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Using macroinvertebrate community composition to distinguish
between natural and anthropogenic sedimentation

A thesis submitted in partial fulfillment of the requirements for the
degree of Master of Science in Environmental Studies at Virginia Commonwealth University.

by

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B.S. Environmental Studies
Virginia Commonwealth University
2010

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To my mom - who was not able to be a part of my journey through graduate school but nonetheless I'm sure is proud - I remembered to pack clean underwear and I'll write if I get work.

Abstract

USING MACROINVERTEBRATE COMMUNITY COMPOSITION TO DISTINGUISH BETWEEN NATURAL AND ANTHROPOGENIC SEDIMENTATION

By Amanda E. Schutt, B.S. Environmental Studies

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Studies at Virginia Commonwealth University.

Virginia Commonwealth University, 2012

Advisor: Dr. Leonard Smock, Director, VCU Rice Center,
Center for Environmental Studies / VCU Life Sciences

Excess fine sediment from human activity is a major pollutant to streams across the U.S.; however, distinguishing human-induced sedimentation from natural fine sediment is complex. The U.S. Environmental Protection Agency recently implemented a protocol for the quantitative field assessment of human-induced sedimentation using measurements of stream geomorphology. Macroinvertebrate community composition, streambed sediment stability, and sediment composition were studied at 49 sites in the James River watershed in central Virginia. Sediment composition was found to be a stronger driver of community composition than sediment stability. Although I was not able to show that macroinvertebrate metrics were related to sediment stability independently of actual fine sediment composition, some metrics, including percent Ephemeridae, a family of burrowing mayflies (order = Ephemeroptera) show promise as valuable tools for regional biologists and resource managers to discriminate among streams considered impaired for sediment pollution.

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Introduction

In 2010, the U.S. Environmental Protection Agency (EPA) released the Chesapeake Bay Total Maximum Daily Load (TMDL), the largest comprehensive watershed “pollution diet” ever developed in order to restore the Bay’s tributaries to water quality standards mandated by the Clean Water Act. The TMDL identified sediment as one of three major sources of non-point source pollution and set a goal of 20 percent reduction in sediment loads to the Chesapeake Bay by 2025 (USEPA 2010). As states develop and implement plans for individual catchments within the Chesapeake Bay watershed, determining the source of sediment, that dictates properties and behavior of sediment in aquatic systems, will become very important to achieving reduction goals. Establishing relationships between sediment source, and thus sediment properties, and well-known biological water quality indicators may provide insightful information on the progress and effectiveness of TMDL regulations.

Benthic Macroinvertebrates

Streams provide habitat for a variety of animals such as fish, amphibians, and aquatic invertebrates. Aquatic invertebrates, such as insects, bivalves, crustaceans and other animals that live on the bottom part of aquatic ecosystems (e.g., streams, rivers, and estuaries) are referred to as benthic macroinvertebrates. Taxonomically, benthic macroinvertebrates are a diverse group of animals with wide variation in habitat requirements, feeding strategies, tolerance to pollution and sensitivity to fluctuations in environmental conditions. These organisms are often sessile or have limited dispersal capability and spend all or part of their lives, typically one year or more, exposed to the conditions of the aquatic environment. Thus, the analysis of overall benthic macroinvertebrate community structure can provide information on local environmental conditions and short-term effects of stressors (Barbour et al. 1999).

Due to the utility of benthic macroinvertebrates as integrators of short-term environmental conditions and stress, and their relative ease of collection and identification, these organisms are widely used as bio-indicators of water quality (Southerland and Stribling 1995). Biomonitoring, or the use of aquatic organisms in water quality assessments, became common across the United States after the 1987 amendments to the federal Clean Water Act Section 101(a), which directs states to assess and monitor freshwater resources to “restore and maintain the chemical, physical and biological integrity of the nation’s waters” (Mebane 2001).

Sediment

As a natural part of the physical environment of the stream ecosystem, sediment is impacted by processes at multiple spatial and temporal scales such as variations in climate and catchment geology (Walling and Moorehead 1989) and land use, soil type, and vegetative cover (Wood & Armitage 1997). In individual stream channels, the sediment present is the result of processes that control sediment supply and transport.

