were accessible without entering private property were selected (Table 2.3).

Table 2.3 Assessed Blue-Line Stream Reaches

Watershed	Reach ID	NHD Reach Code	Strahler Order	Drainage Area (mi^2)
Harrison Fork	HF restoration site	05140103001472	3	3.61
	Wilson Ck	05140103000434	3	5.18
	Wilson Ck d/s of confluence	05140103000433	4	9.52
	Dunne Hollow	05140103000433	1	0.39
Salt River	Bantas @KY-573	05100205000433	4	11.5
	Bantas Welch	05100205000434	3	4.87
	Salt @ Woods Pike	05100205001127	3	2.4
	Bantas @ Byers Ln	05100205005416	1	0.43
UT South Elkhorn Creek	MMSK	05100205007449	1	0.37
Currys Fork*	Ashers Run	05140102002090	3	3.36
	CF1	05140102000250	4	28.50
	CF3	05140102000251	4	19.43
	NC1	05140102000253	3	10.07
	NC2	05140102000253	3	6.13
	SC1	05140102001790	4	9.20
	SC2	05140102001699	3	2.82
Goose Creek†	GC1	05100205001098	4	10.32
	GC2	05100205001098	4	8.09
	GC3	05100205001098	4	6.19
	GC4	05100205001099	3	2.19
	GC5	05100205001099	2	0.92
	GC6	05100205001099	1	0.5
	BB1	05100205001100	3	3.74
	BB2	05100205001100	3	2.67
	BB3	05100205001100	2	1.59
	BB4	05100205001100	2	0.92
	BB5	05100205001100	1	0.56
	GCT1	05100205006815	1	0.57
	GCT2A	05100205006655	2	1.47
	GCT2B	05100205006576	2	0.77
	GCT2C	05100205006565	2	0.33
	GCT2D	05100205006551	1	0.18
	GCT3	05100205006686	1	0.49
	GCT4	05100205006904	2	0.72
	BBT1	05100205006743	1	0.15
	BBT2	05100205006742	2	0.89
	BBT3	05100205006737	2	0.84
	BBT5	05100205006744	1	0.25
	BBT6	05100205006761	1	0.26
	WB1	05100205006794	2	1.2
	WB2	05100205006936	1	0.74
	WBT1	05100205006871	1	0.14

* Currys Fork data were collected in 2007–2010 for a previous 319(h) project (Croasdaile and Parola 2011a).

† Goose Creek data were collected in 2007 and 2008 for a previous 319(h) project (Croasdaile and Parola 2011b).

Bank Erosion Monitoring Sites

The assessed reach (MMSK) in the UT South Elkhorn Creek watershed was selected for comparison of bank pin measurements with dendrogeomorphic measurements because the site was easily accessible, had abundant exposed roots, and had many eroding banks within a short reach to enable efficient collection of many root samples.

Bulk Density Sampling Sites

In the assessed reach of the UT South Elkhorn Creek watershed, six points that appeared to be representative of bank height and material characteristics of the reach were selected for bulk density sampling: three points on the left bank at the upstream and downstream ends and the middle of the reach, and three points on the right bank directly across from those on the left. No other sites were selected for bulk density sampling because field examination of banks at Salt River and Harrison Fork indicated that their bank material compositions were sufficiently similar to those of Currys Fork and Goose Creek that additional bulk density samples would not be necessary.

Unmapped Channel Sediment Production Sites

Channels not represented by the blue-line stream network on USGS 7.5-minute topographic quadrangles were selected for assessment in Harrison Fork and Salt River watersheds. UT South Elkhorn Creek watershed, which has urban development upstream with many unmapped streams in pipes, was not included in the assessment of unmapped channels.

Channel Head Mapping

At least 150 unmapped channels were randomly selected for remote identification of channel heads from aerial photographs of the Harrison Fork watershed and three HUC-14 subwatersheds of the Salt River watershed (Table 2.4). If the channel head of a selected channel was obscured or could not be clearly identified on aerial photographs, the next tributary adjacent to the selected one was substituted.

Table 2.4 HUC-14s Used for the Assessment of Unmapped Channel Sediment Production

Watershed	HUC-14	HUC-14 Name or Description	Combined Drainage Area (mi^2)
Harrison Fork	05140103-220-010 (upper portion)	Harrison Fork watershed upstream of its confluence with Wilson Creek	12.2
Salt River	05100205-330-140	Salt River	12.0
	05100205-330-150	Bantas Fork	
	05100205-330-160	Salt River	
Currys Fork*	05140102-180-100	North Fork of Currys Fork	28.5
	05140102-180-110	South Fork of Currys Fork	
	05140102-180-120	Currys Fork	
	05140102-180-130	Ashers Run	
Goose Creek†	05100205-260-040	Goose Creek	10.3
	05100205-260-050	Ballard Branch	
	05100205-260-060	Goose Creek	

* Currys Fork data were collected in 2007–2010 for a previous 319(h) project (Croasdaile and Parola 2011a).

† Goose Creek data were collected in 2007 and 2008 for a previous 319(h) project (Croasdaile and Parola 2011b).

Unmapped Channel Bank Geometry

The selection of unmapped channel reaches for field assessment was finalized during an initial field evaluation. Nine unmapped channels in the Salt River watershed were selected for documentation of bank geometry and sediment characteristics. Only those reaches that were accessible without entering private property were selected (Table 2.5).

Table 2.5 Confluence Locations of Assessed Unmapped Channels with Blue-line Channels in Salt River Watershed*

Latitude	Longitude	Strahler Order	Drainage Area (acres)
38.35288	−85.05997	2	62.6
38.37585	−85.02020	1	24.6
38.36622	−85.03510	1	3.3
38.37260	−85.04744	1	14.3
38.37317	−85.05297	1	39.3
38.35596	−85.08527	2	36.6
38.38376	−85.04169	1	14.5
38.38718	−85.04434	2	44.7
38.38604	−85.04320	1	15.0

* This list does not include the more than 10,000 ft of unmapped channels that were previously assessed.in Currys Fork and Goose Creek watersheds (Croasdaile and Parola 2011a, 2011b).

Upland Sediment Production Sites

Small farm ponds were evaluated as sites for measuring sediment production from upland surface erosion. Ponds were selected for assessment based on five criteria:

1. A known period of deposition of at least 10 years (±10%). The period of deposition was typically the time since construction or the time since the pond had been dredged or cleaned out. The period of deposition had to be at least 10 years so that enough sediment would have accumulated to be easily measurable.
2. A clearly defined drainage area upslope of the pond. Ponds on top of a ridge were excluded.
3. Absence of a well-defined channel network upslope of the pond.
4. An outfall/spillway configuration that would lead to a high trapping efficiency (Verstraeten and Poesen 2001). Ponds with extensive bank erosion above the inlet were excluded, as were ponds with an outflow that was low enough to be frequently overtopped.
5. Accessibility. Ponds had to be accessible by vehicle with the permission of the landowner.

A total of 40 ponds were selected in four of the five project watersheds (Table 2.6). UT South Elkhorn Creek watershed had no ponds.

Table 2.6 Assessed Ponds

Watershed	Pond Name	Latitude	Longitude	Drainage Area (acres)	**Land Cover** (2001 NLCD)
Harrison Fork	Bernheim	37.86483	−85.5938	18.5	Mixed deciduous forest
Harrison Fork	Hallow	37.83774	−85.55652	11.8	Mixed deciduous forest
Harrison Fork	Hawkins	37.83992	−85.63119	5.9	Herbaceous
Harrison Fork	Hurricane	37.8291	−85.6393	1.2	Herbaceous
Harrison Fork	Keyes	37.84316	−85.63551	7.9	Herbaceous
Harrison Fork	Trailer	37.84188	−85.64319	8.0	Herbaceous & mixed deciduous forest
Salt River	Erwin	38.4826	−85.0598	11.2	Pasture/hay
Salt River	Riggs	38.37415	−85.07386	6.0	Pasture/hay
Salt River	Silvers	38.44859	−85.0065	26.7	Pasture/hay & mixed deciduous forest
Salt River	Webb	38.336833	−85.081833	2.7	Pasture/hay
Salt River	Winters	38.3795	−85.1218	18.1	Pasture/hay
Currys Fork*	Cooper	38.3514	−85.4356	4.0	Pasture/hay
Currys Fork*	Deibel	38.3376	−85.4282	5.6	Pasture/hay
Currys Fork*	Ennes	38.377480	−85.4076	3.1	Mix forest/low res./deciduous forest
Currys Fork*	Forrest	38.3840	−85.3982	4.6	Deciduous forest
Currys Fork*	Ghad	38.3456	−85.4172	13.1	Urban grass/mix forest
Currys Fork*	Lanham	38.3459	−85.3952	7.0	Row crops/deciduous forest
Currys Fork*	Northwood	38.3359	−85.4372	5.5	Row crops
Currys Fork*	Seymour	38.3518	−85.4321	2.5	Pasture/hay/mix forest
Currys Fork*	Yates	38.3516	−85.4035	8.2	Low res./urban grass/mix forest
Currys Fork*	Young	38.3509	−85.4402	6.4	Deciduous forest
Goose Creek†	Crawford	38.11396	−85.00853	8.41	Pasture/hay
Goose Creek†	Gunn	38.20357	−84.98745	8.38	Pasture/hay
Goose Creek†	Hickory Grove	38.13630	−85.01300	5.40	Pasture/hay
Goose Creek†	McDevitt	38.23334	−84.95860	4.99	Deciduous forest
Goose Creek†	Perry 1	38.24029	−84.97437	38.80	Pasture/hay
Goose Creek†	Perry 2	38.23550	−84.97556	1.67	Grassland/herbaceous
Goose Creek†	Sullivan	38.11540	−84.99448	3.53	Deciduous forest
Goose Creek†	Wilson 1	38.25069	−84.99987	9.45	Pasture/hay
Goose Creek†	Wilson 2	38.25171	−84.99892	5.47	Pasture/hay

* Currys Fork data were collected in 2007–2010 for a previous 319(h) project (Croasdaile and Parola 2011a).

† Goose Creek data were collected in 2007 and 2008 for a previous 319(h) project (Croasdaile and Parola 2011b).

Floodplain Deposition Monitoring Sites

The main criterion for selecting the locations for monitoring sediment deposition near blue-line assessment reaches was that the locations would not be disturbed either through mowing or grazing. One of the four Salt River watershed reaches was grazed, and hence, was eliminated from selection. Valley bottoms along the three other Salt River blue-line assessment reaches (Table 2.3) were evaluated according to this criterion, and suitable locations with relatively flat areas away from major obstructions were selected. At Salt River, the abandoned floodplains (terraces) of incised channel reaches were selected for sampling; all other distinct depositional surfaces were located in high-energy areas with platy bedrock that were unsuitable for sampling (Table 2.7). In Goose Creek watershed, actively forming floodplains within incised channel reaches and active floodplains of un-incised channel reaches had been selected for sampling, in addition to the terraces. The active floodplain is the flat depositional surface adjacent to the channel that is constructed by the present river in the present climate and is frequently inundated by the river (Dunne and Leopold 1978). In incised channels, the primary indicator used to identify the actively-forming floodplain was usually a low depositional bench. In channels that were not incised, the active floodplain coincided with the valley flat.

Table 2.7 Locations of Floodplain Sedimentation Measurements

Reach ID	Latitude	Longitude	Bank	Site Type
Bantas @KY-573	38.37625	-85.01366	Left	Terrace
Bantas @KY-573	38.37640	-85.01370	Left	Terrace
Bantas @KY-573	38.37653	-85.01353	Left	Terrace
Bantas @KY-573	38.37638	-85.01339	Left	Terrace
Bantas @KY-573	38.37661	-85.01320	Left	Terrace
Bantas Welch	38.36725	-85.03031	Left	Terrace
Bantas Welch	38.36733	-85.03113	Left	Terrace
Bantas Welch	38.36748	-85.03006	Left	Terrace
Bantas Welch	38.36754	-85.02995	Left	Terrace
Bantas Welch	38.36714	-85.03003	Left	Terrace
Bantas Welch	38.36730	-85.02995	Left	Terrace
Bantas Welch	38.36746	-85.02992	Left	Terrace
Salt @ Woods Pike	38.38639	-85.04351	Right	Terrace
Salt @ Woods Pike	38.38639	-85.04350	Right	Terrace
GC1*	38.15570	–85.01177	Left	Terrace
GC1*	38.15570	–85.01186	Left	Actively forming floodplain within incised channel
GC2*	38.15412	–85.01905	Right	Active floodplain
GC3*	38.14925	–85.02942	Left	Actively forming floodplain within incised channel
GC3*	38.14926	–85.02937	Right	Active floodplain
GC4*	38.14036	–85.03905	Right	Actively forming floodplain within incised channel
GC4*	38.14040	–85.03907	Left	Terrace
GC5*	38.13381	–85.04209	Right	Terrace
GC5*	38.13381	–85.04215	Left	Actively forming floodplain within incised channel
GCT2A*	38.15787	–85.01616	Right	Terrace
GCT2A*	38.15791	–85.01602	Left	Actively forming floodplain within incised channel
GCT3*	38.15357	–85.02344	Right	Actively forming floodplain within incised channel
GCT4*	38.13535	–85.04417	Right	Actively forming floodplain within incised channel
GCT4*	38.13535	–85.04426	Left	Terrace
BB2*	38.14907	–85.04702	Left	Terrace
BB2*	38.14905	–85.04700	Right	Actively forming floodplain within incised channel
BB4*	38.14787	–85.06053	Right	Actively forming floodplain within incised channel
BB4*	38.14794	–85.06052	Left	Terrace
BBT1*	38.15070	–85.03843	Left	Actively forming floodplain within incised channel
BBT1*	38.15072	–85.03838	Right	Active floodplain
BBT3*	38.15205	–85.04871	Right	Active floodplain
BBT3*	38.15211	–85.04871	Left	Terrace
BBT6*	38.14894	–85.06318	Right	Terrace
BBT6*	38.14894	–85.06310	Left	Terrace
WB2*	38.13313	–85.03033	Left	Terrace
WB2*	38.13321	–85.03034	Right	Terrace

* Goose Creek data were collected in 2007 and 2008 for a previous 319(h) project (Croasdaile and Parola 2011b).

In-channel Sediment Deposition Sites

In-channel sediment deposition sites were chosen to represent a wide range of channel sizes (as indicated by Strahler stream order) and to make sure at least one reach was selected per watershed (Table 2.8). Measurements were focused on riffles because the majority of macroinvertebrates are found in the riffles; the mass of sediment in pools is less biologically significant. Because riffle deposition can vary locally even between adjacent riffles, obtaining comprehensive measurements in all watersheds was not practical. Instead, the adopted approach was to select sites that would provide a realistic range of the conditions found in Bluegrass streams.

Table 2.8 In-channel Sediment Deposition Sites

Reach ID	Drainage Area (mi^2)	Strahler (NHD)
MMSK	0.4	1
Currys Fork (SF restoration site)	2.7	3
North Fork (U/S SF conf) NC1	9.7	4
Currys Fork (main stem) CF3	20.2	5
Goose Creek GC1	10.2	4
Ballard Branch BB2	2.7	3
UT Ballard Branch BBT3	0.8	2
Harrison Fork	3.6	3
Salt River	2.5	3

Suspended Sediment Monitoring Sites

Measurement locations near the mouth of all three project watersheds (Table 2.9) were selected based on two considerations: (1) their accessibility; and (2) the location of exposed bedrock to provide a solid base for monitoring equipment installation and to ensure that stage-discharge relationships were not affected by scour of the bed. These sites were supplemented with all of the Bluegrass sites for which data were available from EPA Storet (Table 2.10).

Table 2.9 Suspended Sediment Yield Measurement Sites

Watershed	Latitude	Longitude	Drainage Area (mi^2)	Physiographic Sub-region
Harrison Fork	37.86491	–85.59239	12.2	Knobs
Salt River	38.37628	–85.01310	12.0	Eden Shale Belt
UT South Elkhorn	38.00148	–84.53297	0.37	Inner Bluegrass
Currys*	38.31052	–85.45012	24.5	Outer Bluegrass
Goose†	38.15762	–85.00668	10.3	Eden Shale Belt

* Currys Fork data were collected in 2007–2010 for a previous 319(h) project (Croasdaile and Parola 2011a).

† Goose Creek data were collected in 2007 and 2008 for a previous 319(h) project (Croasdaile and Parola 2011b).

Table 2.10 EPA Storet Sites Used to Supplement TSS/SSC vs. Turbidity Relationships

Stream Name	Station ID	Drainage Area (mi^2)	Station Latitude	Station Longitude	Physiographic Sub-region
Tenmile Creek	KRW026	68.4	38.71495	–84.7495	Outer Bluegrass
Eagle Creek	KRW027	232	38.58317	–84.6801	Outer Bluegrass
Brashears Creek	PRI105	259	38.03722	–85.3406	Outer Bluegrass
Chaplin River	SRW002	250	37.8912	–85.1993	Outer Bluegrass
Sulphur Creek	SRW014	21.6	37.8878	–85.0938	Outer Bluegrass
Sixmile Creek	KRW028	74.3	38.4308	–85.0055	Outer Bluegrass
Beech Fork	PRI041	419	37.81611	–85.2961	Outer Bluegrass
Hinkston Creek	PRI102	259	38.30	–84.24	Inner Bluegrass
Stoner Creek	PRI101	283	38.30	–84.25	Inner Bluegrass
Kentucky River	PRI067	4588	37.82	–84.70	Inner Bluegrass
Rolling Fork	SRW017	483	37.6632	–85.5975	Knobs
Beech Fork	SRW018	752	37.7652	–85.679	Knobs
Cox Creek	SRW013	95	37.9737	–85.5421	Knobs

2.4 DATA COLLECTION

Remote Site Assessment

Geospatial datasets, contour maps, and aerial photographs were reviewed to identify characteristics that could be relevant to field evaluation of channels in each of the three selected watersheds. The following tasks were completed in the review:

1. Channel and valley geomorphic characteristics were recorded from the USGS quadrangle map: elevations of downstream and upstream limits of the blue-line channels; valley lengths; valley slopes; hillside slopes; channel lengths; channel slopes; sinuosities; drainage areas; and valley widths. Valley constrictions or sharp bends that could create backwater during high flows were identified, and channel modifications were recorded:
   a. Blue-line stream reaches in watersheds were examined for evidence of channel straightening, realignment, or other modifications such as excavation for old mill races.
   b. Any structures spanning or encroaching on the stream channels were identified.
   c. The 1960s course of the streams on the topographic map was compared with the present alignment documented by aerial photographs, and discrepancies were recorded.
2. Soil, land use, and hydrology characteristics of the watersheds were identified:
   a. NRCS soil surveys were examined to identify the soil types.
   b. Land use was identified from the USGS 2001 national land cover database (USGS 2008b).
   c. Aerial photographs were examined to identify recent land use changes and possible impacts to channels and valleys.
3. The Bluegrass regional geomorphic assessment completed for KDOW (Parola et al. 2007) was reviewed for information about stream geomorphic characteris-

tics and the effects of geology, historical land use, and current land use on sediment loads and channel evolution.

Blue-Line Stream Bank Sediment Production Measurements

Geomorphic Assessment

Within each of the nine blue-line assessment reaches, eroding banks were delineated as bank segments based on bank height, slope, and vegetative cover: significant changes in any of these parameters denoted breaks between different segments. Channel bed and bank geometry and material characteristics of each segment were photo-documented with a digital SLR camera. The location of each photograph was recorded with a handheld GPS. The locations of the downstream and upstream limits of all eroding bank segments were surveyed using a handheld GPS (Harrison Fork and Salt River) or a robotic total station and rod (UT South Elkhorn Creek). The height of eroding banks within each reach was measured with a pocket rod at the downstream and upstream ends of each eroding segment and at several locations in between. The bank height was measured from the top to the bottom of the eroding surface. The number of measurements depended on the variability of the bank height. Each major change in bank height (>1 ft) was recorded. The percentage of the bank that was eroding was visually estimated for each segment. Any features that would influence the distribution of shear stress during flood flows, such as steep riffles or channel bends, were recorded in a field notebook. Bank segments were recorded as having low, medium, or high near-bank stress (NBS) depending on various factors (Table 2.11). Repeat visits to each site were made (at least four per year) to document any changes in the bank condition and to note any significant processes that might influence erosion rates (e.g., the development of needle ice during winter months or desiccation cracks during summer months).

Table 2.11 NBS Risk Ratings and Parameters

Risk Rating	Planform	Entrenchment	Gradient
Low or very low	Straight or inside of bend	No entrenchment	Below reach average (pool, backchannel)
Moderate or high	Outside of bend	Moderate entrenchment	Reach average (glide, run)
Very high or extreme	Converging, chute flow	Highly entrenched	Above reach average (riffle or rapid)

Dendrogeomorphic Measurements

Measurements of exposed tree roots, root suckers (shoots grown on exposed roots after exposure), and tree stems were collected (Figs. 2.5a-d) to estimate bank erosion rates in the MMSK reach. All exposed bank-line tree roots, suckers, and tree stems within each eroding bank segment were evaluated for sampling, and at least one exposed root was sampled in each segment. The criteria for suitability of roots were that the root was both exposed and alive. Roots that were not anchored at both ends were not sampled, as these were assumed to be dead. If a root was not obviously alive or dead, the bark was removed using a sharp knife; if a green cambium layer was revealed, the root was alive. The only criterion for suitability of root suckers and stems was that they were alive; the presence of leaves was typically sufficient evidence.