There are two main sources that supply sediment to streams – channel sources and non-channel sources (Grimshaw and Lewin 1980, Wood and Armitage 1997). Channel sources include sediment derived from the erosion of the stream bed, bank and bars, backwater areas, and sediment trapped in vegetation. Non-channel sources include runoff erosion from disturbed soil beyond the riparian zone, urban development, agriculture and timber harvesting (Wood and Armitage 1997). Sediment transport is governed by channel properties (e.g., gradient, morphology, roughness and armoring), flow properties (e.g., discharge and floods), and sediment properties (e.g., particle shape, size, and orientation) (Wood and Armitage 1997).

Under natural conditions, streams seek equilibrium between sediment supply and transport however this balance is often interrupted or disturbed, in some cases by anthropogenic

activities. Human disturbances, such as urbanization, agriculture or logging, can alter the physical habitat structure of streams in a variety of ways: channel straightening, loss of pools and large woody debris, and changes in substrate composition, one of the most common being the introduction of excess fine (≤ 2 mm), inorganic sediment (Wood and Armitage 1997, Mebane 2001).

While some fine sediment in streams may be natural and innocuous, sediment supply in human-impacted areas often exceeds the stream's capacity to transport, or flush, sediments during high flow (Relyea et al. 2000). The deposition and accumulation of fine particles on the stream substrate is called 'sedimentation.' Sedimentation occurs naturally where water velocity slows down, such as in backwater areas and dead zones such as pools, near stream banks, in macrophyte beds, and sheltered areas behind large particles like boulders (Wood and Armitage 1997). Although sedimentation is a natural process, human disturbance in the watershed tends to modify the timing and volume of sediment delivery to streams by accelerating sediment erosion and increasing runoff to streams beyond expected natural conditions (Wood and Armitage 1997, Angradi 1999, Zweig and Rabeni 2001, Suttle et al. 2004, Gellis et al. 2009, Burcher et al. 2007, Cover et al. 2008).

Individual streams respond in different ways to sedimentation according to the characteristics of their catchments (i.e., geology, disturbance) and channels (i.e., geomorphology, gradient, Angradi 1999). The effects of sedimentation not only impact the physical environment of the stream, but are also detrimental to aquatic life including benthic flora (e.g., increased turbidity, increased substrate scouring, and impaired substrate suitability for periphyton) and fauna (e.g., harm to respiration structures, reduced substrate habitat availability, complexity, and stability, Nuttall 1972, Richards et al. 1997, Wood and Armitage 1997, Angradi 1999, Zweig and

Rabeni 2001, Allan 2004, Kaller and Hartman 2004, Kaufmann et al. 2004, Harrison et al. 2007, Cover et al. 2008).

Sedimentation and Biodiversity

Benthic macroinvertebrate community composition and distribution are strongly tied to substrate particle size and habitat heterogeneity in the area that is most vulnerable to sedimentation - the upper part or top layer of the streambed (Cummins and Lauff 1969). Due to their high local habitat dependence (i.e., sessile or limited dispersal capabilities), macroinvertebrate diversity is negatively impacted by the infilling of microhabitat interstitial spaces between cobbles and gravel and the deposition of homogenous layers of fine sediment that reduces habitat availability and heterogeneity, and ultimately stability (Minshall 1984, Resh and Rosenberg 1984, Minshall 1988, Richards et al. 1997, Rempel et al. 2000, Allan 2004, Kaller and Hartman 2004, Kaufmann et al. 2004, Rabeni et al. 2005, Burcher et al. 2007). The effects of reductions in streambed stability on macroinvertebrate community composition are not well-studied but may include macroinvertebrate mortality, stress or behavioral drift dispersal (Freeman and Schorr 2004).

In some instances, the benthic community may be resistant to short-term or 'pulse' increases in fine sediment loading, such as occurs during post-storm high discharge events, if the community composition includes well-adapted or resilient taxa. For example, some macroinvertebrate taxa associated with depositional areas in certain regions have unique morphological and physiological adaptations for coping with fine sediment such as protected gills, burrowing appendages, sclerotization, or hard shells. Examples include species of worms (Oligochaeta), freshwater clams (Sphaeriidae), and some taxa of Sialidae (order Megaloptera), the true fly families Ceratopogonidae and Tipulidae, the dragonfly family Gomphidae, and the

mayfly family Ephemeroidea (Schloesser et al. 2000, Freeman and Schorr 2004, Suttle et al. 2004).