At each selected tree, the root, sucker, or stem that met the above criteria and was furthest out from the intact soil of the stream bank was sampled. If a sucker was present on sampled root, it also was sampled. Where multiple roots, suckers, or stems were located the

Figure 2.5a Exposed root measurement, L, used to calculate lower limit of erosion rate.

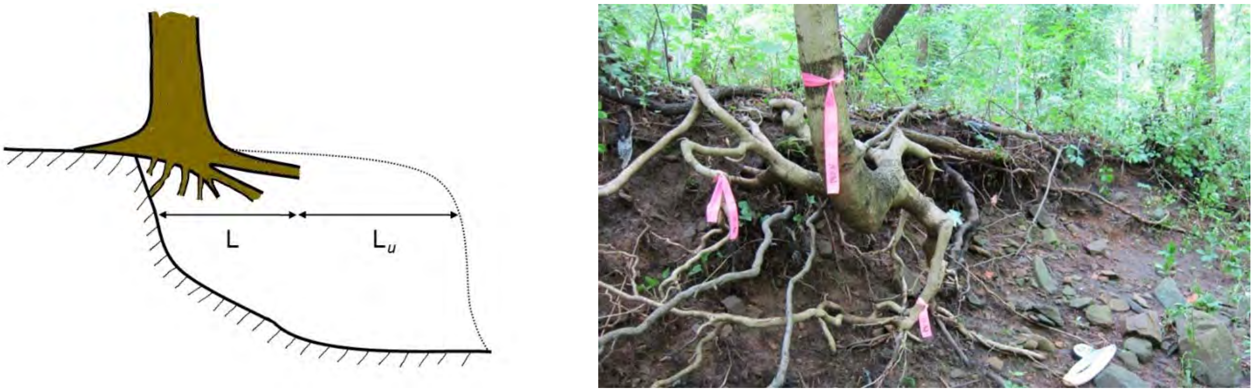

Figure 2.5b Upright tree measurement, L, used to calculate lower limit of erosion rate.

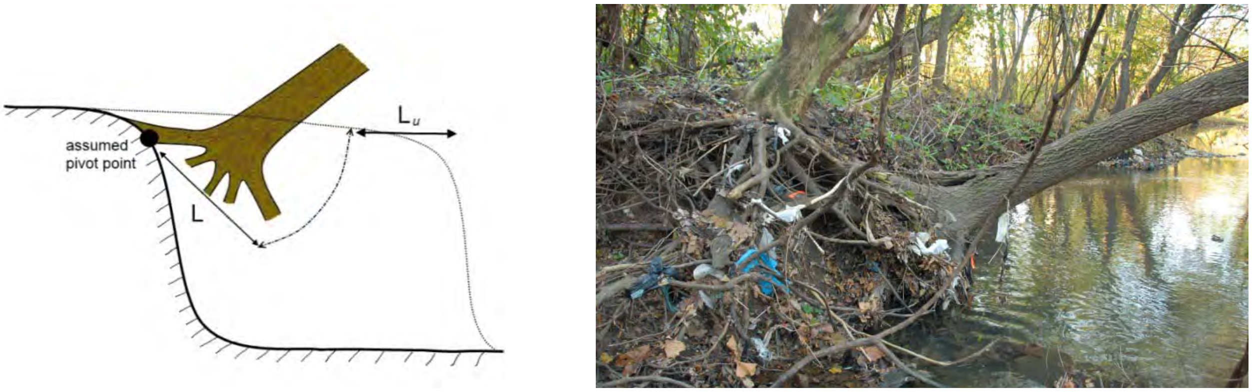

Figure 2.5c Fallen tree measurement, L, used to calculate lower limit of erosion rate.

Figure 2.5d Root-with-sucker measurement, L, used to calculate a lower limit of erosion rate.

same distance from the bank, the smallest (assumed to be the youngest) root, sucker, or stem was sampled. Roots, suckers, and stems with diameters of less than 3 in were sampled by cutting a disc approximately 3 in long with a handsaw. Discs with a rotten core or missing material were rejected. Stems with a diameter greater than 3 in were sampled only from large trees with a root ball undermined by erosion. These stems were cored using a Haglöf increment borer (0.200-in diameter) following standard methods (Phipps 1985). Samples were collected in 83 locations within the reach (Fig. 2.6).

The distance from the bank to the root, the orientation of the root, and the tree species were recorded. Some roots could not be identified as belonging to a particular tree, so the species was not determined. The amount of flex in each root was also recorded. The flex was estimated by moving the root by hand as far as possible normal to the streamflow direction and using a pocket rod to measure the displacement distance. The length and height of the eroding bank were also measured, along with the percentage of bank eroding.

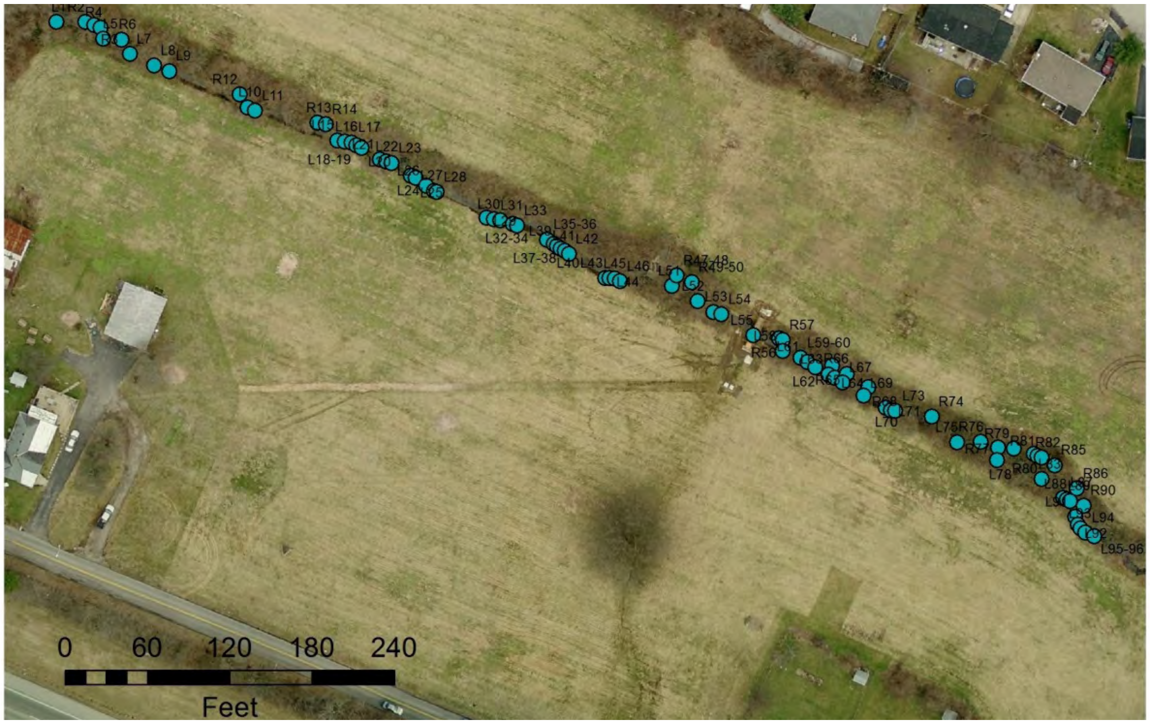

Figure 2.6 Location of bank pins and exposed tree roots along the study reach. At each location, 2–4 pins were installed in a vertical line.

Bank Pin Measurements

Bank pins were installed in May 2011 at the MMSK reach. A total of 260 pins were installed at the 83 locations where roots were sampled. Pins were installed in a vertical line with approximately 1 ft of space between each pin. Each location had at least two pins but no more than four: one at the toe of the bank, one at the bankfull level, and if bank height exceeded 3 ft, one or two between those two points. The pins were constructed of 0.25-inch-diameter steel rods of 3 ft in length. These rods were driven into the bank with 0.1 ft left exposed to make them easier to find in repeat visits. The exposed segment of the pins would also facilitate locating the pins if deposition were occur. Although the pins were primarily to measure erosion, sloughing of loose material had been observed at a few bank sections on previous site visits, so covering of the pins was a concern at this site.

The first erosion measurements after the pins had been installed were made in August 2011. The measurements were taken from the face of the pin to the intact soil bank. Measurements were made in millimeters and were accurate to ±1 mm (±0.003 ft). The bank pins and more general bank conditions were photo-documented at least once every three months for the next year, and the pins were resurveyed after one year in August 2012.

Bulk Density Samples

At each of the six selected bulk density sampling locations in the MMSK reach, two or three bank sediment samples were taken in a vertical line along the bank. Samples were collected using the drive cylinder method described in ASTM D2937-90. The test method involves obtaining a relatively undisturbed soil sample by driving a 2-in diameter thin-walled cylinder into the stream bank material and removing a test sample. The test samples were 2 in in length.

Unmapped Channel Sediment Production Measurements

Unmapped Channel Geomorphic Assessment

Bank geometry and sediment characteristics of each segment were photo-documented with a digital SLR camera. The location of each photograph was recorded with a handheld GPS. The locations of the downstream and upstream limits of all eroding bank segments were surveyed using a handheld GPS. The height of eroding banks within each reach was measured with a pocket rod at the downstream and upstream ends of each eroding segment and at several locations in between. The bank height was measured from the top to the bottom of the eroding surface. The number of measurements depended on the variability of the bank height. Each major change in bank height (>1 ft) was recorded. The percentage of the bank that was eroding was visually estimated for each segment.

Channel Head Mapping

Aerial photographs of Harrison Fork and Salt River watersheds were of sufficient resolution for channel heads to be identified without a field investigation. Channel heads were identified on the photographs, and their locations were recorded in ArcGIS.

Upland Sediment Production: Pond Surveys

Soil erosion models are widely used for estimating upland erosion rates because they are more efficient than field measurements. The use of models without field measurements, however, is subject to great uncertainty and may produce results that are contrary to observed conditions (Trimble and Crosson 2000; Reid and Dunne 1996). Because no field-calibrated or -verified models were available for Bluegrass watersheds, field measurements of pond sediments were recorded to estimate the total annual sediment production from eroded uplands. Mass erosion, which includes landslides and debris flows, is not prevalent in the Bluegrass region, except in the Cincinnati/Northern Kentucky area and in other locations along the Ohio River (Potter 2007), and thus was not considered as a part of this assessment.

Pond surveys were conducted in 2009 in the Salt River watershed and 2010 in the Harrison Fork watershed. The ponds and upland land cover characteristics, including any grazing, were photo-documented with a digital SLR camera, and the location of each photograph was recorded with a handheld GPS. The local landowner was briefly interviewed to obtain a history of land use, including details on the type and intensity of any grazing, and whether any construction had occurred during the time since the pond was built. Area and depth of sediment deposition were measured, and bulk density samples of pond sediments were collected at each pond. The pond perimeter and the volume of sediment deposited above the water surface were surveyed using a total station and rod. The pond perimeter was defined as the top of deposited sediment. Deposited sediment was visually distinct from the surrounding soil; it was generally layered, poorly consolidated, and minimally vegetated. Depth measurements could not be obtained using the total station due to the difficulty in keeping the boat and survey rod stationary enough to take a reading. Instead, a survey grid around the pond perimeter was established, and cross-section measurements collected from the boat were referenced to that survey grid. The number of cross sections surveyed ranged from 4 to 11, depending on the size and shape of the pond. Along each cross section, two series of measurements were made: the depth to the top of deposited sediment and the depth to the bottom of deposited sediment (marked by increased resistance due to bedrock or clay liner). At least seven pairs of measurements were recorded along each cross section.

To estimate bulk density, a series of sediment cores were collected in each pond using a modified open push tube sampler (ASCE 2000; McKean and Nordin 1986). The sampler was modified by replacing the metal tube with PVC to reduce weight and cost, and by adapting the handle so it could close the valve while submerged. At least five submerged cores were collected at each pond. All submerged sediment cores were extracted from the PVC on site using compressed air and were transferred to the laboratory for further analysis.

Above the water surface, only one core was collected per pond because this sediment covered a much smaller area than the submerged sediment. The surface cores could not be extracted without removing surrounding sediment, so a simplified sampling procedure was used: a thin-walled PVC tube was inserted until stiff resistance was met, and the core was then loosened by removing the surrounding sediment using a spade and by hand. Once the core was detached from the surrounding sediment, the core was twisted and removed for further analysis.

Floodplain Deposition Monitoring

Measurements of sediment deposition had been made in Goose Creek using AstroTurf® mats. The AstroTurf® mats were 1-by-1 ft and were secured using metal pins driven into the ground on each corner. Although relatively cheap and easy to install, removing the sediment from the mat to obtain sufficiently accurate samples was time-consuming, and organic material (i.e., leaves and small twigs) had to be removed, which took additional time. In this project, clay pads were used as a marker for sediment deposition. The method was selected based on its use in studies conducted by the USGS in Maryland (Noe and Hupp, 2005; Kroes and Hupp 2010). The clay pads consisted of approximately 1-by-1ft powdered white feldspar clay with a thickness of 0.2 ft. They were placed onto an area cleared of leaves and vegetation. The clay pads become fixed marker horizons after absorption of soil moisture, and can be revisited to obtain a measurement of sediment deposition over the clay pad. Although some studies have focused on sedimentation during individual events (Steiger et al. 2001), for this study the total effect of sediment deposition over an annual period was judged to be more important than inter-flood variations. Measuring deposition over a year integrates the effects of floods that deposit sediment and subsequent floods that may erode sediment, resulting in measurement of the net deposition rate.

In-Channel Sediment Deposition Measurements

For all selected sites, the length and width of at least five riffles were measured using a tape and were recorded in a field notebook. The location of each riffle crest was recorded using a handheld GPS to estimate the riffle-to-riffle spacing. Channel bed characteristics were photo-documented with a focus on how deep the sediment would need to penetrate to fill up voids between the gravel and cobble framework.

Suspended Sediment Monitoring

A monitoring station was established at each yield measurement site. The stations recorded measurements of turbidity, water surface elevation, and average flow velocity. Each sediment monitoring station had three pieces of equipment: a Campbell Scientific (previously D&A Instruments) OBS3+ turbidity sensor; a Campbell Scientific CR200 or CR800 datalogger, and a Campbell Scientific CS450 vented pressure transducer. The equipment was mounted on a tree to minimize the possibility of flood damage. A Sontek Argonaut SW measured flow velocity during floods.

At the Salt River and Harrison Fork sites, an automated pump sampler (Teledyne ISCO) was used to collect water samples during floods because manual sampling would have been impractical (e.g., at night) or dangerous (e.g., when velocities were very high). The ISCO was installed first at Salt River and then was moved to Harrison Fork. A small wooden platform was constructed on the terrace to hold the ISCO above flood stage. The inlet to the ISCO was mounted on a hinged rod attached to the bed. The rod had a float attached to the end that kept the sensor above the stream bed and away from bedload movement (Fig. 2.7). During floods where the water stage was above the length of the 5-ft rod, the sensor was at

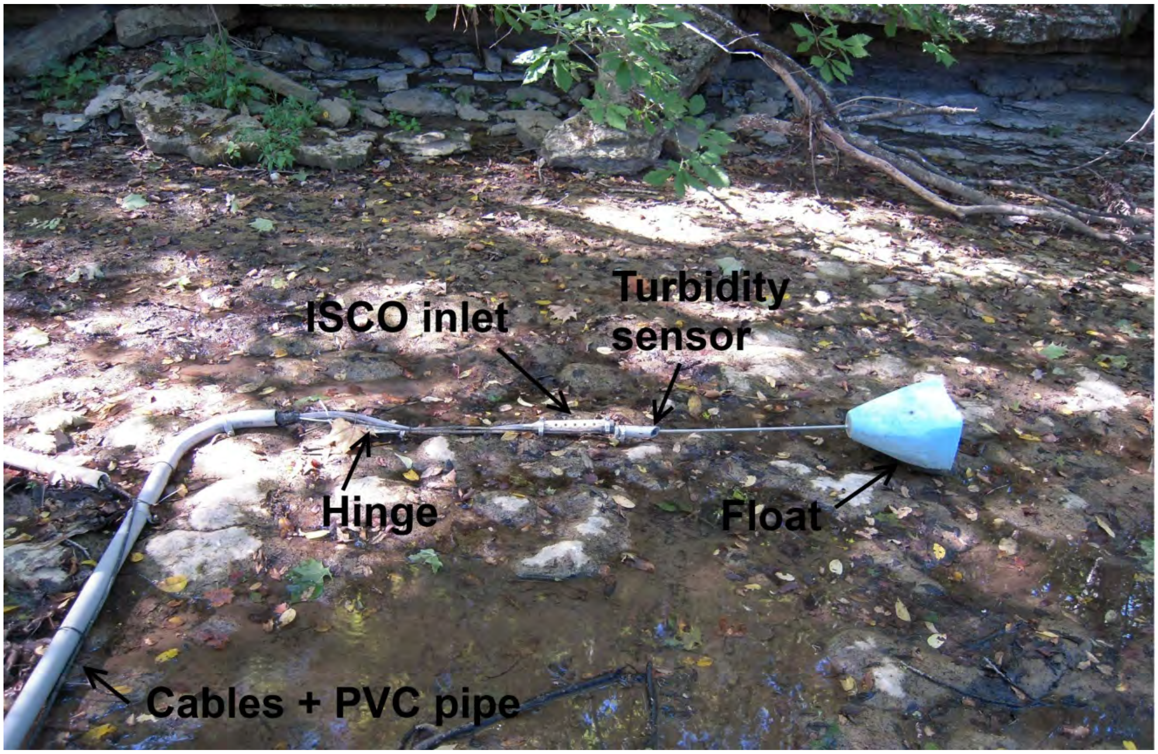

Figure 2.7 Sediment station with turbidity sensor, ISCO inlet, and hinged rod. The pressure transducer was typically installed near the channel bank to minimize the potential for flood damage.

less than the half the depth. The sensor did not have a wiper, so its face was cleaned every two weeks to limit biofouling. The sensor had a high nephelometric turbidity unit (NTU) range (0-4000 NTU) for recording data during very turbid flows. It recorded 60 individual NTU readings at 1 Hz and stored the mean value and the standard deviation. The sensor recorded two alternating sets of data, one immediately after the other: a low range reading (0-1000 NTU) first for 1 minute, then a higher range reading (0-4000 NTU) for 1 minute.

The ISCO was initially set to collect a water sample every 10 minutes after the stage had reached a trigger value. Early results at Salt River, however, indicated that this frequency was too high: many samples had very low suspended sediment concentrations (SSC) and corresponding turbidity readings and did not provide a range of values that would be necessary to develop a statistically significant relationship between the two parameters. To increase the range of turbidity values and SSCs captured by the station and ISCO, the trigger was adjusted to take a sample at every change in turbidity of 100 NTU or greater.

The ISCO samplers experienced numerous mechanical problems that resulted in periods of missing data. At Salt River, high shear stress during flood events twice ripped the sampler tubing out, preventing any samples from being collected. Ice buildup in the collection tubing also resulted in empty sample bottles during flood events when the datalogger clearly indicated that samples had been triggered. The build-up of ice in the sampler tubing was also a problem at Harrison Fork.

2.5 DATA ANALYSIS

Blue-Line Channel Erosion

Erosion Rate Estimates from Dendrogeomorphic Measurements

The age of all wood samples was determined by ring counting using a stereomicroscope (Fig. 2.8). Samples were prepared by sanding them with progressively finer grits of sandpaper down to 600-grit. In studies where samples have long tree-ring series, rings from each sample are commonly cross-dated with others from the same site in order to assign a calendar year to each ring and identify missing or false rings. The use of this method of limiting error was precluded by the collected samples’ relatively short tree-ring series and numerous growth disturbances, such as many years of compression wood (Malik and Matyja 2008). Instead, if the precise age of a sample was uncertain, the lower and upper possible

Figure 2.8 Stereomicroscope view of root cross-section.

ages were recorded to estimate the uncertainty. The lower age was estimated by omitting possible false rings, and the upper age included all rings, some of which may have appeared due to density fluctuations. By this method, a relatively rapid estimate of the sample age was obtained with a precision of about 5−20% (1−4 years).

For each tree sampled, a representative erosion rate was identified based on the age of the individual root, sucker, or stem samples and the root-to-bank distance measurement, L (Figs. 2.5a−d). Using the method described by Vandekerckhove et al. (2001), a lower bound estimate of the soil erosion rate was obtained from sampled tree roots or stems age and distance measurements, while the upper bound rate was estimated from the root suckers ages. The annual rate of erosion, e_{rd} (ft/yr), was calculated as

$$e_{rd} = L/T_m$$

where L (ft) is the measured distance from the exposed root to the bank surface, and T_m (yr) is the measured age of the sample.