In contrast to short-term increases in sediment loading, urban development and land use conversion can cause prolonged or continuous elevated sediment delivery. This type of disturbance is ultimately more destructive to macroinvertebrate abundance and diversity, and may permanently alter or shift the natural community composition by eliminating sensitive taxa (Wood and Armitage 1997). Although the taxa listed above are known to occur in naturally sedimented areas, there is little information about their presence or absence under conditions of excess human-induced sedimentation. Knowing which taxa are sensitive to the negative impacts of anthropogenic sedimentation would be a valuable tool for resource managers to discriminate among streams considered impaired for sediment pollution (Relyea et al. 2000).

Quantifying Sedimentation

In streams nationwide, excess fine sediment is widely recognized as a leading cause of water quality impairment because of concerns of increased turbidity, habitat degradations and, decreased productivity; however, separating anthropogenic sediment from natural fine sediment variability is difficult and complex (Mebane 2001, Sutherland et al. 2002, USEPA 2007, 2010). There are a variety of methods for evaluating sediment, ranging from unobtrusive visual assessments in the field to complex laboratory sorting and identification to detailed studies of channel sediment transport at individual systems (Trimble 1999, Knox 2006, Mebane 2001). The first type of study is often qualitative and susceptible to bias, while the latter types of studies have been criticized for being expensive, laborious, and not feasible for state agencies to incorporate into large regional assessments (Kaufmann 2008).

The EPA recently developed the Relative Bed Stability (RBS) index, which allows for a quantitative evaluation of anthropogenic influence on sedimentation by 1) calculating the natural sediment particle size that ought to exist in a given stream and 2) measuring the actual magnitude of deviation from natural sediment conditions (Kaufmann et al. 1999). The RBS methodology will be fully explained in the methods section, but the major measurements include bankfull channel dimensions, longitudinal thalweg depth profile, water surface slope, a woody debris tally, and a systematic pebble count. RBS is similar to other methods of evaluating substrate, sedimentation, and bed stability (Dietrich et al. 1989, Buffington and Montgomery 1999, Kappesser 2002), however it is the most-recently validated method. RBS is also currently being used for sedimentation assessment by the EPA and state water quality monitoring programs because it utilizes data collected in synoptic regional stream assessments and can be used for hypothesis testing of the effects of human influence on streambed sediment size (Kaufmann 2008, Hughes et al. 2010).

Study Significance

The Mid-Atlantic Piedmont eco-region is a transitional area between the Appalachian Mountains and the coastal plain (Omernik 1987, Figure 1). A series of land use conversions and increasing human development over the past 200 years, which have exacerbated the soil conditions of this erosional terrain (Wiken et al. 2011), has made sedimentation one of the leading causes of stream impairment in this region (Walter and Merritts 2008, USEPA 2010).

Many moderate- to low-gradient streams in this region are severely incised, have steep eroding banks and transport abnormally high quantities of suspended sediment (Gellis et al. 2009, Walter and Merritts 2008). These conditions create difficulties for environmental monitoring agencies because their biologists often make on-site decisions on how to apply

EPA's Rapid Bioassessment Protocols (RBP) for water quality assessments. These protocols dictate specific methods, including macroinvertebrate sampling procedures and habitat assessment, based on the distinction of high- vs. low-gradient streams (Barbour et al. 1999, Willis and Hill 2010 pers. comm.). These decisions are highly susceptible to individual bias because they are formed based on any available, visible indicators of gradient, such as the presence of a riffle-pool sequence. Often is it difficult to determine if riffles are absent or if the riffles are present but buried under layers of fine sediment (personal communication Shanabruch and Smigo 2010, personal communication Willis and Hill 2010).

The time and resource investment required for macroinvertebrate sampling and identification does not reasonably allow environmental monitoring agencies to sample using both high- and low-gradient methods (Herbst and Silldorff 2006). Therefore, to provide scientific support for the selection of a particular method, biologists need to be able to determine if the sedimentation in a given stream is expected under natural geomorphic conditions or if it is in excess of natural sediment loads. The RBS method, which provides rigorous quantitative assessments of stream sediment conditions, coupled with the strength of benthic macroinvertebrate community bioindicators, will strengthen conclusions from field assessments and allow researchers to be better informed of the ecology of benthic organisms (personal communication Willis and Hill 2010).

The overall goal of this study was to determine if and how benthic macroinvertebrate community composition could be used to distinguish between conditions of natural sediment and anthropogenically-induced excess sediment as quantified by the Relative Bed Stability method. To address this goal, I examined overall community structure using metrics to determine which aspects of the community, if any, were related to the degree to which stream sediment was

attributable to human activity. Community metrics that are responsive specifically to sedimentation from human activity would be valuable tools for water resource managers to discriminate among streams considered impaired by sediment pollution and in monitoring stream health and the effectiveness of sediment pollution reduction measures like the Chesapeake Bay TMDL.

Methods

Study Area

The James River watershed is 26,511 square kilometers and stretches across the state of Virginia, covering four major physiographic regions, including the Piedmont (Omernik 1987, Figure 1). The Piedmont physiographic province is a transitional zone located between the Blue Ridge mountains to the west and the Coastal Plain along the Atlantic coast. As a result of the Piedmont's location in this transitional zone, tributaries to the James River tend to be moderate- to low-gradient streams. Historically considered a hickory-oak-pine forested eco-region, the Piedmont has experienced clear cutting, agriculture, and is now returning to forest with pockets of intense urban and suburban development (Cole and Ware 1997). As a combined result of the overall regional gradient, highly erodible soils, and land use practices, many James River tributaries in the Piedmont region appear to have high sedimentation and lack clearly visible riffle areas, despite existing well-buffered forested riparian areas.

Site Selection

I used a subset of the 100-site list of the 2010-2011 sampling phase of Virginia Commonwealth University's (VCU) Interactive Stream Assessment Resource (INSTAR) project, available online at <http://instar.vcu.edu>. This subset was comprised of 49 randomly-selected sites in wadeable (1st-3rd order) tributaries of the James River and Appomattox River (Figure 2). Each

of the sites was visited once between 19 April and 16 November 2011 to collect physicochemical and Relative Bed Stability parameters.

Biological Parameters

A sample of the benthic macroinvertebrate community was collected using the Rapid Bioassessment Protocol (RBP) multi-habitat approach (Barbour et al. 1999) by the VCU INSTAR project at 45 of the 49 study sites prior to the beginning of this study. Samples were systematically collected from all major habitat types including cobble or riffle areas, snags, submerged areas of vegetated banks, and sandy areas using 20 jabs or kicks with a standard 0.3-m wide, 500- μ m mesh D-frame dip net (Barbour et al. 1999). Additional samples of the macroinvertebrate community were collected in the same manner as for past INSTAR collections (EPA RBP multi-habitat approach) at the four sites which did not have a sample already on record at the beginning of the study. Thus, one macroinvertebrate community sample was collected and then identified in the following manner for each of the 49 study sites.

All samples were preserved in the field using 70% isopropyl alcohol with Rose Bengal stain and transported to the laboratory. Each sample was subsampled using a systematic method whereby the entire sample was spread into a mesh-bottomed sorting tray divided into grids. A random number generator was used to select the grids for subsampling. From each grid, all macroinvertebrates were separated from plant and other animal material for identification. Random selection of grids continued until the number of individuals selected reached 220 or greater, pending the complete processing of the last grid selected. Most taxa were identified to genus. Immature specimens and some Diptera (e.g. Chironomidae and Simuliidae) were identified to family and some non-insect taxa were identified to higher taxonomic levels. The number of individuals in each sample varied (range = 200 to 451); to control for this variation in

subsampling protocol, and because total abundance was not of specific interest in this study, random subsampling was conducted using R statistical software (R, version 2.14.1) to the lowest abundance in the dataset, thus creating 200-count samples.

Macroinvertebrate community composition is described using metrics, or measurements of taxonomic or functional traits of the species present that reflect important ecological principles and are expected to respond to the effects of stressors, that are scored based on samples collected using standardized bioassessment methods (Karr 1991, Barbour et al. 1995). Comparing metric scores allows for the assessment of community differences among sites or streams. A suite of thirty one metrics was calculated, including those describing taxonomic richness and diversity, feeding guild composition, measures of relative pollution tolerance, and individual habitat preferences and morphological characteristics (Table 1). These metrics were selected because their relationship to fine sediment in streams is well-established (Rosenberg and Resh 1992, Merritt and Cummins 1996, Barbour et al. 1999) and these metrics were predicted to be related to sediment stability.