The estimated erosion rates either underestimate or overestimate the actual erosion rates, depending on the type of sample collected. Because the tips of tree roots have to grow in soil, the age of each root (T_m) is greater than the time elapsed since the root was exposed (T_e): $T_m > T_e$. Because T_m, rather than T_e, is used in calculating the rate of erosion (e_{rd}), the calculated erosion rate will be an underestimate of the actual rate (e_e): $e_{rd} < e_e$ (Fig. 2.5a). Likewise, calculations from tree stems were based on the same principle: the tree grew prior to erosion, and therefore, the age of the tree represents the maximum possible time over which erosion could have occurred, so $e_{rd} < e_e$ (Figs. 2.5b and c). Conversely, root suckers grow on a root after exposure and thus mark the lower limit of time elapsed since the exposure, so $T_m < T_e$, and $e_{rd} > e_e$ (Fig. 2.5d).

Tree roots and root suckers from the same root provide upper and lower bounds of the erosion rate. The root form can give clues as to the extent of the unmeasured length of bank erosion (L_u). Asymmetrical root growth with bark-covered scars where roots had broken off indicated that the root had been exposed for a number of years, whereas a symmetrical basal flare at the base of the trunk and exposed xylem where roots had broken off indicated that the tree grew on the floodplain, not on an eroding bank.

Erosion Rate Estimates from Bank Pin Measurements

An average annual erosion rate, e_{avg} (ft/yr), for each bank pin site on blue-line assessment reaches was estimated by weighting the rate measured at each erosion pin by the proportion of the bank represented by each of the pins as follows:

$$e_{avg} = (L_{n1}B_{n1} + L_{n2}B_{n2} + L_{n3}B_{n3} + L_{n4}B_{n4})/(T_d * 365)$$

where Ln (ft) is distance from the end of exposed bank pin n to the bank surface, Bn is the percentage of the bank height accounted for by pin n, and T_d (days) is the duration of field deployment of the pins. Typically, the top pin covered about 40–50% of the height of the bank, whereas the lower two or three pins covered 20–30% each. The average annual erosion rate was used in estimations of sediment production.

At the MMSK reach, the erosion rate of each individual pin was calculated separately as

$$e_{ind} = (L_nB_n)/(T_d * 365)$$

in order to identify the difference in erosion rate between those pins that were inundated during flood flows and those pins that were located high in the bank and thus were not inundated and were subject to weathering processes without shear stress.

Bulk Density Estimates

The bulk density, ρ_b, of each bank sediment sample from the MMSK reach was calculated using the procedures described in ASTM D2937-90. The samples were dried in an oven to remove any moisture and then were weighed. The mass was then divided by the volume of the sample. An average bulk density of MMSK bank sediments was estimated as the average of all ρ_b values.

Unit Sediment Production Estimates

The erosion rates estimated using erosion pins (e_{rp}) and dendrogeomorphic measurements (e_{rd}) were used to estimate the volumetric rate of sediment produced from each eroding bank, V_B (ft^3/yr), which was estimated from

$$V_B = (L_{LB} \text{ x } E_{LB} \text{ x } H_{LB} \text{ x } e_r) + (L_{RB} \text{ x } E_{RB} \text{ x } H_{RB} \text{ x } e_r)$$

where the subscripts $_{LB}$ and $_{RB}$ denote the left and right banks, respectively, L (ft) is length of assessed bank, E is the percentage of the bank eroding, H (ft) is bank height, and e_r (ft/yr) is the annual erosion rate estimated using erosion pins (e_{rp}) or dendrogeomorphic measurements (e_{rd}). The volumetric rate of sediment production estimated from each bank was summed for all of the assessed reaches.

The mass of sediment produced from bank erosion per unit length per year—or unit sediment production, USP_{BL} (tons/ft/yr)—was then estimated from

$$USP_{BL} = \frac{\sum(V_B \times \rho_b)}{L_R}$$

where ρ_b (tons/ft^3) is the average bulk density of bank sediments, and L_R (ft) is the length of the reach. At sites where bank pin data were not available but bank geometry information had been collected, an erosion rate representing an expected amount of erosion due to weathering was used in the calculation of USP.

Unmapped Channel Erosion

Drainage densities that can be used to estimate the length of unmapped channels were estimated using an ArcGIS-generated channel network and field data. Sediment production rates for reaches in Salt River were calculated from field measurements of bank height, length, and percentage area of eroding banks, together with estimated erosion rates due to weathering.

Unmapped Channel Extent

Blue-line streams drawn on USGS topographic maps represent only a portion of the drainage network (Leopold et al. 1964; Mark 1983; Hansen 2001; OHEPA 2002; Rosenfeld et al. 2002), and many headwater channels not shown as blue-line streams are distinct watercourses with eroding banks. Estimating the extent of these unmapped channels is therefore necessary for estimating sediment production from bank erosion. The starting point for these channels, and hence the channel network, is the channel head. By determining the drainage area, or flow accumulation area, at which channel heads occur, a channel network can be generated using standard ArcGIS routines.

Drainage areas of each channel head were measured from 30-ft resolution digital elevation models (DEMs) in ArcGIS. The drainage areas of all channel heads were tabulated, and summary statistics (mean, median, mode, standard deviation) were calculated. Using the channel head summary statistics as the points at which the channel network begins, channel networks were generated in ArcGIS Spatial Analyst. The channel network generation was performed on a 30-ft resolution DEM for the Goose Creek watershed according to the following steps:

1. Calculate flow direction for each cell (Jenson and Domingue 1988).
2. Calculate flow accumulation for each cell (Jenson and Domingue 1988).
3. Identify the flow accumulation threshold value that represents the start of the channel network, and designate all cells below this value as channel.
4. Calculate stream order (Strahler 1957).
5. Convert raster dataset to vector.
6. Estimate length of channel network.

A number of channel networks were generated to see which best approximated the real channel network, and hence provided the most accurate measure of bank length. The flow accumulation area for the channel heads was changed in each network while all other parameters were kept constant. The channel head drainage areas ranged from less than 0.5 acres to more than 6 acres. The mean, median, and mode of all channel heads were used as initial flow accumulation areas. The mean, median, and mode ±1 standard deviation also were used.

From the drainage network generated using the maximum channel head area, the streams were ordered according to the Strahler (1957) method, and all first- and second-order streams were identified. The third- and higher-order stream reaches corresponded to the blue-line streams very closely and therefore were not included in the analysis of unmapped channels.

A drainage density—the total length of channel per unit area (Horton 1945)—was estimated for each of the three drainage networks that had been generated using the maximum, minimum, and mean channel head areas. Drainage density, D_d (mi/mi^2), was estimated from

$$D_d = \frac{\sum L}{A_d}$$

where $\sum L$ is the total channel length in a basin of area A_d. The drainage densities of the blue-line streams for Currys Fork, Goose Creek, Harrison Fork, and Salt River watersheds were also estimated in order to calculate the proportion of the drainage network not represented by the blue-line stream network.

Unmapped Channel Sediment Production

A unit erosion rate, UER (ft^3/ft/yr), was estimated for unmapped assessment reaches in Salt River watershed from

$$UER = \frac{H_{ave} \times E \times e_{hw}}{L_r}$$

where H_{ave} (ft) is the average bank height for all assessed first- or second-order streams, E (ft) is the length of assessed banks, e_{hw} (ft/yr) is the headwater average erosion rate for all assessed first- or second-order streams, and L_r (ft) is the total reach length of assessed unmapped channels. The erosion rate, e_{hw}, was the weighted average of all erosion pin readings (n = 86) taken from previously assessed sites with a drainage area of less than 3 mi^2 (n = 29) in the Goose Creek watershed. The average bank height and the length of eroding bank were averages estimated from more than 10,000 ft of assessed unmapped channel reaches (5996 ft for first-order and 4391 ft for second-order).

The USP for unmapped channels, USP_{UC} (tons/ft/yr), was estimated from

$$USP_{UC} = (\rho_b)\ (UER_{1st})(L_{r\text{-}1st\text{-}order}) + (\rho_b)\ (UER_{2nd})(L_{r\text{-}2nd\text{-}order})$$

where the lengths of first- and second-order streams, $L_{r\text{-}1st\text{-}order}$ (ft) and $L_{r\text{-}2nd\text{-}order}$ (ft), were measured from the drainage network generated using the mean drainage area.

Sediment Production from Upland Surface Erosion

Pond Survey Data

The in situ bulk density, ρ_C (lb/ft^3), of each sediment core was estimated from

$$\rho_C = \frac{M_C}{V_C}$$

where M_C (lb) is the oven-dried mass of the core, and V_C (ft^3) is the in situ volume of the core. The mass was obtained after the samples were dried in the oven at 110°C for 24 hours. The in situ volume was used because (1) this volume was measured for many points, not just core locations, and (2) the in situ volume was easier to accurately measure than the volume after drying, when the sediment core shape became very irregular. The bulk densities for submerged sediment cores in each pond were averaged to give ρ_{subm}; the bulk density for the sediment toe at the pond inlet is denoted ρ_{toe}.

The cross section data collected in the field were entered into an Excel spreadsheet, and two lines were generated at each cross section, one for the top of the deposited sediment layer and one for the bottom of the deposited sediment, representing the original land surface immediately after pond construction.

The cross-sectional data were then exported to AutoCAD together with the perimeter survey and data surveyed above the water surface. A triangulated irregular network (TIN) was generated for both the top and bottom of deposited sediment using automated routines in the Autodesk Land Desktop Terrain Editor. The difference in volume between the two TINs was estimated in AutoCAD and represented the volume of deposited sediment. Separate TINs were generated for the sediment toe at the pond inlet, which was above the water surface. The volume of submerged sediment was then multiplied by ρ_{subm} for each pond to estimate the mass of submerged sediment in each pond. The above-water sediment mass was estimated in the same way using ρ_{toe} values.

The upland sediment production rate for each pond, S_p (tons/acre/yr), was estimated from

$$S_p = \frac{M_T}{DA \times T}$$

where M_T (tons) is the total mass of sediment deposited in and around the fringe of the pond, DA (acres) is the contributing drainage area, and T (yrs) is the deposition period. This upland sediment production rate is a net erosion rate: the difference between the rate of soil loss from upslope of the pond and the rate of soil deposition upslope of the pond. The assumed trapping efficiency of the ponds was 100%, based on the very small contributing drainage areas (Verstraeten and Poesen 2001), although the efficiency may have been lower during large flood events. Loss of sediment during large floods was the primary cause of uncertainty of these sediment yield estimates: the other major potential source of error include land disturbances that added sediment but were not documented. Pond surveys were chosen in part because measurement errors, from surveying and sampling, are relatively small (i.e., surveying errors are typically <1% of total volume).

The land cover for each pond was determined initially by examination of the 2001 National Land Cover Database (NLCD) GIS coverage (USGS 2008b). Any land cover that accounted for at least 10% of the contributing drainage area was recorded (Table 2.6). Most ponds had a dominant land cover (covering greater than 90% of the contributing drainage area). Where the land cover was listed as "pasture/hay," more information was required: erosion rates for intensely grazed pasture could be very different from those where the fields are used only for hay. For these ponds, the intensity of grazing was determined based on inspection of the photo-documentation and discussions with landowners.

GeoWEPP Modeling

A simple geospatial soil loss model (Geo-spatial Interface for Water Erosion Prediction Project, or GeoWEPP, was applied to Currys Fork and Goose Creek watersheds. The GeoWEPP interface was selected to analyze sediment production from upland surface erosion because it is relatively easy to use, uses commonly available geospatial datasets, and uses the widely-used and physically based WEPP model. The WEPP model has the advantage over the Universal Soil Loss Equation in that it models soil loss and soil deposition rather than soil loss alone. The upland sediment production rate, S_m, output by the GeoWEPP model is the net erosion rate: the difference between the rate of soil erosion (soil loss) and the rate of soil deposition. More documentation on the WEPP model is given in Flanagan and Nearing (1995); more documentation regarding the GeoWEPP interface is given in Minkowski and Renschler (2008).

The GeoWEPP simulation runs for a user-specified interval. The Goose Creek and Currys Fork watershed GeoWEPP simulations were run using 50 years of climate data from the Kentucky River Lock and Dam 4 climate station in Frankfort and Louisville International Standiford Field airport climate stations, respectively, which were the closest stations available in the WEPP program's climate dataset (Nicks et al. 1995). The other inputs for the GeoWEPP simulations were the 2001 NLCD (USGS 2008b), soil types (NRCS 2009), and topography (USGS 30-ft DEMs). To run GeoWEPP, each soil type was converted into a GeoWEPP soil file, which has various soil properties such as interrill erodibility, critical shear, effective hydraulic conductivity, percent organics, percent clay, etc. Similarly, the land cover type was converted into a GeoWEPP management file. Using field observations, interviews with landowners, and the results of the pond surveys, the GeoWEPP soil file and GeoWEPP management files were calibrated to conditions in Goose Creek and Currys Fork watersheds. Guidance on individual soil parameters came from the *Soil Survey of Anderson and Franklin Counties*, *Kentucky* (McDonald et al. 1985) and from the *Soil Survey of Oldham County* (Whitaker 1977). Soil types were changed to "flaggy" (i.e., containing platy rock fragments or “flagstones”) where appropriate in Goose Creek watershed, but soil files were otherwise unmodified. The land cover management file required greater modification: the default “fallow” land use, for instance, produced very high erosion rates not representative of fallow land in the watersheds.

The GeoWEPP typically predicts soil loss and deposition rates from hillslopes and from channels. Because the channel routing/sediment transport model is not very sophisticated (Bill Elliot, pers. comm. 2009), only the hillslope component of the model was used. The output data from each hillslope were imported in an Excel spreadsheet, and the total sediment production, M_{hill}, (soil loss minus deposition) was estimated for all hillslopes. The total mass of sediment produced from upland erosion, M_{up}, within each subwatershed was estimated as the sum of the M_{hill} values from all hillslopes. The modeled sediment production rate, S_m, was estimated by dividing M_{up} by the area of subwatershed.

The upland sediment production rates estimated from the pond data were used to assess the accuracy of a GeoWEPP model for the watershed. The sediment production rate predicted for each pond’s hillslope using GeoWEPP was plotted as a function of each upland erosion rate estimated from the pond surveys. An ordinary least-squares regression was calculated between the estimated (GeoWEPP) and observed (pond) data and was compared to the line of perfect agreement ($x = y$).

Floodplain Deposition

Clay pads were visited 6 months after installation, and again after another 6 months. If deposited sediment had been present, the depth of sediment (ft) would have been measured and used to calculate a rate of sediment deposition (ft/yr). No calculations were made, however, because the only sediment that was captured was not relevant to measurement of deposition; it appeared to be soil from rainsplash on adjacent ground rather than from deposition during a flood.

In-channel Sediment Deposition Masses

Sediment stored in riffles (siltation) was calculated for all five watersheds based on surveyed riffle dimensions, sediment porosity and depth of infiltration. The mass of sediment required to embed a riffle, M_e (lbs), was calculated as

$$M_e = w_r * l_r * d_s * v * BD_r$$

where w_r (ft) is the riffle width, l_r (ft) is the length of the riffle, d_s (ft) is the depth of sediment intrusion into the riffle, v is the void ratio not occupied by cobbles and gravels, and BD_r (lbs/ft^3) is the bulk density of the embedding sediments.

Suspended Sediment Load Estimates

Turbidity Data Reduction

Data correction routines in Aquarius Time Series analysis software were used to remove faulty readings (i.e., values below 0 NTU and/or above the sensor limit of 4000 NTU) and to interpolate between good readings.

Turbidity datasets were corrected using time series software (Aquarius) according to USGS guidelines (Wagner et al. 2006). Typical corrections include spike removal, removal of negative readings, and occasional removal of false readings due to sediment covering the sensor. Some small gaps (<4 hrs) were filled by linear interpolation during periods of constant or slowly changing stage.

Water Sample Analysis

Measurements of SSC were obtained from the water samples by using ASTM Standard Test Method D 3977-97, Test Method A – evaporation (ASTM 2000). Although TSS and SSC values are derived from different laboratory procedures, differences between the two parameters are least significant in samples with no sand component (Gray et al. 2000), which is often the case in the Bluegrass. When sand is present in the sample, it may settle, which would reduce the number of sand-sized particles subsampled for the TSS procedure.

Turbidity–SSC Relationship Development

An SSC-turbidity relationship was developed by ordinary least squares regression between the SSC from water samples and the turbidity readings recorded during the same time intervals (Fig. 2.9). This relationship was then applied to all turbidity readings to estimate SSC for each reading. Where the turbidity reading was above 1000 NTU, the data from the upper range readings were used; below 1000 NTU, the lower range readings were used.

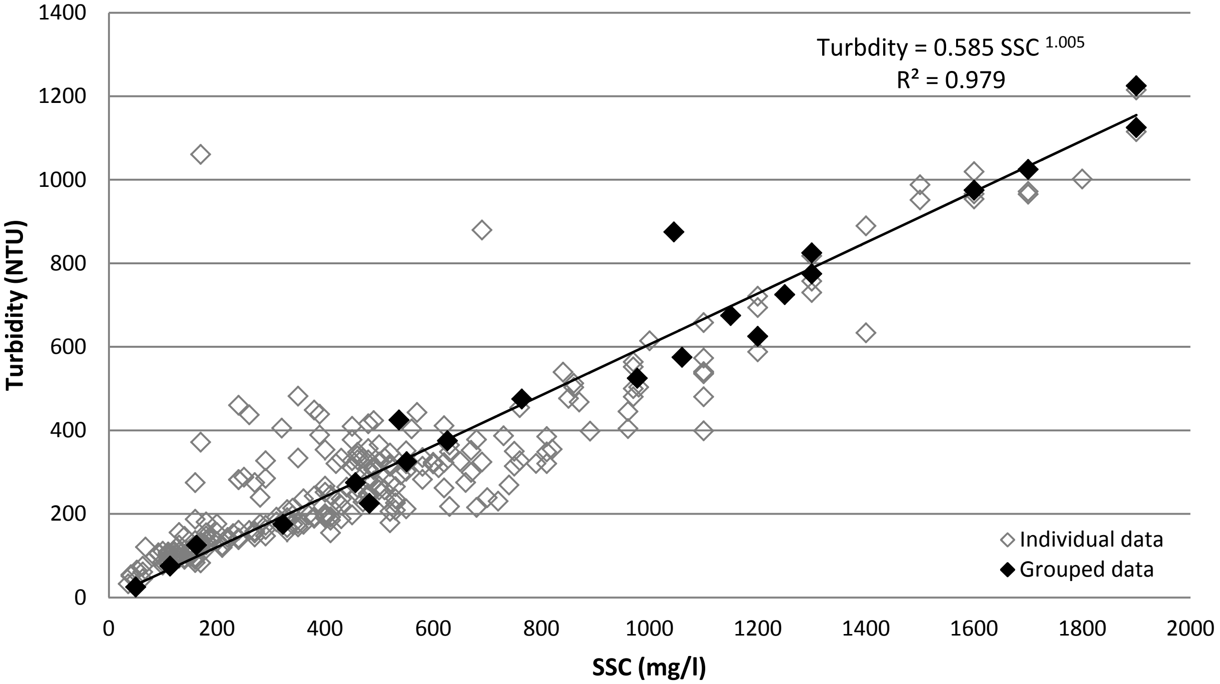

Figure 2.9 Turbidity–suspended sediment concentration used to calculate mass of sediment transported.

Sediment Load Calculations

This relation was then applied to all turbidity readings to estimate SSC for each reading. Each SSC reading was multiplied by a conversion factor to convert from mg/l to lbs/ft^3. For each discharge measurement the total flow volume for each 10 minute period (in·ft^3) was calculated. The SSC (lbs/ft^3) was then multiplied by the volume of flow for each measurement interval (ft^3) to give the sediment load for each 10 minute period (lbs). All sediment transport in each time interval was summed over the duration of 2009 to calculate total load (lbs/yr).

2.6 TRAINING DEVELOPMENT

Five field visits and two lecture presentations were developed to introduce KDOW TMDL and NPS personnel to the following sediment assessment data collection methods:

- Sediment production due to bank erosion
- Identifying the extent of channel network
- Sediment production due to upland surface erosion
- Collecting continuous stage and turbidity data for sediment yield calculations

The field training days were organized as a demonstration of the particular measurement technique followed by a question-and-answer session. The approach throughout the training was on the transfer of practical methods to obtain reliable field data, given the operational limitations of KDOW.

3. Results and Discussion

3.1 SEDIMENT PRODUCTION AND STORAGE

Blue-line Streams

Erosion Rates

Bank erosion rates measured in UT South Elkhorn Creek, Currys Fork, and Goose Creek watersheds varied from 0.0 to 1.4 ft/yr. The highest erosion rates were found at South Fork Currys Fork prior to the 2012 construction of a stream restoration (Fig. 3.1). Reaches in Goose Creek draining less than 1 mi^2 also had banks where the erosion rate was measured at over 1 ft/year. The highest rates were found in bends with high shear stress.