Physical Parameters

The Virginia Department of Environmental Quality (DEQ) Probabilistic Monitoring Program (ProbMon) (Dail et al., undated document) recently implemented the Relative Bed Stability (RBS) method, as described by Kaufmann et al. (1999, 2008). I collected data to produce both sediment stability metrics (RBS) and sediment composition metrics (observed median sediment size, percent sand, percent silt, percent fines, and percent mean embeddedness, Table 2) by following the RBS protocol, as described below.

At each of the 49 stream sites, a sample reach was established with a length equal to 40 times the average channel width determined from at least three randomly selected points. The

reach established for RBS data collection was positioned as far from obvious road influences (e.g. unnaturally large pool areas and armored or clearly reinforced banks to support bridges), while still positioned to overlap the reach previously sampled for macroinvertebrates by the VCU INSTAR project. This was accomplished by approximately aligning one end of the RBS reach with the beginning of the macroinvertebrate sampling reach as determined from field notes. Because the reach for RBS data collection was always longer (minimum of 150 m) than the standard 100 m reach established for macroinvertebrate collection (Barbour et al. 1999), the RBS reach extended farther upstream or downstream of the macroinvertebrate sampling reach.

Eleven evenly-spaced transects were established within the RBS reach. At each transect, wetted width, bankfull width and height, incised bank height, and if present, bar width, were measured. Along each transect, five points were established at even intervals from the left to right bank (0, 25, 50, 75, and 100 % across the transect). At each point, the depth of the water was measured and a random substrate particle was selected. The diameter of that random substrate particle was measured, which then assigned that particle to a substrate class (e.g., bedrock, gravel, sand, etc.) and the percent embeddedness of that substrate particle was calculated.

Between transects, the depth of the thalweg, or the deepest part of the channel, was measured at regular spatial intervals to account for variation in the size and distribution of pools. Pieces of at least partially-submerged large woody debris (diameter ≥ 0.1 m and length ≥ 1.5 m) were tallied to approximate channel roughness and resistance to flow. Finally, stream gradient was measured across the entire reach using an auto-leveling NWI®NRL802 Rotating Laser. Data were recorded on a modified ProbMon habitat form (Appendix A).

For each site, the RBS score was calculated as the ratio of the observed substrate median diameter (D_{50}) to the critical median substrate diameter that would be mobilized at bankfull flow (D^*_{cbf}):

$$RBS = \frac{D_{50}}{D^*_{cbf}} = \frac{D_{50}}{(13.7 R^*_{bf} S)}$$

Observed substrate median diameter (D_{50}) was calculated from the field pebble count and substrate size classification. These data were used to produce sediment composition metrics such as percent sand and percent silt. Critical median substrate diameter (D^*_{cbf}) was approximated as the product of a constant (13.7), the effective hydraulic radius (R^*_{bf}), which is the mean bankfull hydraulic radius estimated by various channel dimensions and corrected for large woody debris, and stream gradient (S). A detailed description of the methodology and calculations is given in Kaufmann et al. (1999).

The RBS score is not related to macroinvertebrate community metrics in a linear fashion (Figure 3); therefore for convenience and to normalize variances, RBS scores are expressed as $\text{Log}_{10}RBS$ or LRBS scores (Kaufmann et al. 1999). LRBS scores range from negative four (-4) to two (2) (Figure 4). In streams considered to be “reference sites” by monitoring programs such as DEQ’s ProbMon, the LRBS score should be near zero (0). This score indicates that the observed substrate size is equal to the critical or predicted substrate size, suggesting that the stream is at a state of equilibrium. Deviation from zero indicates increasing levels of sediment related impairment. Negative scores indicate over-sedimentation ($D_{50} < D^*_{cbf}$) and positive scores indicate under-sedimentation ($D_{50} > D^*_{cbf}$) or armoring of the channel.

Physicochemical Parameters

Select water chemistry parameters were measured to attempt to account for water quality conditions that may have obscured sediment relationships (Kaller and Hartman 2004) and to maintain compatibility with VADEQ's ProbMon data set. Water temperature, pH, and conductivity were measured using a YSI model 556 multimeter (YSI, Inc., Yellow Springs, Ohio) and dissolved oxygen was measured using a Lamotte Test Kit (Lamotte, Inc., Chestertown, Maryland) just prior to the collection of RBS data at each site.