In all watersheds, the action of weathering was very important, especially freeze-thaw during winter months. Most banks were composed of cohesive material (silt and clay) and did not appear to erode even during large floods unless weathering had occurred. The typical sign of weathering was a loose friable layer on the bank surface; sometimes ice was observed in this layer (Fig. 3.2). The prevalence of weathering was related to vegetative cover; only banks with bare soil were observed to weather. Due to the prevalence of weathering in the erosion process, the majority of reach-averaged erosion rates were between 0.15 ft/yr and 0.4 ft/yr regardless of estimated near bank shear stress (Fig. 3.3). Most eroding banks in the Bluegrass can be expected to erode at rates of at least 0.09 to about 0.24 ft/yr due to weathering processes alone.

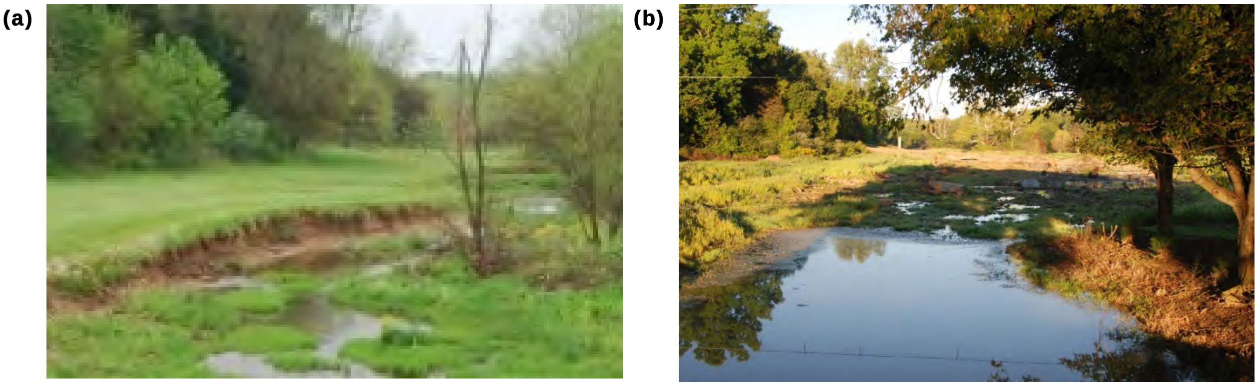

Figure 3.1 South Fork Currys Fork (a) before and (b) after restoration. Bank heights and local sediment supply were dramatically reduced, and in-channel sediment storage potential was increased due to the construction of a wide, frequently-inundated floodplain.

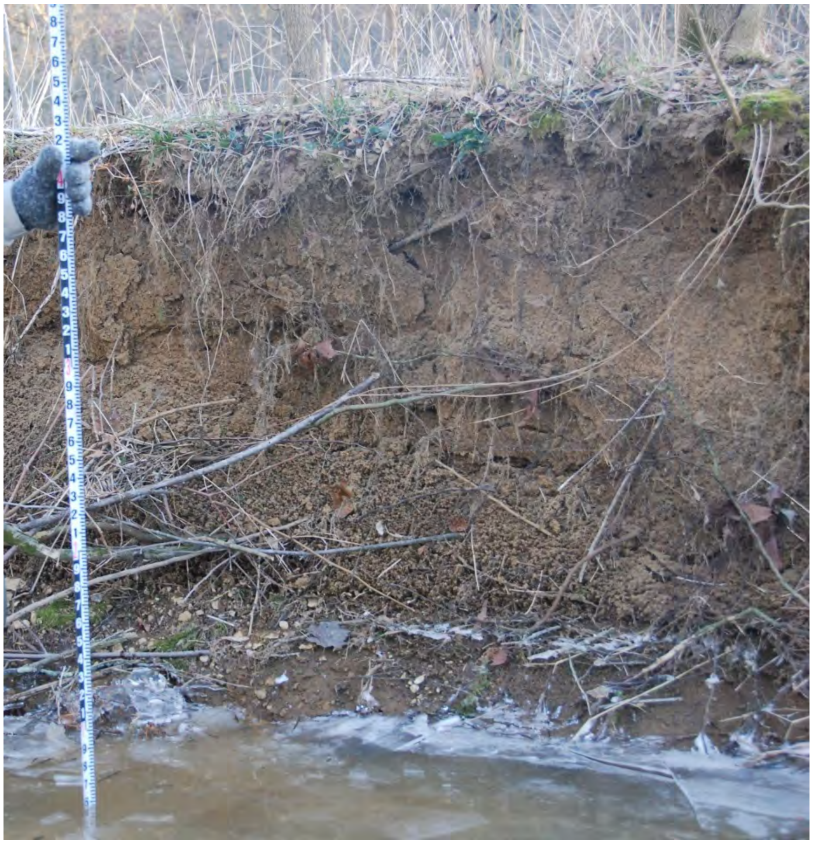

Figure 3.2 Currys Fork weathering bank. Jan 2008.

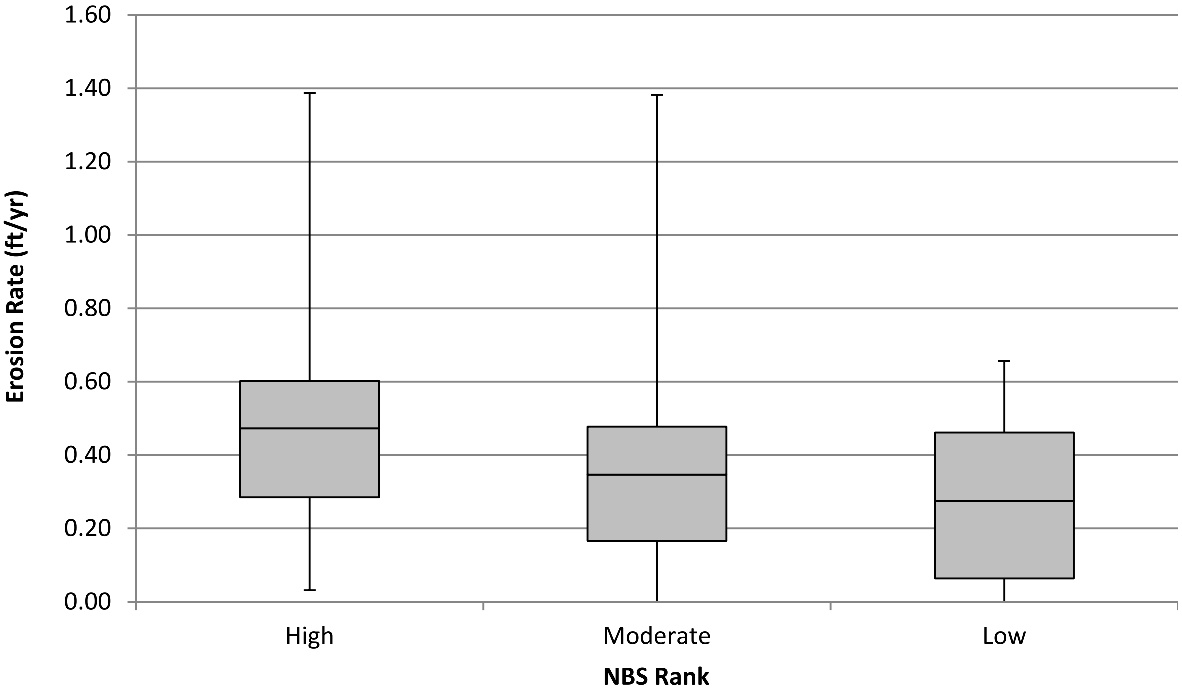

Figure 3.3 Due to the prevalence of weathering in the erosion process, the majority of reach-averaged erosion rates were between 0.15 ft/yr and 0.4 ft/yr regardless of estimated near bank shear stress.

The relative importance of weathering compared to flow as an erosive process was documented at UT South Elkhorn, where some of the monitored bank areas received no flow during the monitoring period but still eroded. A maximum erosion rate of 0.52 ft/yr was estimated for bank pins installed at the base of the channel, which received low flow for much of the year as well as occasional flood flows. Bank pins that were located above the highest point that flow reached during the monitoring period (i.e., pins that could not have been scoured by the flow) eroded at an average rate of 0.09 ft/yr, with a maximum rate of 0.58 ft/yr. The bank pins near the top of the banks at UT South Elkhorn were installed in soil that was heavily reinforced with tree roots; without these roots the value of erosion rate due to weathering processes alone presumably would have been even higher.

The accuracy of bank erosion rates quantified by field measurements will be variable depending on the type, density, frequency, and duration of measurements. The erosion rates measured using dendrogeomorphic methods and those measured using bank pin methods were significantly different (Fig. 3.4). A number of erosion pins showed a zero erosion rate over the monitoring period, whereas the exposed root method showed nonzero erosion rates. The number of erosion pins, 83 sets of 2−4 pins, meant that the zero values did not strongly influence the estimate of the sediment production rate. At a site with less intensive monitoring, this could have resulted in a large underestimate of sediment production. Erosion rates calculated using exposed tree roots were, on average, 0.07 ft/yr higher than those measured with the bank pin method. In other years, perhaps with more precipitation or more freeze-thaw cycles, this pattern could be reversed. The underlying problem with erosion pins is the short time frame over which measurements are collected: using exposed roots or a longer sampling frame (if practical), are ways to minimize this source of error. The dendrogeomorphic technique provides estimates over periods of between 5−50 years, moderating the effect of short-term fluctuations due to extreme floods or droughts.

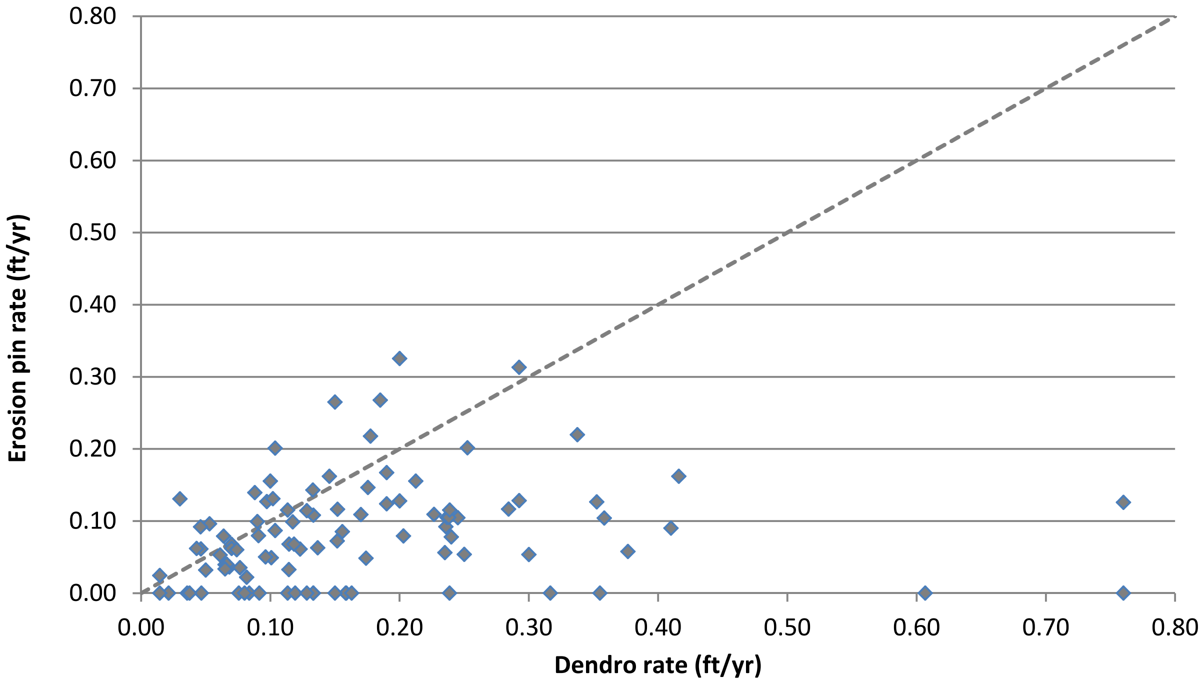

Figure 3.4 Erosion rates measured using dendrogeomorphic methods were significantly different from those measured using bank pins.

Blue-line Stream Sediment Production Rates

The sediment production rate per unit length, or unit sediment production (USP), varied from 12 tons/mile/year to 323 tons/mile/year (Table 3.1 and Fig. 3.5). The highest UPSs were in Currys Fork watershed near the confluence with Floyds Fork, where bank heights are greater than 10 ft (Fig. 3.6), and at the confluence of North Fork and South Fork Currys Fork, where bank heights are at least 8 ft. These reaches are deeply entrenched, but the bank heights rapidly decrease away from the confluences. This local variability of bank height, erosion rate, and hence sediment production was also characteristic of the other four

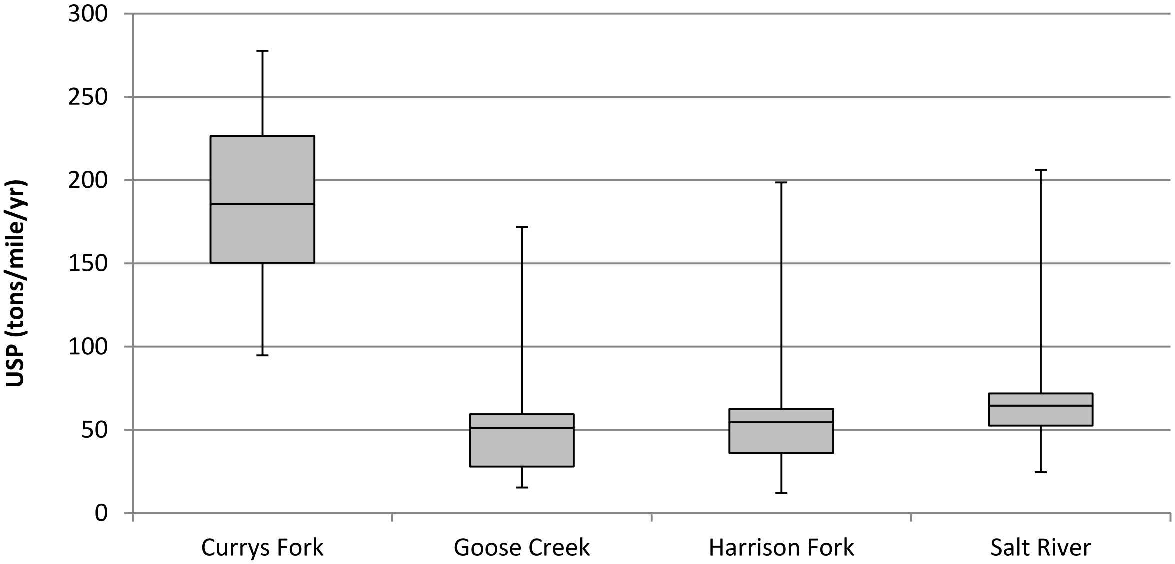

Figure 3.5 Ranges of unit sediment production for blue-line streams. A single USP was reported for UT South Elkhorn Creek because the reach was relatively short. Within this reach, however, the sediment production from individual bank segments varied considerably due to local differences in vegetative cover and root reinforcement.

Figure 3.6 Highest USP was recorded at the downstream reaches of Currys Fork near the confluence with Floyds Fork.

Table 3.1 Blue-line Unit Sediment Production

Reach ID*	NHD Reach code	Strahler	DA (mi^2)	USP (tons/mi/yr)
HF restoration site	05140103001472	3	3.61	45
Wilson Ck	05140103000434	3	5.18	44
Wilson Ck below confluence	05140103000433	4	9.52	116
Dunne Hollow	05140103000433	1	0.39	12
Bantas @KY-573	05100205000433	4	11.5	67
Bantas Welch	05100205000434	3	4.87	86
Salt @ Woods Pike	05100205001127	3	2.4	62
Bantas @ Byers Ln	05100205005416	1	0.43	25
MMSK	05100205007449	1	0.37	163
Ashers Run	05140102002090	3	3.36	148
CF1	05140102000250	4	28.50	323
CF3	05140102000251	4	19.43	186
NC1	05140102000253	3	10.07	257
NC2	05140102000253	3	6.13	95
SC1	05140102001790	4	9.20	196
SC2	05140102001699	3	2.82	153
GC1	05100205001098	4	10.32	48
GC2	05100205001098	4	8.09	41
GC3	05100205001098	4	6.19	87
GC4	05100205001099	3	2.19	36
GC5	05100205001099	2	0.92	21
GC6	05100205001099	1	0.5	15
BB1	05100205001100	3	3.74	51
BB2	05100205001100	3	2.67	51
BB3	05100205001100	2	1.59	53
BB4	05100205001100	2	0.92	172
BB5	05100205001100	1	0.56	139
GCT1	05100205006815	1	0.57	19
GCT2A	05100205006655	2	1.47	57
GCT2B	05100205006576	2	0.77	60
GCT2C	05100205006565	2	0.33	58
GCT2D	05100205006551	1	0.18	19
GCT3	05100205006686	1	0.49	28
GCT4	05100205006904	2	0.72	91
BBT1	05100205006743	1	0.15	52
BBT2	05100205006742	2	0.89	52
BBT3	05100205006737	2	0.84	52
BBT5	05100205006744	1	0.25	176
BBT6	05100205006761	1	0.26	190
WB1	05100205006794	2	1.2	28
WB2	05100205006936	1	0.74	28
WBT1	05100205006871	1	0.14	28

* Reach IDs are numbered consecutively from downstream to upstream on each blue-line channel.

watersheds. Variation in USP in all five watersheds was considerable within reaches of the same stream order (Fig. 3.7) and between adjacent stream reaches (Table 3.1). Much of the variation is due to differences in the percentage area of eroding banks, the height of the banks, and local shear stress conditions (Table 2.11). These reach-scale differences were more important factors in determining the USP than the specific physiographic subregion in which the watershed is located. Therefore, local mapping of these parameters would be important for accurate determination of USP in other Bluegrass streams. Without these local measurements, use of the USP estimates (Table 3.1) would probably result in an underestimation of sediment production from bank erosion.

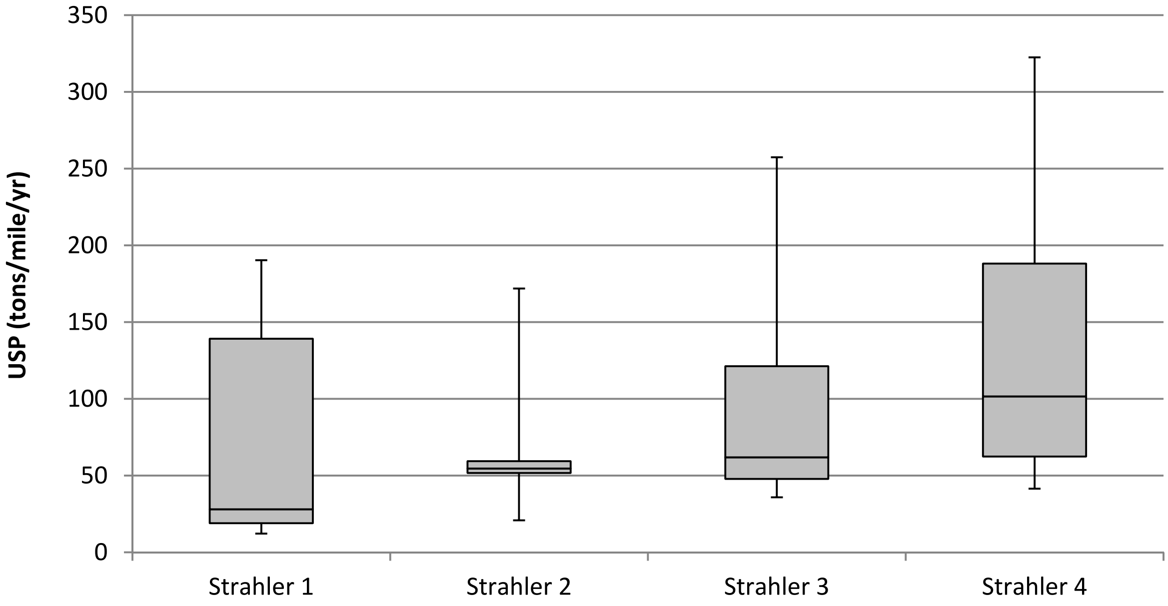

Figure 3.7 Variation in unit sediment production with stream order for blue-line streams.

Unmapped Channels

Blue line streams represent the most visible part of the drainage network but are fed by many small tributaries. Because these small tributaries are often not represented by blue-line streams on USGS topographic maps, they are referred to herein as unmapped channels. They also are not included in the USGS (2008a) National Hydrologic Dataset (Simley and Carswell 2009). In the Bluegrass, these streams are small and steep with little or no floodplain, and they are ephemeral or intermittent in flow.

Channel Extents

Mapping of channel heads in the Bluegrass indicated that the channel network often starts far from the upstream end of blue-line streams and that many channels are not recorded on 7.5-minute topographic maps. The percentage of the total drainage network that is represented by blue-line channels ranged from 10% to 39% (Table 3.2). The drainage density varies with the degree of incision to the landscape. Currys Fork watershed in the Outer Bluegrass, for example, is a much less dissected landscape and has a much smaller drainage density than Goose Creek in the Eden Shale Belt (Fig. 3.8).

Table 3.2 Drainage Densities and the Proportion of Stream Network Represented by Blue-line Streams

Watershed	Source Area (mi^2)	Total Network Length (mi)	Blue-line Network Length (mi)	Total Drainage Density (mi/mi^2)	Blue-line Drainage Density (mi/mi^2)	% of Network Shown by Blue-lines
Salt River	0.0025	130	25	10.8	2	19
Harrison Fork	0.0013	218	33	17.8	2.7	15
Currys Fork	0.0036	229	88	8	3.1	39
Goose Creek	0.0005	234	24	22.7	2.3	10

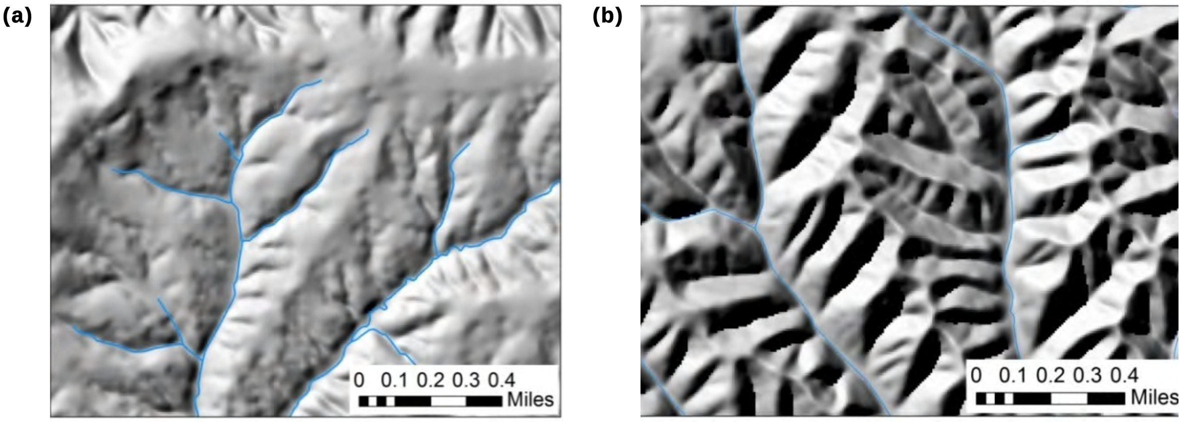

Figure 3.8 The landscape in (a) Currys Fork watershed is much less dissected than in (b) Goose Creek watershed. As a result, drainage density is higher in Goose Creek.

Unmapped Channel Sediment Production Rates

The USP estimated for the unmapped portions of each watershed was highest in the Salt River watershed and lowest in the Currys Fork watershed. The variability within a watershed, however, was as great as the difference between watersheds (Fig. 3.9). The highest reach-average rates of sediment production were found in Goose Creek watershed, where bank heights were over 4 ft even close to the drainage divide (Fig. 3.10). In these headwater streams, the dominant cause of bank erosion is probably weathering, as a stage of 4 ft would only be attained during a 100-yr or larger flood (Hodgkins and Martin 2003). Sediment production estimates varied considerably between different reaches within each watershed. This variation was due in part to the wide range of bank heights, which varied from 5.5 ft in gully-like steep reaches to less than 0.5 ft in reaches with lower slopes. Some of the stream reaches had very high banks (over 5 ft) that would not have been predicted from regional curves or other regional relationships that focus on the height of the active floodplain (bankfull) rather than the height of the bank, the top of which is often at the level of a terrace.

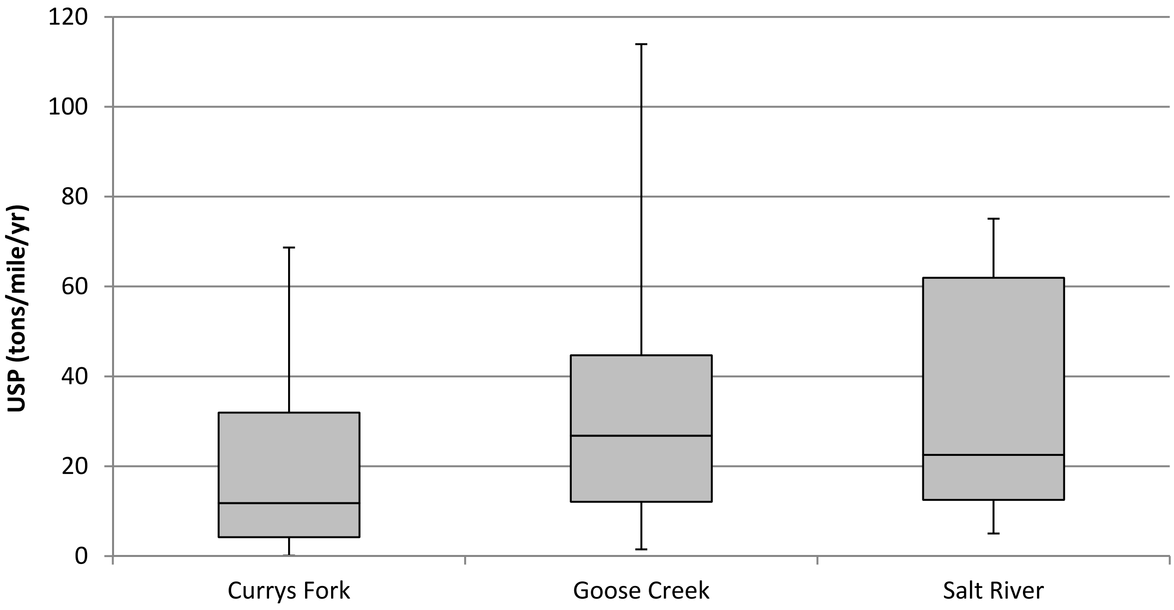

Figure 3.9 USP for unmapped channels by watershed.

Figure 3.10 Unmapped channel in Goose Creek watershed. Drainage area is less than 0.1 mi^2.

Uplands

The sediment production rates from uplands, as estimated from the pond surveys, represent a net erosion rate: the difference between the eroded upland sediments and the sediment stored upslope of the ponds. Rates of sediment production from uplands, on average, were below the levels at which BMPs are recommended by the US Department of Agriculture (USDA) for preserving soil sustainability (Fig. 3.11). Typical acceptable soil loss tolerance values, or T values, established by the USDA range from about 2 tons/acre/yr to 5 tons/acre/yr for Bluegrass soils (Wischmeier and Smith 1978). In each surveyed watershed, the highest estimated rates were more than 2 tons/acre/yr and less than 5 tons/acre/yr. Drainage area did not have a significant influence on the upland sediment production rates (Fig. 3.12).

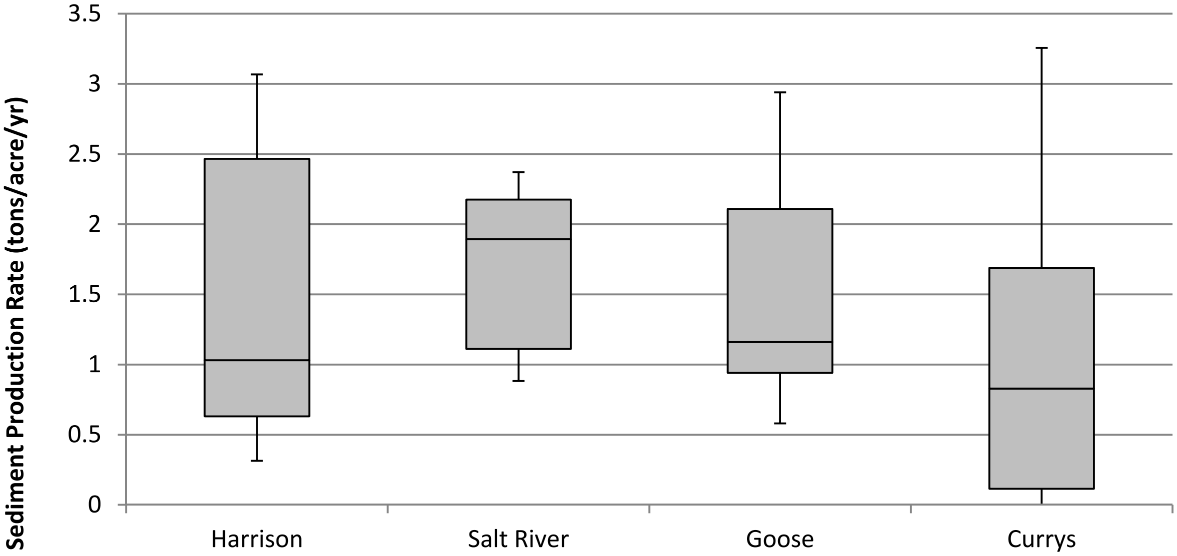

Figure 3.11 Upland sediment production as measured from pond surveys.

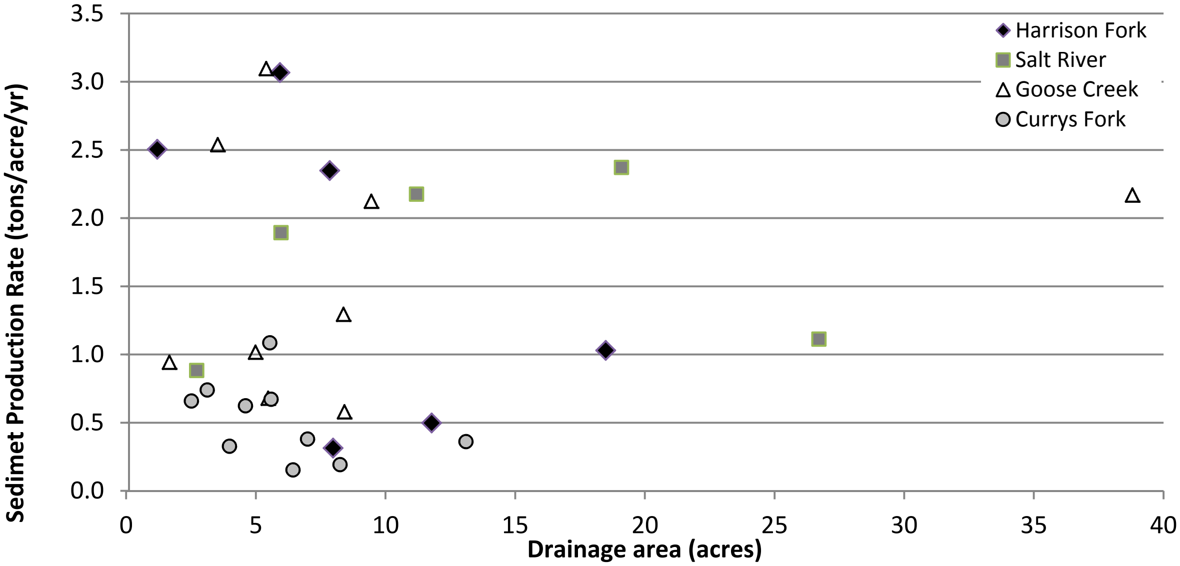

Figure 3.12 Drainage area did not have a significant influence on the upland sediment production rates.

The two land uses that were associated with higher-than-average sediment production were grazing and construction. Grazing was the land use associated with the highest rates of sediment production (Fig. 3.13). The intensity of grazing was particularly important, as sites with moderate grazing (limited numbers of horses or cattle) were not significantly higher than sites with no grazing. Current geospatial datasets for land use (e.g., USGS (2008b) 2001 National Land Cover Database) typically list all grazed land as "hay/pasture," which does not provide sufficient information to estimate sediment production, given the importance of grazing intensity variations. Local estimates of grazing history from brief site visits or other available sources would be important for estimating the severity of soil loss and hence sediment delivery to the drainage network in other Bluegrass watersheds. The second land-use variable that produced higher-than-average rates was construction. Ponds in Currys Fork, Harrison Fork, and Salt River watersheds all had recent residential disturbances related to small-scale construction that could have affected sediment yields.

The output of the GeoWEPP model for Currys Fork watershed indicated that more sediment is produced from hillslope erosion than from bank erosion in all four subwatersheds (Croasdaile and Parola 2011a). Because sediment production from upland surface erosion occurs over a large area, however, implementation of sediment-reducing BMPs would be more difficult than BMPs to reduce bank erosion.

The mass of eroded upland sediment that is deposited (stored) on hillslopes and floodplains was shown by the GeoWEPP models to be relatively insignificant, varying from 2.6% to 6.1% of the total mass of sediment eroded from uplands. Subwatersheds with wide floodplains and long hillslopes with deposition zones at the base of the slope had the highest percentage of sediment deposition on hillslopes.

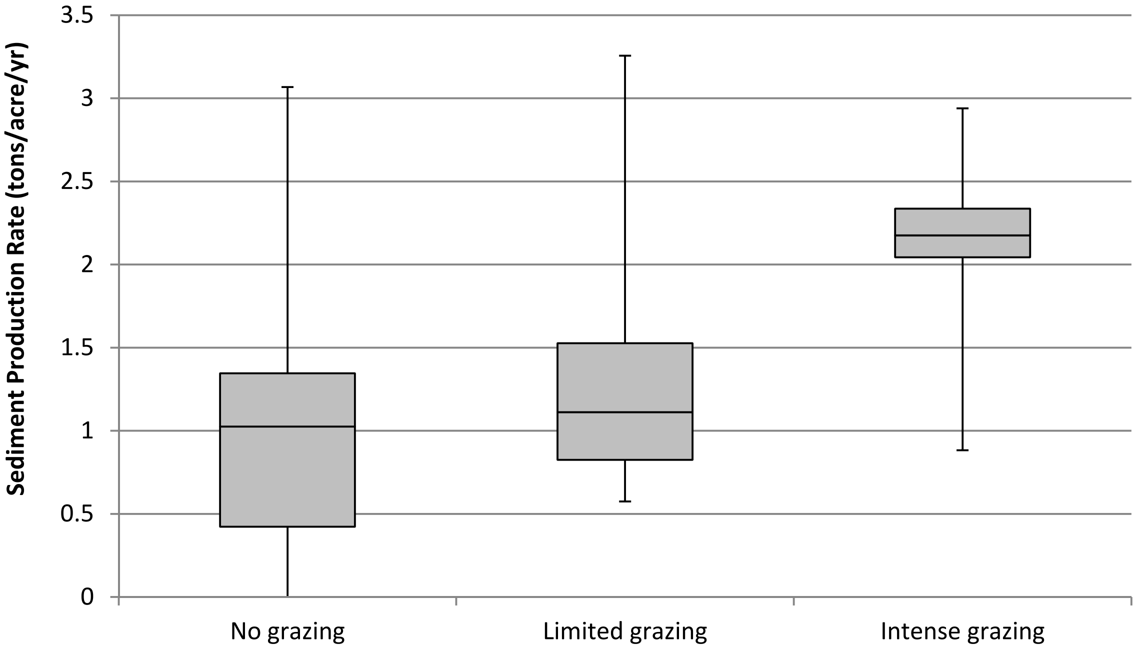

Figure 3.13 Grazing intensity and sediment production rates in uplands.

In-Channel Sediment Storage

The storage of fine sediment on riffles within the channel was found to vary greatly depending on the channel morphology. The frequency of riffles was the main factor in determining the amount of sediment that was required to embed these features: many reaches were comprised of planar bedrock sections with infrequent short riffles. In these reaches, small amounts of sediment deposition would affect the majority of riffle habitat.

The mass of sediment stored within the riffles was a small percentage, typically less than 2%, relative to the amount of sediment production from uplands and banks. Hence, even drastic reduction in sediment production from uplands or stream banks far upstream from the reach of interest (i.e., the reach being assessed for siltation impairment) may have no impact on siltation at a site. Moreover, while most of the total load is transported during high-flow events, it is also transported out of the reach of interest. The potential for deposition during floods is low because sediment is mobilized and transported through a reach before velocity has slowed sufficiently for deposition to occur. High flows tend to clean the riffles and reduce embeddedness. Because embeddedness is primarily caused by local sediment sources, reductions of those sources can be effective in reducing embeddedness in nearby riffles.

Floodplain Sediment Storage

The major influences of sediment deposition in Goose Creek watershed appeared to be the presence of downstream flow obstruction, such as a narrow bridge, culvert or other structure; the valley slope (steeper valleys showed fewer signs of deposition); and channel entrenchment (entrenched streams accessed the floodplain infrequently and had lower deposition rates than unentrenched streams). Measured deposition rates ranged from 1.2 to 224 tons/ha/yr (Table 3.3), with generally much lower rates on floodplain terraces than on active floodplains near the channel. The highest reading came from a mat installed on a low bench upstream of an obstruction that caused backwater during high flows.

Comparable data for deposition rates are not available in Kentucky. In the Eastern US, only a handful of studies have measured floodplain deposition, and those are from the Chesapeake Bay area. The Goose Creek rates are relatively high compared to rates reported in Maryland, which ranged from 1.65 to 17.1 tons/ha/yr (Gellis et al. 2009). This discrepancy may not be as extreme as it appears, however; it may be due in part to the difference in measurement locations: the measurements in Goose Creek were from active or actively forming floodplains and the floodplain terrace, whereas the Maryland study measurements were only from the floodplain terrace.

Table 3.3 Goose Creek Watershed Sediment Deposition Rates

n = 18	Sediment Deposition Rate, D (tons/ha/yr)
Mean	43.9
Median	30.8
Min	1.2
Max	224.3
St. Dev	51.2

Total sediment deposition, M_{dep}, on floodplains and terraces in Goose Creek watershed was estimated at 1537 tons over a one-year period. The accuracy of this estimate is uncertain due to the wide area over which deposition can occur and because the deposition may vary locally. Nevertheless, the sediment storage is of the same order of magnitude as the sediment production from bank erosion on blue-line streams.

Clay pads in the Salt River watershed captured very little sediment, and they therefore weathered and fragmented after about seven months. The sediment that was captured appeared to be soil from rainsplash on adjacent ground rather than from deposition during a flood. Hence, sediment deposition rates for all Salt River sites were assumed to be zero or so close to zero as to be negligible. The lack of deposition was due to the entrenched and incised condition of the stream reaches and associated lack of overbank flooding. Overbank events were not observed at Harrison Fork or the MMSK reach during the study period.

3.2 SEDIMENT LOAD AND YIELD

Sediment–Turbidity Relationships

Relationships between turbidity and SSC were generally linear (Fig. 3.14), which is typical (e.g., Rasmussen et al. 2009). The relationships between turbidity and suspended sediment were very similar between physiographic sub-regions. The relationship for Currys Fork was slightly steeper than for other watersheds, indicating a higher SSC for the same turbidity. This difference may have been due to the presence of some sand in the Currys Fork samples. The Currys Fork data did agree well with other published data that were collected primarily from Kentucky streams and rivers located in watersheds with some sandstone geology and associated sand in the suspended load (Williamson and Crawford 2011).

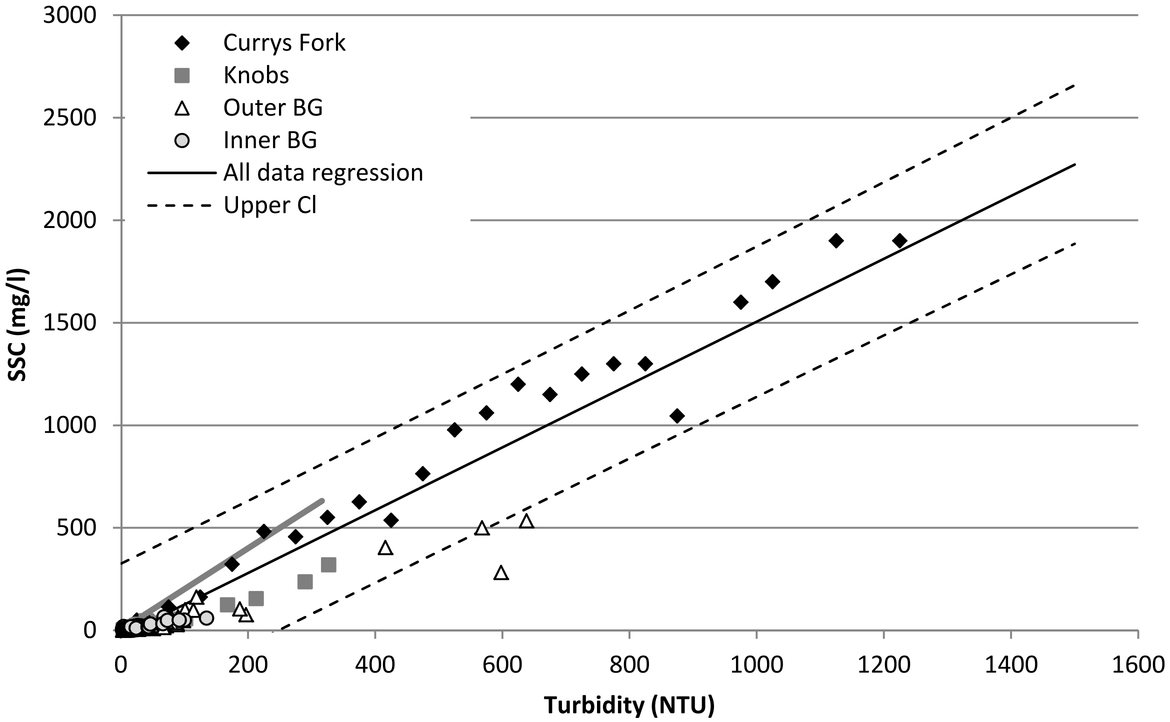

Figure 3.14 Relationships between turbidity and SSC for Bluegrass sub-regions.

Annual Sediment Loads and Yields

Sediment yields in the Bluegrass ranged from 141 tons/mi^2/yr to 1046 tons/mi^2/yr (Table 3.4). Currys Fork had the highest load per square mile and the highest USP from blue line streams. UT South Elkhorn, despite having predominantly urban land use with tributaries redirected through stormwater pipes and a very small contributing drainage area compared to the other sites, had a similar yield to the other watersheds. Because this small watershed lacked the unmapped channels and uplands that were present in the other watersheds, channel bank erosion appears to be the dominant sediment source there. The Salt River watershed had the lowest sediment yield but also, by far, the most anabranched sections and potential storage sites (Fig. 3.15). Re-creation of anabranched stream reaches via stream restoration could potentially increase sediment storage. This potential could be verified and evaluated by implementing restoration of anabranched reaches on a small scale and then monitoring sediment storage.

Table 3.4 Annual Sediment Loads and Yields

Site Name	Watershed Area (mi^2)	Sediment Load (tons/yr)	Sediment Yield (tons/mi^2/yr)
Harrison Fork	12.2	6344	520
Salt River	12.0	1692	141
UT South Elkhorn	0.37	170	459
Currys Fork	28.5	29811	1046
Goose Creek	10.3	7014	681

Figure 3.15 Salt River has many anabranched (multi-channel) reaches with numerous abandoned side channels that provide sediment storage areas.

At each sediment station, the turbidity typically peaked well before the stage for the vast majority of flood events (see Fig. 3.16). The turbidity then declined back to near-zero well before the stage receded to base flow. This pattern of turbidity peaking before stage produces a clockwise hysteresis when turbidity is plotted against stage (or discharge) (Fig. 3.17). Clockwise hysteresis is evidence of the dominance of a local sediment supply either from tributaries or in-channel sources, with sediment supply from upstream being less significant (Williams, 1989; Goodwin et al. 2003; Lefrançois et al., 2007). Periods of high turbidity and low velocity seldom occur, and the potential for deposition during floods is low because sediment is mobilized and transported through a reach before velocity has slowed sufficiently for deposition to occur. The velocity at which sediment might deposit can be estimated from the settling velocity for individual particles. The settling velocity is about 0.01 ft/sec for silt-sized particles and even less for clay (Fig. 3.18), which is much lower than the velocity of water over a riffle but might be experienced in a pool during low-flow conditions. The settling velocity is dependent on the shape of the particles, which is accounted for by a shape factor, C, although this effect is noticeable only for grain sizes greater than 0.1 mm.

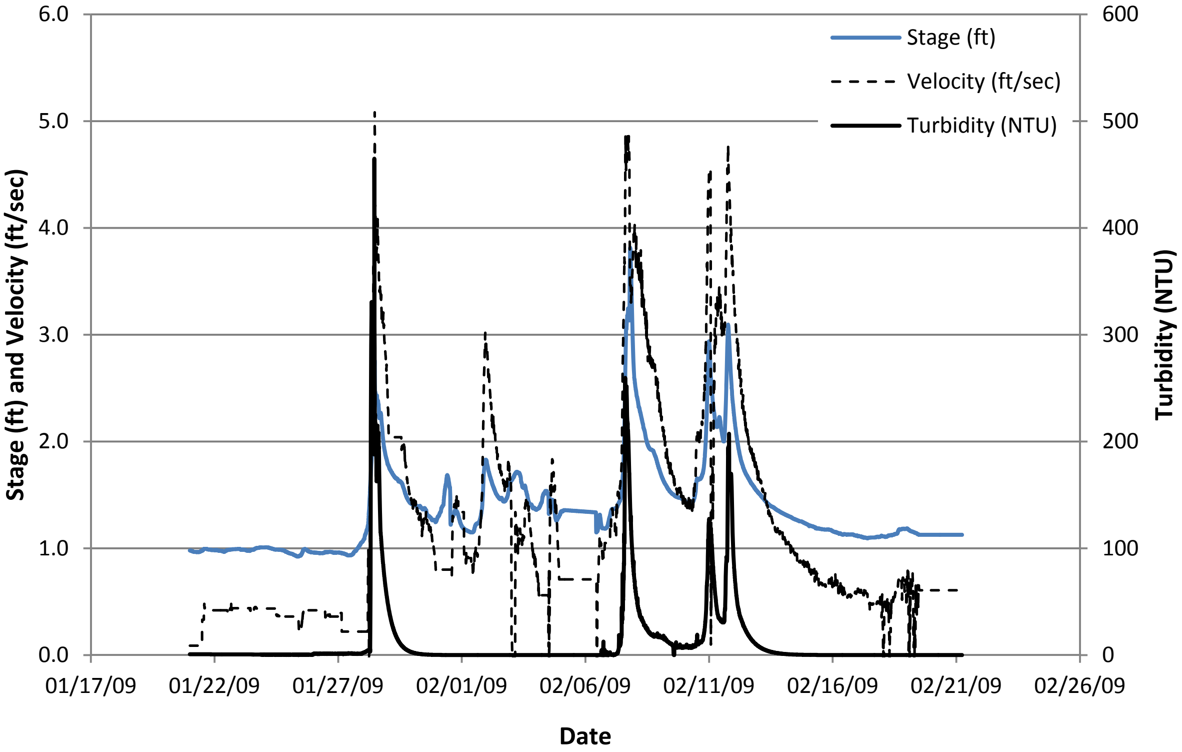

Figure 3.16 Stage, velocity, and turbidity measured at CF2 site in Currys Fork watershed. Turbidity peaks and recedes to zero before the flow velocity falls sufficiently for sediment to deposit.

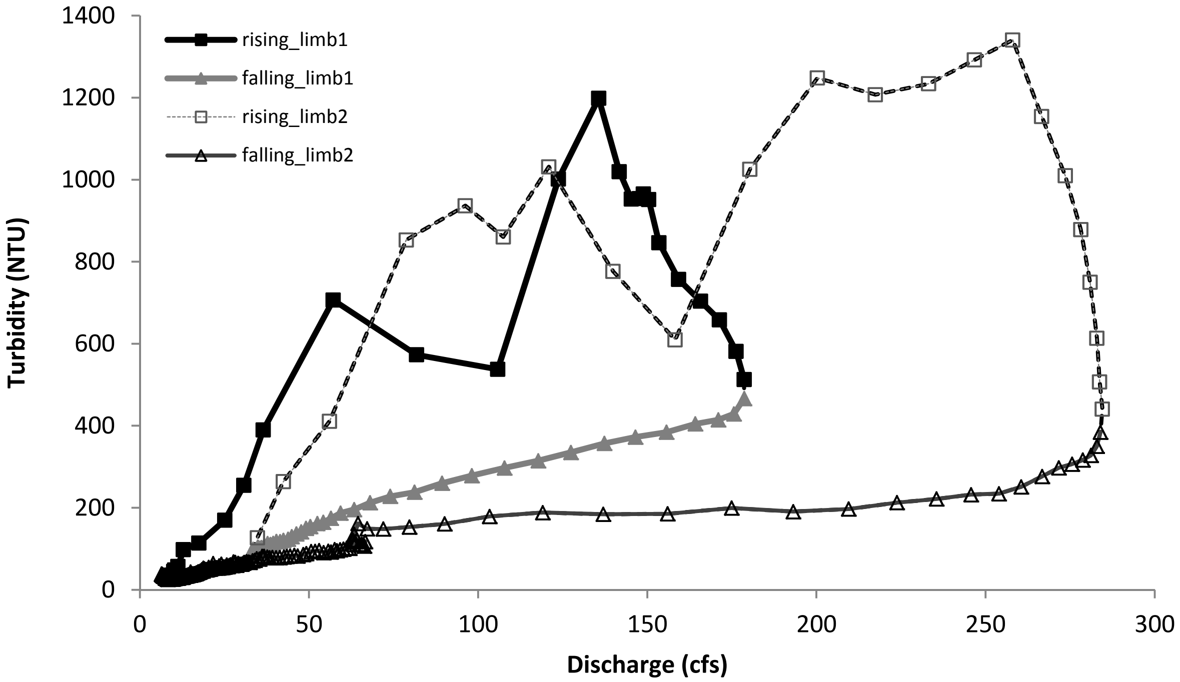

Figure 3.17 The pattern of turbidity peaking before discharge produces clockwise hysteresis loops when turbidity is plotted against discharge, as shown here for two consecutive flood events.

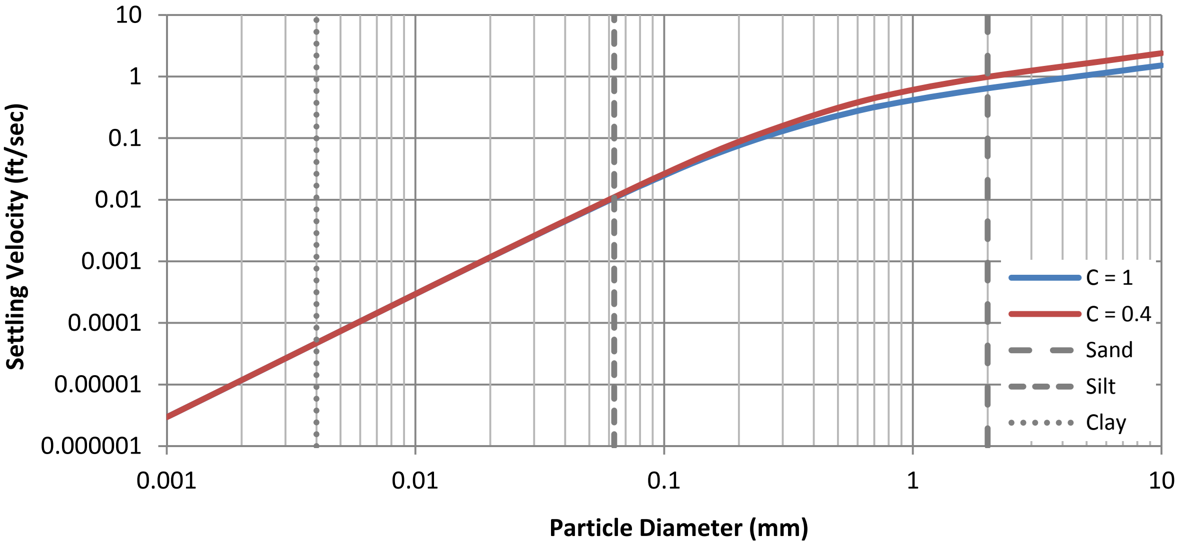

Figure 3.18 Settling velocity for individual particles calculated using equation of Ferguson and Church (2004). The shape factor, C, generally lies between 0.4 and 1.0 for natural riverine sediment.

Sediment Load and Embeddedness

Two conditions must be met for fine-grained material to embed a riffle substrate: an adequate supply of fine sediment must be conveyed by the flow, and local stress conditions must allow deposition of fine-grained material. The stress conditions for deposition of fine-grained material are most likely to occur in small streams during summer and fall low-flow periods. The fine sediment supply and stress conditions were observed to occur together in three types of locations in Bluegrass channels:

1. Immediately downstream of a high, weathering stream bank or an eroding hillslope that comprises the stream bank: a surficial crust of bank material loosened by weathering detaches and falls to the base of the stream bank, washes to the base of the bank or into the channel by rainfall, or, in the lowest portion of the bank, washes directly into the water by wave action or minor increases in flow and stage. The fine sediments derived from weathered bank material are deposited in the channel when flow velocities are low, typically following periods of little or no precipitation. Low flow in the channel is capable of transporting the fine sediments only a short distance, and some of the sediments are deposited along the edge of the water and in other very low-velocity areas of downstream riffles. If weathering and transport of the fine material persists without a large flood to remove sediment, then accumulation may cover a substantial portion of the riffle or even the entire substrate. Algae, aquatic vegetation, and herbaceous vegetation growing in and along a riffle (Fig. 3.19) can enhance accumulation of sediment (Thornton et al. 1997).
2. Immediately downstream of the confluence of a tributary channel with another much larger channel: when rainfall produces runoff in a small tributary, it delivers fine sediment to confluences with downstream larger channels. When flow velocity and depth in the larger channel downstream of the confluence do not respond significantly to the rainfall event either because of the longer response time of the larger channel's watershed or because of non-uniform rainfall, the larger channel may not have sufficient flow to transport the fine sediment supplied by the tributary. The sediment therefore deposits near the confluence and in downstream riffles. Deposits in channels were particularly pronounced downstream of confluences of small tributaries with bare, weathering banks where large volumes of sediment accumulated following freeze-thaw cycles and then were transported into the larger downstream channels during subsequent small storm events (Fig. 3.20) (Croasdaile and Parola 2011a).
3. Upstream of channel obstructions or contractions that promote sediment deposition by creating backwater during floods, when sediments from both local and distal sources are transported: channel morphological features such as bends with a small radius of curvature, channel boundary contractions, or large woody debris jams (Fig. 3.21); and structures such as culverts, weirs, or bridges. Channel obstructions can reduce velocities sufficiently for some fine sediment to deposit (Gurnell and Sweet 1998). These locations are effective at storing sediment and reducing loads to downstream reaches.

In any of these situations, the proportion of the load that is deposited on the riffle is not fixed but instead varies between riffles and is strongly dependent on multiple variables. During low-flow periods, supplied sediment is transported only a short distance downstream, and load measurements in any given channel will vary depending on proximity to local sediment sources; immediately downstream of a low- and/or base flow deposition area, the measured load would be negligible. During floods, when sediment is transported from local and distal sources to those same locations, the flow conditions may be sufficient to mobilize fine sediment from the bed and ensure that embeddedness does not persist in those riffles. Thus, the riffles could be intermittently impaired and unimpaired by embedded sediments.

Figure 3.19 Siltation can aggravate and be aggravated by growth of algae. This occurred during late spring before leaf-out and during mid-summer prior to the cessation of base flow.

Figure 3.20 This small tributary supplies sediment to Salt River downstream of Bantas fork confluence following small storms when the velocities in the main stem are low enough for sediment to deposit on riffles.

Figure 3.21 Debris jams (formed by fallen trees or by beavers) cause reduced flow velocities upstream of the obstruction and can cause temporary embeddedness of riffles and filling of pools.

The mass of sediment required to embed riffles is related to the size of the stream (Table 3.5). In larger streams, base flows with velocities greater than the settling velocities of suspended sediments reduce the potential for embeddedness. In all of the assessed streams, however, the percentage of the annual sediment load required to embed riffles within a 1000-ft reach is small, ranging from 0.16% to 1.6%. Detailed information is extremely limited regarding the mass of sediment required to embed riffles and the characteristics of that sediment (i.e., grain size, density, organic content, etc.), so comparisons of these load estimates with published data are not possible. Based on errors of estimates of riffle widths, lengths, sediment characteristics, and frequency, however, the error of the load estimates is roughly estimated to be 50−300%. Even at the upper limit of this error estimate, the mass of sediment necessary to embed riffles is much smaller than the annual sediment load of any of the watersheds.

The mass of sediment stored within embedded riffles was a small percentage relative to the amount of sediment delivered from upstream. Hence, even a drastic reduction (e.g., 98%) in sediment production from uplands or stream banks far upstream from the reach of interest may have no impact on siltation in that reach. While most of the total load is transported during high-flow events, it is also transported out of the reach of interest. The potential for deposition during floods is low because sediment is mobilized and transported through a reach before velocity has slowed sufficiently for deposition to occur. High flows generally “clean” the riffles and reduce embeddedness. Because embeddedness results from local sediment sources, impairment reductions can be effective over short distances, and assessments of sediment sources should focus on sources that are close to the embeddedness.

Table 3.5 Masses of Sediment Required to Embed Riffles

Reach ID	Drainage Area (mi^2)	Strahler (NHD)	Average Riffle Width (ft)	Average Riffle Length (ft)	Riffle–Riffle Spacing (ft)	Sediment to Embed Single Riffle (lbs)	Sediment to Embed Riffles in 1000-ft Reach (tons)	Annual Load (tons/yr)	% Load for Reach Embed-dedness
Harrison Fork	3.6	3	16	18	126	1376	5.5	1872	0.29
Salt River	2.5	3	19	29	352	1342	1.9	352	0.54
MMSK	0.4	1	7	6	150	87	0.3	170	0.17
Currys Fork (SF restoration site)	2.7	3	18	16	196	1402	3.6	2772	0.13
North Fork (U/S SF conf) NC1	9.7	4	37	34	166	8982	27.0	10094	0.27
Currys Fork (main stem) CF3	20.2	5	58	63	392	26718	34.1	21150	0.16
Goose Creek GC1	10.2	4	38	28	99	2591	13.1	6950	0.19
Ballard Branch BB2	2.7	3	18	12	67	1052	7.8	1118	0.70
UT Ballard Branch BBT3	0.8	2	14	15	90	1023	5.7	348	1.63

3.3 TRAINING AND TECHNOLOGY TRANSFER

Training provided to the KDOW TMDL section included five field days and two presentations regarding bank production assessment methods. During the project period, advice also was provided to the TMDL section during field visits and via email regarding the collection of suspended sediment samples and monitoring protocols and equipment specifications for water level sensors and turbidity sensors.

Sediment Production

Three field visits (January 7, 2008; January 8, 2008; and February 20, 2008) were made to the Salt River watershed with KDOW's TMDL section. TMDL section personnel installed bank pins, assessed and recorded bank characteristics (including BEHI and NBS parameters), photo-documented the site, and collected GPS locations of all photos and bank pin locations. No embeddedness was observed in the impaired reach (Bantas Fork into Salt River, river miles 0.0 to 6.2) during these visits. Riffles were typically clean, broken, cobble-sized bedrock with minimal fine material (Fig. 3.22); pools were infrequent and typically scoured to bedrock.

The limitation of the bank pin method—specifically, the need to collect data over a minimum of a one-year time span—was discussed during the field visits. As a result of these discussions and subsequent conversations about the TMDL section's need for efficient monitoring methods, ULSI implemented the dendrogeomorphic monitoring technique for calculating bank erosion rates and associated sediment production rates based on using exposed tree roots. Details of calculating bank erosion rates using this technique were presented to KDOW in Frankfort on September 29, 2011, and to KDOW and other agencies at the EPA/KDOW §401 conference in Tennessee on November 16, 2011.

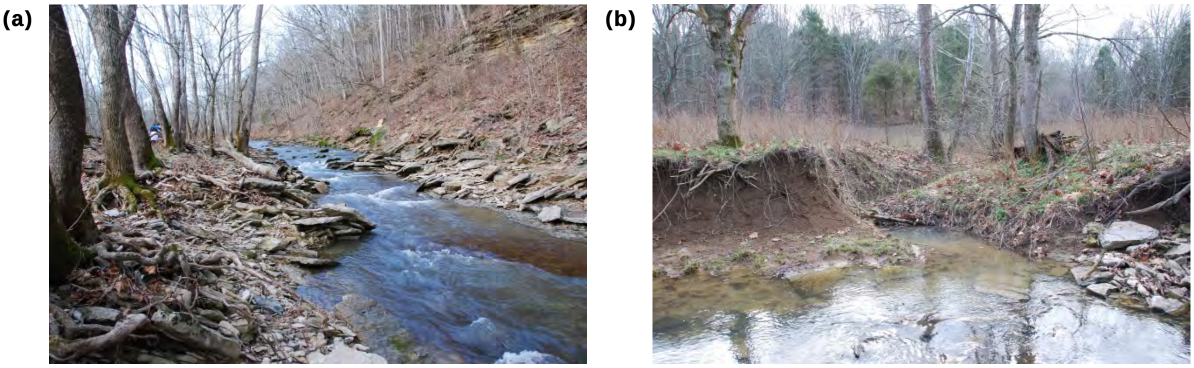

Figure 3.22 (a) The majority of riffles in Bantas Fork into Salt River were composed of clean broken pieces of bedrock. (b) Fine-sediment deposits were limited to marginal areas and were typically supplied from a small eroding tributary.

A visit to a pond coring site was made in July 2008 to observe the procedures used to estimate sediment load from upland erosion. The pond surveying method used for this project (see Upland Sediment Production: Pond Surveys in Section 2.4) was judged to be too time consuming to be practical for TMDL to use: one pond typically requires two days of fieldwork using a boat and total station, and more than one pond would be required in a watershed to identify representative rates.

Sediment Loads

A field visit in July 2008 to Salt River was made to review turbidity/SSC/water stage measurement equipment. The use of and limitations of turbidity sensors and ISCOs was discussed. The importance and time-consuming nature of collecting continuous stage and discharge data were discussed: the lack of available gage stations on small streams outside of the Louisville and Covington metro areas was determined to be an impediment to data collection for sediment loads. On February 28, 2013, a field visit to Strodes Creek watershed was conducted to evaluate potential sites for one of TMDL's watershed monitoring projects and to discuss monitoring strategies.

4. Conclusion

This project has identified a crucial lesson for developing sediment protocols that are cost-effective, are practical, and target the cause of WAH impairment: total sediment loads are not causally related to sediment deposition that causes riffle embedment, and reducing the total sediment load may not reduce siltation/sedimentation at a reach. Embeddedness is often caused by a local supply of fine-grained sediment in the Bluegrass, and the extent of the problem causing embeddedness may be limited to a stream reach that is much shorter than the distance to the next upstream confluence or change in land use, which are the parameters used by KDOW to define the limits of impaired reaches. The assumption that the impairment will extend to the next major confluence or change in land use is not supported by observations in the Bluegrass. On the contrary, our observations indicate that at most impaired sites, the source of sediment causing embeddedness was from nearby unvegetated banks or small tributaries with unvegetated banks. Moreover, while most of the total load is transported during high-flow events, it is also transported out of the reach. The potential for deposition during floods is low because sediment is mobilized and transported through a reach before velocity has slowed sufficiently for deposition to occur. High flows tend to clean the riffles and reduce embeddedness. Prolonged turbidity, which would suggest the potential for sediment deposition as a flood recedes and flow velocities fall, was not observed. Typically, turbidity peaked well before stage for the vast majority of flood events. Turbidity values had declined to near zero when velocities were sufficiently low for sediment deposition to occur.

A general rule is that the closest sources of sediment are probably the most significant. Therefore, an accurate identification of causes of sedimentation would require delineation of the portion of the channel network and watershed that can supply sediment under the relatively low-velocity conditions that can embed riffles. Another situation under which embeddedness develops is in reaches where a downstream structure, such as a bridge, culvert or debris jam, causes backwater conditions. These structures may be providing important functions, such as controlling the grade of the stream or providing habitat, so removal may not be desirable or practical.

Based on the results from this project and from other ULSI projects conducted within the Bluegrass region, we believe that focusing on identifying local sediment sources and calculating local sediment loads will be a more efficient way of developing potential solutions for WAH impairment due to siltation/sedimentation than sediment assessments conducted at the watershed-scale. The mass of sediment stored within the riffles was a small percentage of the sediment produced from uplands and banks, typically less than 2% of the annual fine sediment load. Hence, even drastic reduction in sediment production from uplands or stream banks far upstream from the reach of interest may have no impact on siltation at a site. Reducing the local source of fine sediment is the key to reducing riffle embedment in the Bluegrass or other regions where silt and clay are the primary sediment size ranges embedding riffles. Because embeddedness results primarily from local sediment sources, reductions of those sources can be effective in reducing embeddedness in nearby riffles. ULSI stream restorations have demonstrated that embeddedness can be reduced within a short sequence of riffles and pools by reducing the local supply and that this reduction does not necessarily require the application of watershed-scale BMPs.

At all study watersheds, the action of weathering, especially freeze-thaw during winter months, was a very important component of sediment production from banks. Most banks were composed of cohesive material (silt and clay) and did not appear to erode even during large floods unless weathering had occurred. Only banks with bare soil were observed to weather. To estimate the amount of sediment produced by weathering requires no information on the flow history of a reach but does require that the length of the reach, the height of the banks, and the proportion of exposed soil be determined and combined with a reference rate of erosion due to weathering. A sediment production rate due to weathering can then be calculated that would provide a lower bound estimate of the contribution from bank erosion.

Upland sediment production is typically the largest contributor of total sediment load to a watershed. Where the upland sediment production is observed to be contributing to embeddedness, a reduction in supply to downstream waters may be more cost effective than reducing the soil loss itself, because upland surface erosion occurs over such a wide area. This could be achieved by storing sediment before it enters the small headwater channels and gullies at the upper extents of the drainage network. Where stream and floodplain restorations are implemented in reaches in the uppermost areas of the blue-line channel network, the local supply from eroded upland soils could be reduced by gully control measures in unmapped tributaries (i.e., reaches with drainage areas of less than about 4 hectares). The USDA-NRCS provides technical guidance on the selection and installation of various methods of controlling and treating gully erosion (USDA 2007), and we recommend contacting the NRCS for technical guidance. The options for load reduction most applicable to rural watersheds would probably be gully plugs, debris jams, or check dams. These barriers would not only trap sediments but would also slow the downslope movement of water, which could lower the rate of bank erosion in the gullies. Construction of dams or gully plugs can be a simple process requiring a limited amount of materials: typically, locally sourced rocks, woody debris and soil. Check dams could be constructed alone or in conjunction with permeable reactive barriers (PRBs) stacked in pyramid form. PRBs are constructed of porous media bags filled with crushed stone, which filters nutrients or contaminants from the water leaching through the bags (USEPA 1998).

4.1 PROJECT MEASURES OF SUCCESS

Four sets of criteria were established to evaluate project success. These criteria measure the success of the activities and products that were designed to accomplish the four objectives of the project. The project fully met all but one of the success criteria (2c), which it partially met. The reason that success criterion 2c was not fully met was that the floodplain storage rates were so low that the installed deposition monitoring pads disintegrated before a measureable sediment mass had accumulated. Despite the poor performance of the installed pads, the observation that sediment accumulation was so low supports an assumption of very low rates of floodplain aggradation along the incised and entrenched streams.

Objective 1: The development of consistent and reliable field procedures to identify the sediment sources from selected watersheds in the Bluegrass region in which the stream is designated as sediment impaired or for which a sediment TMDL is under development.

Criterion 1a: A geomorphic reconnaissance assessment procedure using standard methods is developed that can be used to identify the dominant erosion processes and significant sediment sources.

A geomorphic assessment procedure (Appendix C) was developed that is effective for identifying sediment sources and erosion processes that are significant contributors to embeddedness.

Criterion 1b: Training in the measurement of sediment loads and sediment production for use in watershed-based assessments is provided to KDOW.

Training was provided during five field days (see Section 3.3).

Criterion 1c: Watersheds are selected for study in consultation with Nonpoint Source Section and TMDL personnel and, if a TMDL is under development in that watershed, this project assists in TMDL calculation.

Salt River into Sixmile Creek was selected for study in consultation with KDOW TMDL. KDOW NPS was consulted in the selection of the other two sites, Harrison Fork and UT South Elkhorn Creek.

Objective 2: The quantification of sediment production and storage in the selected watersheds.

Criterion 2a: Geomorphic data are collected that quantify hillslope sediment production rates and evaluate the sediment delivery to the downstream gullies and stream channels.

Total sediment production rates from uplands in four watersheds were estimated (see Uplands in Section 3.1). These upland sediment production rates are net erosion rates: the difference between the sediment eroded from uplands and the sediment stored upslope of the ponds. These net rates represent the sediment delivered to downstream channels.

Criterion 2b: Geomorphic data are collected that quantify sediment supply from gullies.

Sediment produced by gully erosion was quantified in all watersheds with well-defined gully networks (see Unmapped Channel Sediment Production Rates in Section 3.1).

Criterion 2c: Geomorphic data are collected that quantify in-channel and floodplain storage volumes and sediment erosion rates from stream bank erosion.

The mass of sediment stored within the riffles was estimated to be a small percentage of the annual sediment production from the watershed (see In-Channel Sediment Storage in Section 3.1). Floodplain storage volumes had been previously quantified for Goose Creek watershed (see Table 3.3); no floodplain storage was observed in Harrison Fork and UT South Elkhorn watersheds, where flood flows did not overtop the banks during the monitoring period. At Salt River, the installed clay pads disintegrated before a measureable amount of sediment had been deposited, indicating very low sediment deposition rates, albeit over a shorter timespan (7-8 months) than the intended one-year measurement period. Unit sediment production rates (USP) for bank erosion were developed for reaches in all five study watersheds (see Table 3.1).

Objective 3: The development of a suspended sediment sampling program to provide information on transport rates during individual events and to provide verification data for estimates of sediment production and storage.

Criterion 3a: Suspended sediment concentration and turbidity are measured, and the results of this assessment are used to calibrate/verify the sediment production and storage rates from upland erosion and bank erosion in mapped and unmapped channels.

Measured SSC and turbidity were used to calculate fine sediment yields at Harrison Fork, Salt River, and UT South Elkhorn. The turbidity time series data indicated that suspended sediment sources were predominantly local, as turbidity peaked well before stage in the vast majority of events at all sites (see Section 3.2).

Criterion 3b: Relationships between suspended sediment concentration and turbidity can be developed and can be used in future projects to estimate SSC from rapidly-made turbidity measurements.

Well-defined relationships between flood SSC and turbidity were developed from Currys Fork and Salt River data and supplementary data from KDOW monitoring sites within each Bluegrass physiographic sub-region (see Section 3.2). These turbidity–SSC relationships can be used to estimate sediment loads based on turbidity data for other watersheds, and data for some areas could be supplemented with more TSS-turbidity data from the EPA STORET database (e.g., sites near Covington or Louisville, which have large amounts of available data relative to more rural sites).

Objective 4: The development and dissemination of methods suitable for estimating sediment loads in watersheds in the Bluegrass region.

Criterion 4a: A method is developed that can be used for quantifying sediment produced by bank and gully erosion in different physiographic sub-regions of the Bluegrass. The method is shared with KDOW TMDL and NPS Sections if requested.

The USPs developed for the blue-line and unmapped assessment reaches (Table 3.1 and Figure 3.9) can be used as reference rates for other channel reaches in these watersheds. Sediment production in other watersheds in the Bluegrass could be estimated in three different ways (in order of increasing accuracy and cost): using reference USPs directly, using reference USPs and local field measurements of channel bank dimensions, or using field measurements of erosion rate and channel bank dimensions. A second technique, using dendrogeomorphic methods for estimating reach-scale bank erosion, also was evaluated (see Section 3.1) and was found to be an efficient and accurate method for quantifying sediment produced from bank erosion over periods of 5–50 years. The dendrogeomorphic method was presented as a lecture to KDOW TMDL and NPS personnel on August 25, 2011, and at the EPA §401 conference in Tennessee on November 16, 2011.

Criterion 4b: Presentations of how data were collected from this assessment project and how these data can be used to form the basis of future sediment assessments and sediment TMDL projects, saving time and money for NPS and TMDL section personnel, are presented to KDOW.

Training provided to the KDOW TMDL section included five field days and two presentations regarding bank sediment production assessment methods (see Section 3.3). As a result of discussions with the TMDL section about their need for efficient monitoring methods, ULSI also attempted to identify monitoring techniques that would be less fieldwork-intensive than those employed for this project. One idea that we have proposed is the development of an assessment method to focus on loads contributing to sediment deposition rather than on total watershed loads. This conclusion has been shared with KDOW through this report, via email communications with NPS staff, and during field visits with NPS and TMDL personnel. In addition, practical examples of stream restoration methods to reduce embeddedness have been demonstrated to KDOW personnel through §319(h)-funded Natural Channel Design Working Group visits to stream restoration projects designed by ULSI. Knowledge and information gained through this project have contributed to the engineering approach used in the stream restoration designs. A final presentation of information is to be presented to KDOW TMDL and NPS sections in 2014.

4.2 LESSONS LEARNED

Lesson: Commonly used methods to measure siltation, such as pebble counts or visual assessments of embeddedness, are not suitable for calculating load reductions as they do not calculate a mass of sediment.

Methods for estimating the mass of sediment causing siltation could be improved to ensure that data obtained in different watersheds are of comparable accuracy and precision. The estimates of sediment required to embed riffles in this project used measured riffle length and depth together with visually estimated values for sediment infiltration values and literature values for riffle porosity. Infiltration depths and riffle sediment porosity data for Kentucky streams were not available, but methods applied in the UK and western USA (e.g., Carling and Reader 1982; Jones et al., 2011) could be applied to the Bluegrass.

Lesson: The amount of deposition required to cause detrimental impacts for aquatic communities should be clearly defined to support the development of numeric criteria for sediment in evaluations of water quality.

More information on aquatic biological community requirements for riffle embeddedness would allow targets for embeddedness to be more ecologically significant. In West Virginia, EPT taxa richness significantly decreased ($p < 0.05$) in streams where fine substrate particles (<0.25 mm) exceeded 0.8–0.9% of riffle substrate composition (Kaller and Hartman 2003). The applicability of such thresholds should be assessed for Bluegrass streams and could be used to set targets for local sediment reduction.

Lesson: Nutrient concentrations should be measured at sites where sediment deposition only occurs in months with abundant algal growth.

Embeddedness has a strong seasonal component, being much more common during summer months, when flow is low and in-stream water temperatures are high. The growth of algae within the streams can enhance and contribute to embeddedness. Algae acts to reduce flow velocities near the bed of the channel and can also trap sediment that would otherwise be transported downstream. A combined nutrient/embeddedness assessment may indicate whether nutrient reduction might be a better approach to improve WAH than sediment reduction.

Lesson: Hydrological conditions play a critical role in determining the potential for sediment deposition.

Recent precipitation and runoff records, if available, should be considered when evaluating the cause of riffle siltation, as periods of prolonged drought or low flow could be responsible. Sites where siltation is observed during low-flow periods should be revisited after normal rainfall to ensure that the hydrological regime is not a dominant factor in siltation development. If sediment load reduction to downstream waters rather than onsite WAH improvement is the project focus, sediment loads should be measured for rising limb, falling limb, and base flow periods. This hydrograph separation would allow the amount of sediment that is available for deposition to be calculated, and the load transported during the rising limb would be assumed to exit the reach and not be deposited. Such an analysis was recently conducted for nutrients in UT South Elkhorn Creek (Parola et al. 2013) and could be applied to sediment loads.

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Appendices

Siltation and Sediment Source Assessment Protocol

Michael A. Croasdaile
University of Louisville Stream Institute
Dept. of Civil and Environmental Engineering
Louisville, Kentucky 40292

1. Introduction

This document is intended to be a technical guide for Kentucky Division of Water (KDOW) personnel who are evaluating streams in the Bluegrass physiographic region for sediment impairment and/or for development of sediment total maximum daily loads (TMDLs). The purpose of this protocol is to identify the channel sediment sources responsible for siltation on riffles, to estimate the sediment production rates of those sources, and to measure the mass of sediment deposited on riffles. If appropriate siltation targets can be set, then the procedure could be used for TMDL development. The protocol comprises three main activities: field identification of embeddedness locations and the sources and/or causes of the impairment; quantification of embeddedness and loads; and estimation of a required load reduction to reduce embeddedness.

The primary condition for use of this protocol is that the material embedding riffles is silt-sized and finer, and that riffles are composed of cobble or coarser material, which is typically broken limestone bedrock in the Bluegrass. This protocol is not applicable to streams with predominately sand-sized sediment loads or where the bed substrate comprises sand and gravel that are frequently mobilized. In these situations, the sediment delivery and deposition during high flows might be much more important and would need to be included in any sediment assessment.

The protocol described herein is based on data collected in several Bluegrass watersheds as described in Section 2.4 of this report (Croasdaile and Parola 2013). It has not been subject to field testing or input from experienced field practitioners outside ULSI. As a result, the protocol should be subject to a review and validation process (USEPA 2007).

2. Sediment Impairment in Bluegrass Streams

Sedimentation/siltation is the most common cause of impairment in Kentucky streams. As of 2010, it was the cited cause of impairment for 3190 miles of streams, compared to 220 miles cited for turbidity, which was the second-most common sediment-related cause of impairment (KDOW 2010). Siltation/sedimentation is the deposition of fine sediment over a coarser substrate. In the Bluegrass, siltation/sedimentation is primarily caused by silt-sized particles and is referred to as siltation in this protocol. Siltation often causes riffle embeddedness, which is generally defined as the degree to which fine sediments surround coarse substrates on the surface of streambeds (Sylte and Fischenich 2002). Numerous studies have documented the correlation of embeddedness with degraded benthic habitat and reduced diversity and abundance of macroinvertebrates (Waters 1995; Angradi 1999; Lowe and Bolger 2000). The protocol is focused on identifying the underlying causes for the development of siltation and the associated embeddedness that impair warm-water aquatic habitat (WAH).

Sediment sources can be grouped into channel sources and non-channel sources (Wood and Armitage 1997). Channel sources are primarily composed of the bed and banks of the stream and tributaries, whereas non-channel sources are upland surfaces subject to rills, gullies, and other soil erosion processes, mass failures (e.g., landslides), and anthropogenic activities (e.g., construction, logging). Siltation generally occurs in the Bluegrass due to channel sources only, because delivery of sediment from distal, non-channel sources occurs during larger flood events, where the flow velocities are too high for siltation to occur over riffles.

Two conditions must be met for fine-grained material to embed a riffle substrate: an adequate supply of fine sediment must be conveyed by the flow, and local stress conditions must exist to allow deposition of fine-grained material. These conditions are met and substantial areas of riffle embeddedness occur in three types of locations in Bluegrass watersheds (Location Types 1−3):

1. Immediately downstream of a high, weathering streambank or an eroding hillslope that comprises the streambank: a surficial crust of bank material loosened by weathering detaches and falls to the base of the streambank, washes to the base of the bank or into the channel by rain-fall, or, in the lowest portion of the bank, washes directly into the water by wave action or minor increases in flow and stage. The fine sediments derived from weathered bank material are deposited in the channel when flow velocities are low, typically following periods of little or no precipitation. Low flow in the channel is capable of transporting the fine sediments only a short distance, and some of the sediments are deposited along the edge of the water and in other very low-velocity areas of downstream riffles. If weathering and transport of the fine material persists without a large flood to remove sediment, then accumulation may cover a substantial portion of the riffle or even the entire substrate. Algae, aquatic vegetation, and herbaceous vegetation growing in and along a riffle can enhance accumulation of sediment (Thornton et al. 1997).

2. Immediately downstream of the confluence of a tributary channel with another much larger channel: when rainfall produces runoff in a small tributary, it delivers fine sediment to confluences with downstream larger channels. When flow velocity and depth in the larger channel downstream of the confluence does not respond significantly to the rainfall event either because of the longer response time of the larger channel's watershed or because of non-uniform rainfall, the larger channel may not have sufficient flow to transport the fine sediment supplied by the tributary. The sediment therefore deposits near the confluence and in downstream riffles. Deposits in channels were particularly pronounced downstream of confluences of small tributaries with bare, weathering banks where large volumes of sediment accumulated following freeze-thaw cycles and then were transported into the larger downstream channels during subsequent small storm events (Croasdaile and Parola 2011).

3. Upstream of channel obstructions or contractions that promote sediment deposition by creating backwater during floods, when sediments from both local and distal sources are transported: channel morphological features such as bends with a small radius of curvature, channel boundary contractions, or large woody debris jams; and structures such as culverts, weirs, or bridges. Channel obstructions can reduce velocities sufficiently for some fine sediment to deposit (Gurnell and Sweet 1998). These locations are effective at storing sediment and reducing loads to downstream reaches.

In any of these situations, the proportion of the load that is deposited on the riffle is not fixed but instead varies between riffles and is strongly dependent on multiple variables. During base flow periods, supplied sediment is transported only a short distance downstream, and load measurements in any given channel will vary depending on proximity to local sediment sources; immediately downstream of a low- and/or base flow deposition area, the measured load would be negligible. During floods, when sediment is transported from local and distal sources to those same locations, the flow conditions may be sufficient to mobilize fine sediment from the bed and ensure that embeddedness does not persist in those riffles. Thus, the riffles could be intermittently impaired and unimpaired by embedded sediments. In areas of the channel that are backwatered during floods, however, when sediment from upland sources constitutes much of the load, as little as 0.5 tons of sediment would be sufficient to embed a single riffle. The persistence of embeddedness in these locations would depend on the stability and permanence of a backwater-inducing feature, and sediment supplies would have to be virtually eliminated throughout the watershed in order to reduce flood loads sufficiently to prevent embeddedness in backwater locations. These locations provide habitat and are effective at storing sediment and reducing loads to downstream reaches, however, and in many cases function as grade control.

3. Impairment Assessment

Task 1. ***Remote assessment.*** Prior to a field assessment, existing watershed information should be reviewed to identify potential causes of impairment and to determine the channel extent to be assessed and the timing of the field visit.

a. ***Develop preliminary list of potential causes.*** Typically, if an assessment of embeddedness is to be conducted, then a determination of some kind of impairment has already been made. If the determination was made as part of a wider investigation, then that assessment data should be analyzed. Review the data to identify as much of the following information as possible:

- Length of the assessed reach
- Number of riffles assessed
- Time of assessment
- Type of water quality samples collected
- Type of biological data collected
- Stage data from gaging station (as close as possible) for the month preceding the assessment, or if not available, rain gage data

The information that led to the selection of the assessment reach, such as biological data that showed nonsupport for WAH, should be critically evaluated:

(1) What data indicate that the reach is impaired by siltation?
(2) What are the strengths and weaknesses in the data used in the assessment, how representative are the data of the reach as a whole, and how representative were conditions at the time of assessment?
(3) What additional information may need to be collected in the field to verify the initial identification of impairment and its causes?

Based on the reviewed data, try to evaluate whether local factors could be contributing to the development of embeddedness. The following are suggestions of questions that might inform a preliminary list of potential causes:

(1) Was embeddedness found in a particular part of the reach, or was it widely distributed (only relevant if more than one riffle was assessed).
(2) Could a downstream structure or confluence be causing backwater? Can you calculate the expected maximum extent of the backwater (Fig. C.1), using contours from a topographic map to estimate valley slope (Fig. C.2)?
(3) Was sufficient evidence collected to suggest that the embeddedness was not solely a result of very low flow? Did a recent flood occur prior to assessment? Did the channel receive any rain in the preceding two weeks (or more for larger streams)? Was flow low at the time of assessment?
(4) Was algal coverage of the bed significant? Does sediment appear to have been trapped in areas where algal growth is pronounced? Are areas of the bed that have no algal cover embedded?
(5) Do tributaries join the reach immediately upstream of the assessed riffle(s)?
(6) Does the stream course run into or is it adjacent to the hillside upstream of the embedded riffle(s)?
(7) Do topographic maps or aerial images indicate any features that would produce high stream banks in the reach upstream of the embedded riffle(s), i.e., an old mill dam, an old abandoned pond, a bridge, or a major confluence? Old topographic maps can be viewed at http://www.historicaerials.com/ and can provide important information of past stream configuration that may not be present in the contemporary topographic maps.

b. ***Determine the preliminary extent of the field assessment reach.*** Based on the specific assessment objectives and the potential list of sources and causes outlined above, the extent of the field assessment should be determined. If data were collected for a single site indicating nonsupport, then the assessment might focus on the reach immediately upstream of that study site. For watershed based plans, an understanding of the embeddedness throughout the watershed might be needed, in which case the procedures applied to a single reach can be replicated in adjacent reaches. The extent of the field assessment should be at least 1000 ft or 10 riffle-pool sequences (whichever is longer) to obtain a representative sampling of riffles. The preliminary extent may be lengthened

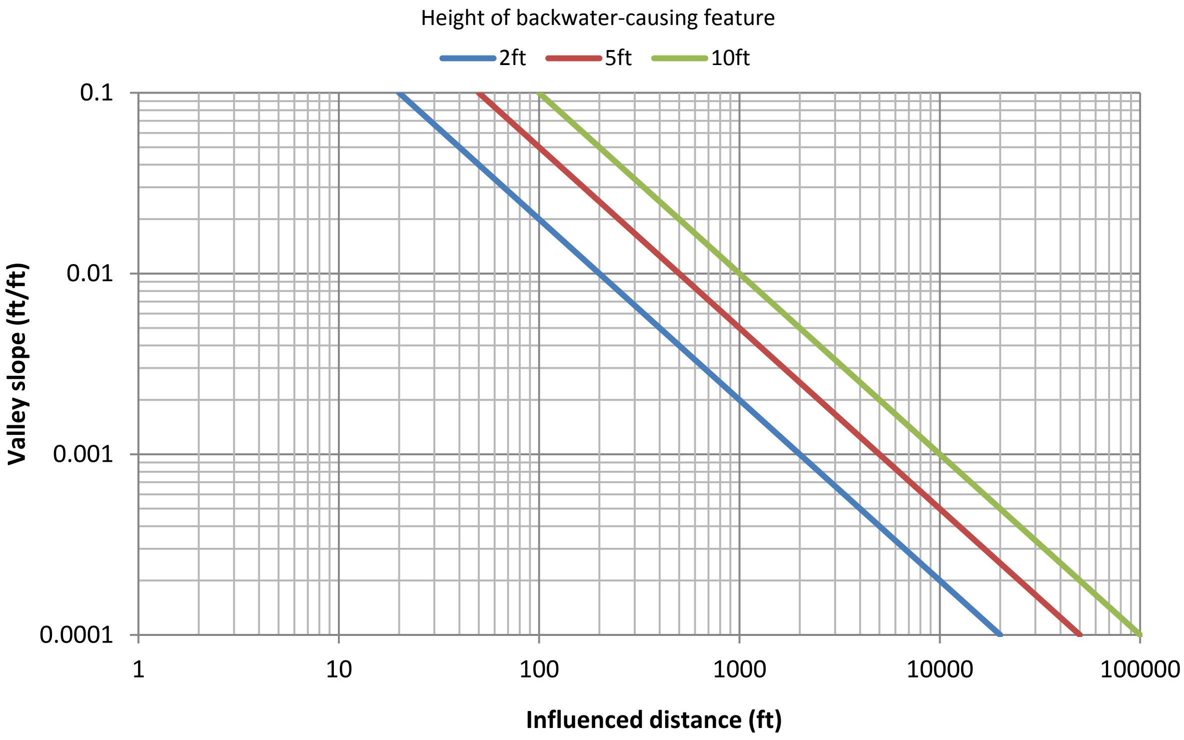
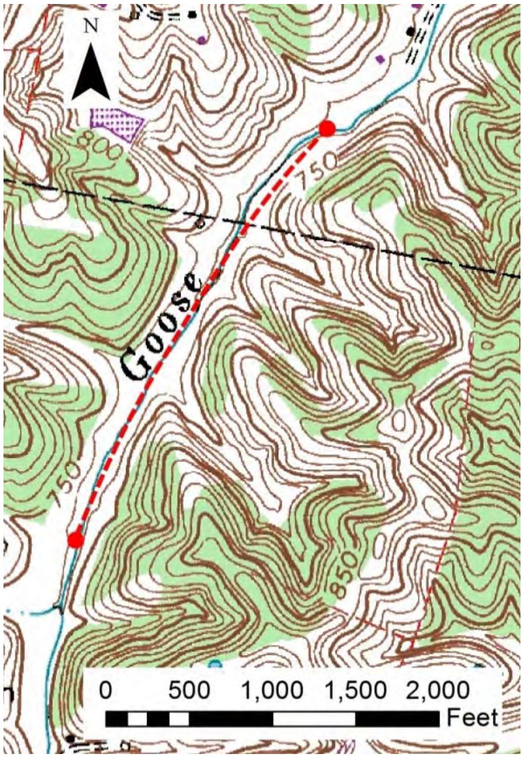


Figure C.1 Extent of backwater based on valley slope and the height of the obstruction. Any feature that significantly slows down the flow during sediment transporting flows could be considered: clearly dams would exert the strongest influence but even tight, short-radius bends can cause of backwater until they are overtopped. Other common causes of backwater are culverts, short-span bridges, and debris jams. The lines are approximate only, and the type of obstruction is important: a 5-ft-high dam will produce greater backwater than 5-ft-high banks.



$$\text{Slope} = \frac{\text{Elevation difference}}{\text{Length}}$$

Note:

- Contours should be measured from where they converge near the stream (see upper and lower red dots).
- Slope will be approximate, as local slope may vary considerably between contours.

Figure C.2 An approximate measure of valley slope can be made from contours on a USGS topographic map.

during the field assessment if necessary. The following considerations should be incorporated into the selection of the assessment reach:

- If a backwater-causing feature is identified as a potential cause of siltation, then the assessment should include 2−3 riffles downstream of the structure to compare with those upstream of the structure.
- If a major confluence is identified as a potential cause of backwater and source of sediment, then the assessment should include riffles close to the confluence and upstream of the backwater-influenced area (Fig. C.1) to allow a comparison between backwatered and non-backwatered areas.
- If any features might obstruct the supply of sediment to downstream reaches, such as a dam or reservoir, then this would represent a sensible upstream limit of the field assessment reach.

The preliminary extent of the assessment reach(es) should be marked on a topographic map that can be taken in the field and marked with relevant observations. Alternatively, a handheld GPS with topographic map and study limits stored internally can be used.

c. ***Determine the timing of the field visit.*** If embeddedness was observed during a period of little or no flow, then a field visit should be made during a spring rainy period to see whether embeddedness is also observed during higher base flow conditions. This is particularly true if the assessment was conducted during a particularly dry year. Monthly records of the Palmer Drought Severity Index (PDSI) are available from the National Climatic Data Center (NOAA-NCDC 2013). The PDSI indexes normal as 0 and drought as negative values; for example, −2 is moderate drought, −3 is severe drought, and −4 is extreme drought. If the original embeddedness was observed when the PDSI was negative, then an additional visit during non-drought conditions is essential.

Task 2. Field assessment. A field assessment should be conducted after the remote assessment to define the extent of embeddedness and identify potential sources.

Synchronized GPS readings and photographs should be taken of all riffles, eroding banks, channel boundary materials, and any features that may be contributing to sediment supply (e.g., tributaries, eroding hillsides) or to the deposition of sediment (e.g., channel obstructions, tight bends, constrictions, or grade control structures). The synchronized photographs and GPS points will enable any field observations to be georeferenced on topographic maps or aerials, if required. Field sketches may be a useful supplement to photographs to document any important processes that might be contributing to sediment production or deposition.

a. ***Eliminate backwater as a cause of siltation impairment.*** If a structure causes backwater, does embeddedness extend beyond the backwater, i.e., is embeddedness restricted to a particular location? If yes, then the decision of whether to conduct a source assessment should be made relative to the study goals: if even localized embeddedness is a problem or occurs at a critical time for WAH, then continue with the assessment. If embeddedness is not observed in any of the riffles upstream of the backwater within the assessment reach, however, then depending on the assessment objectives, you may reasonably conclude that the embeddedness is caused by local hydraulics due to a structure and that further assessment is unnecessary.

b. ***Eliminate low flow as a cause of siltation impairment***. Are riffles embedded in the spring or in periods of sustained base-flow? If embeddedness is restricted to low-flow or drought conditions, then the decision on whether to conduct a source assessment should be made relative to the study goals: if summer embeddedness is a problem or occurs at a critical time for WAH, then continue the assessment. For projects where BMP implementation and reduction of embeddedness will be the final outcome, then further source assessment may not be an effective use of funding. Seasonal low flow may produce embeddedness, and the mass of sediment required to embed riffles during these times may be small, so local BMPs could be readily implemented to reduce this embeddedness.

c. ***Map embedded riffles and potential sources.*** The first objective in identifying sources is to determine whether riffle embeddedness is restricted to specific areas or is widely distributed through the reach. Mapping each embedded riffle will permit the extent of potential sources to then be determined. The second objective of the source assessment is to identify the sediment sources that are causing embedded riffles. A general rule for Bluegrass streams is that the closest sources of sediment are probably the most significant. Siltation is often caused by a local supply of fine-grained sediment, typically nearby unvegetated banks or small tributaries with unvegetated banks. The further a source is from a riffle, the lower the probability that the sediment is delivered to a riffle under a flow condition at which it could deposit. An effort should be made to determine the portion of the channel network and watershed that can supply sediment under the relatively low-velocity conditions that can embed riffles.

The extent and area of riffle embeddedness and of bare soil in the study reach should be mapped, but the approach here is diagnostic—the aim is to test the hypothesis that the closest sediment source is the cause of embeddedness. Answers to the following questions may help to determine whether the hypothesis can be disproven:

(1) Are riffles that are close to bare eroding soil more embedded than riffles that are further from the bare eroding soil?
(2) Are riffles embedded more on the sides than in the center? This typically occurs in low-flow periods when sediment cannot have traveled from distal sources.
(3) Are riffles embedded to a greater degree on the side closest to the sediment source than on the other side?
(4) If eroding banks are the main identified source, can a reach without high eroding banks be located, and does it have embedded riffles?

Any tributaries in the reach should be evaluated as a potential sediment source:

(1) Are riffles that are immediately downstream of tributary confluences more embedded than those located between confluences? A field visit after rainfall can be particularly instructive, as it may show where plumes of sediment can enter the main channel and deposit near the confluence when velocities are insufficient to transport the sediment out of the reach (Fig. C.3).
(2) Is a sediment deposit at the confluence?

(3) Does the siltation of riffles in the main stem terminate at the tributary (i.e., it does not extend upstream of the confluence)?
(4) Are banks in the tributary exposed and eroding?
(5) Is fine sediment stored in the bed of the tributary channel (Fig. C.4)?

Figure C.3 Extreme example of a tributary supplying sediment after small rainfall event while the main stem is still at baseflow (South Fork Currys Fork).

Figure C.4 Confluences of small tributaries with the main stem of South Fork Currys Fork (left) and Goose Creek (right). The arrow shows the deposit of fine sediment stored in the tributary that is readily flushed into the main stem during small rainfall events. If the stage in main stem rises then the sediment is transported out of the reach; if not, the sediment will be stored in the main stem.

Conclusions about sediment sources should be continually reevaluated during the field assessment. Questions such as these will help to confirm that the findings are consistent with field observations:

(1) If bank sediments are suspected as the source, are they of the same gradation as the siltation sediments?
(2) Under what conditions could sediment deposit on the riffles? Are all riffles embedded, or is there a distinct pattern?
(3) What is the role of algae or other aquatic vegetation in trapping sediment? Is the "sediment" truly inorganic sediment? Material deposited on the bed may contain a significant portion of organic material, mainly dead algae.

d. ***Identify sources of sediment waves or pulses.*** If embeddedness is widely distributed throughout the reach and no local source can be identified, then a land disturbance nearby probably produced a "wave" or slug of sediment that is blanketing the streambed and riffles. In this case, the field assessment should be extended upstream until a probable source is identified (Fig. C.5).

Figure C.5 Widespread blanketing of the bed with fine sediment is unusual and is probably caused by a nearby disturbance of the land and clearing of vegetation. In Goose Creek the effects of heavy machinery moving in and out of the creek produced a slug of sediment that smothered riffles and pools for about 500ft and was not observable more than 2000ft downstream.

e. ***Collect supporting samples (optional).*** Local site conditions will determine what additional information could be used to help increase confidence in the source determination. Two sampling activities are likely to be useful:

(1) Collect sediment samples from banks and from the riffle, and compare the grain-size distributions. If sediment in the riffle is sand, and bank materials are silt/clay, or vice versa, then the banks would be an unlikely source.
(2) Sample bed sediment for percentage organic material. During summer months, a large proportion of the "sediment" embedding riffles may be organic material such as dead algae, cattle feces, or leaf litter (Udelhoven et al. 1998; Braccia and Voshell 2007).

Task 3. Data organization and external review of sources. Following the field assessment, the GPS points should be entered in GIS so basic length measurements can be calculated, photodocumentation should be downloaded and field notes should be scanned as portable document format (PDF) files for digital archiving.

At this point, verification of your source determinations may be useful from someone with local knowledge of the watershed or adjacent watershed. Do the selected sediment sources and causes of siltation match the experience of other scientists, engineers, or resource managers with knowledge of the watershed?

4. QUANTIFICATION OF LOCAL SEDIMENT LOADS

For §319-funded watershed plans, "source" is defined as the area that contributes a pollutant (KDOW 2010, p. 99). Depending on the project objectives, the source of sediment may be defined sufficiently as the tributary or subwatershed without further source assessment. For projects where a greater level of detail is required, including TMDLs, then measurements of the load may be necessary. This involves two steps: first, identifying the crucial period of sediment delivery, and second, measuring the load during those critical times.

Task 4. Identifying period of critical loads. Flow is the main environmental factor governing the development of siltation and resulting embeddedness. For most sites, embeddedness will vary with season. Embeddedness is much more likely during low flow, and low flow is more likely during the late summer and fall. The time period for which loads are estimated should correspond to those low-flow periods. If embeddedness is observed throughout the year, however, the time period can be the entire year.

Task 5. Quantify bank erosion sediment production. Depending on the size of the reach and number of eroding banks, all the banks may be measured individually, or the population may be sampled and an average rate used to calculate total sediment production. The contribution from banks that have been identified as a source of riffle-embedding material may be estimated using three different methods:

a. ***Rate Measurement Method***: This method uses field measurements of erosion rate and bank geometry. Erosion rate measurements are obtained from erosion pins, dendrogeomorphic methods, or repeat surveying. Bank geometry measurements can be obtained using a pocket rod and measuring tape or total station surveying equipment. More specific details about installation of erosion pins and dendrogeomorphic measurements are provided in Section 2.4. Repeat surveying of bank profiles can be conducted using surveying equipment (Harrelson et al. 1994) or bank profiles (Rosgen 2006).

These measurements are combined to obtain local rates of sediment production as follows:

$$M_b = E_m * L * H * E * BD * (T/365) \quad \text{(C.1)}$$

$$\text{and } M_r = \Sigma\, M_{b1} + M_{b2} + \ldots\, M_{bn} \quad \text{(C.2)}$$

where M_b (lbs/yr) is the mass of sediment produced by an individual eroding bank, E_m (ft/yr) is the measured erosion rate for the target period, L (ft) is length of eroding bank, H (ft) is bank height, E is percentage area of the bank experiencing active bank erosion, BD (lbs/ft^3) is the bulk density of bank sediments, and T (days) is the time period for which load estimates are critical. M_r (lbs/yr) is the mass of sediment supplied to a reach, as a sum of individual eroding banks.

b. ***Reference Erosion Rate Method***: Local erosion rates estimated using reference rates are combined with local bank geometry measurements (collected with pocket rod and measuring tape):

$$M_b = E_r * L * H * E * BD * (T/365) \quad \text{(C.3)}$$

where E_r (ft/yr) is a reference rate of erosion. The reference rate should be used based on the assessor's experience. In the Bluegrass a low rate that would be expected due to bank weathering processes alone would be around 0.2 ft/yr.

c. ***Reference Unit Sediment Production Method***: A reference unit sediment production is scaled by the period of embeddedness. Ideally, a reference unit sediment production value would have been measured within the same watershed or in an adjacent watershed within the same physiographic subregion. The reference USP values in Table 3.1 could be used. The level of uncertainty of using a reference rate alone, however, cannot be determined: errors could be due to erosion rate, bank height, percentage eroding bank, and length of eroding banks. The use of USP is therefore recommended only for gross estimates of bank erosion that can be compared to the amount of material required for embeddedness.

5. LOAD REDUCTIONS

Task 6. Prioritize load reduction strategies. During high flows, deposition of silt-sized particles cannot occur except for some minor intrusions into the riffle framework. Therefore, the loads that are most relevant to embeddedness are those that are transported during low-flow periods. Because flow velocities during low flow are low, especially in pools, most sediment during these flows will be unable to travel through a series of pools. Hence the maximum travel distance for sediment particles is short, possibly as short as a single pool. For these reasons, prioritization should be given to the sediment sources within the affected reach or immediately upstream of it. Without addressing these proximal causes, even comprehensive sediment reduction elsewhere might produce no reduction in embeddedness.

Task 7. Develop siltation targets. The target for embeddedness will vary upon project objectives. Relatively little guidance on setting siltation thresholds is available for WAH. In West Virginia, EPT taxa richness significantly decreased ($p < 0.05$) in streams where fine substrate particles (<0.25 mm) exceeded 0.8–0.9% of riffle substrate composition by weight (Kaller and Hartman 2003). The data from West Virginia were collected by scooping samples from riffles, so some fine sediment likely was lost, and this number is artificially low. Another approach would be to use percentage fines by bed area as measured in a pebble count; this approach was adopted in an EPA-approved TMDL for the Upper Rio Grande watershed (NMED 2005). Alternatively, a target could be set based on the riffle embeddedness condition required for the parameter to be classified as optimal in an RBP assessment (Barbour et al. 1999): gravel, cobble, and boulder particles should be no more than 25% surrounded by fine sediment. If the applicability of such thresholds were assessed for Bluegrass streams, they potentially could be used to develop targets for local sediment reduction.

The mass of sediment presently in the riffles can be used as a baseline to calculate load reductions. The mass of sediment, M_e (lbs), required to embed a riffle can be calculated as

$$M_e = w_r * l_r * d_s * p * BD_r \qquad \text{(C.4)}$$

where w_r (ft) is the riffle width, l_r (ft) is the length of the riffle, d_s (ft) is the depth of sediment intrusion into the riffle, p is the porosity of the riffle sediment, and BD_r (lbs/ft^3) is the bulk density of the embedding sediments. Width and length are measured using a measuring tape. The depth of intrusion can be estimated with a pocket rod or, for deeper deposits, by driving a metal stake into the deposit and measuring the depth of fine sediment with a pocket rod. Porosity is defined as the ratio of the space taken up by voids to the total volume of sediment. Porosity is a dimensionless number less than 1, and it may be expressed as a percentage. Porosity can be calculated from

$$p = \frac{V_V}{V_t} = \frac{V_{t-}V_S}{V_t} = \frac{V_t - (m_s/\rho_s)}{V_t}$$

where V_v is the volume of the void or pore spaces, V_t is the total volume of sediment, and V_s is the volume of the sediment without pores. The dry mass of the sediment is m_s and particle density is ρ_s. Alternatively, porosity may be computed from

$$p = \left(1 - \frac{\rho_b}{\rho_s}\right)$$

which is a more convenient method, requiring only the bulk density of the sediment mixture, ρ_b, to be calculated (with a particle density of 2.65 g/cm^3 assumed). Porosity should be estimated from reference values (Table Porosity), or a typical value of 0.3 can be used. During fieldwork, the riffle crest location should be recorded with a handheld GPS. The GPS coordinates should be used to calculate the riffle frequency in ArcGIS or Excel.

The mass of individual riffles can be measured separately and then summed to estimate the total mass of sediment required to embed riffles within a reach. Alternatively, the average riffle width and length and intrusion depths can be used in Equation C.4 to estimate average mass per riffle. This mass multiplied by the riffle frequency will produce an estimate of the total reach mass.

Table C.1 Porosity of Bed Sediments

Sediment composition	Porosity	Reference
Gravel	0.3-0.6	Das (2008)
Natural mixtures (UK stream)	0.13	Carling and Reeder (1982)
Natural mixtures (Western USA)	0.02-0.36	Milhous (2001)

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