Data Analysis

The goal of data analysis was to select macroinvertebrate community metrics that could effectively differentiate between natural sediment and anthropogenic sedimentation. To address this goal, a tiered correlation analysis approach was used to examine the relationships between three groups of variables: macroinvertebrate metrics, sediment composition metrics, and the sediment stability metric LRBS. All relationships were evaluated using Pearson product moment correlation analysis (R, version 2.14.1).

First, I determined which macroinvertebrate metrics had significant, moderate to strong, linear correlations ($r \geq 0.4$, $p < 0.05$) with LRBS. To assess the presence of a linear relationship, I examined scatterplots of pairwise relationships between each macroinvertebrate metric and LRBS. The $r \geq 0.4$ criterion was established based on a clear break in correlation coefficients at that level upon review of the calculated values. Metrics that did not meet all three of these criteria were excluded from the following tiers of analysis.

Next, I examined the relationships between macroinvertebrate metrics and sediment composition metrics to determine if the macroinvertebrate metrics that had significant, moderate to strong, linear correlations ($r \geq 0.4$, $p < 0.05$) with LRBS also had similar relationships to the

sediment composition metrics. Although the relationship between macroinvertebrate community composition and fine sediment is well-established in the literature (Angradi 1999, Mebane 2001, Freeman and Schorr 2004, Kaller and Hartman 2004, Rabeni et al. 2005), determining the relationships between the specific macroinvertebrate metrics and sediment composition metrics that were selected for this study was an important assumption for proceeding with further analysis. In this tier, sediment composition metrics that did not exhibit significant, moderate to strong, linear correlations with macroinvertebrate community metrics ($r \geq 0.4$, $p < 0.05$) were excluded from further analysis.

Finally, I examined the relationships between sediment composition and sediment stability to determine if the sediment composition metrics had significant, moderate to strong, linear correlations ($r \geq 0.4$, $p < 0.05$) with LRBS. Given ecological and mathematical relationships between sediment and substrate stability (substrate stability is a characteristic of sediment size and sediment size classifications directly determine the numerator of the Relative Bed Stability ratio), a confounding relationship was expected. Therefore, partial correlation analysis was used to determine if the macroinvertebrate metrics selected by the above tiered analysis approach were related to LRBS independent of the influence of the actual sediment size composition.

The independence of the macroinvertebrate – sediment stability relationship

Partial correlation analysis provides evidence of the degree of independence in the relationship between an explanatory and response variable, controlling for the effects of a third potentially confounding variable. Mathematically, partial correlation analysis removes the influence of suspected confounding variables by examining correlations among residuals or errors of prediction (Kendall and Stuart 1973).

Partial correlation analysis has been used in ecological studies to remove the influence of confounding variables to test the strength of underlying relationships between biotic and abiotic variables (Tilman and Downing 1994). In my study, partial correlation was used to remove the effects of each of the selected sediment composition variables individually and independently from each of the selected macroinvertebrate metrics and from LRBS scores. For example, to examine the relationship between EPT Richness and LRBS independently of percent sand, I took the residuals from the linear regression of EPT Richness on percent sand and the residuals from the linear regression of LRBS on percent sand and determined if those two sets of residuals were correlated. This procedure was then repeated for each of the macroinvertebrate metrics, independently partialing out each sediment composition metric one at a time, without adjusting the significance level.

Partialing out sediment composition from both the explanatory and response variables was important because, as described above, substrate composition is a primary factor structuring macroinvertebrate communities and because substrate size is the key component of the numerator of the LRBS ratio. Thus the goal of partial correlation analysis was to determine if the relationship between macroinvertebrate metrics and LRBS was an artifact of actual sediment present in the stream, or if there were community metrics that were actually related to sedimentation attributed to human activity.

Partial correlation relationships were analyzed using Pearson product-moment correlation analysis (R, version 2.14.1). A macroinvertebrate metric was considered to be related to LRBS and independent of the influence of actual sediment present if the correlation of the metric and LRBS was significant after partialing out the effects of each of the sediment variables in separate partial correlation analyses ($p < 0.05$, uncorrected for multiple comparisons). Continuing with the

example provided above, the relationship between EPT Richness and LRBS would be accepted as independent only if all the correlations of residuals were significant across every single one of the sediment composition metrics.

Identifying the major drivers of macroinvertebrate community composition

I used nonmetric multidimensional scaling (NMS) to visualize the variation among sampling sites with respect to macroinvertebrate community composition. NMS is a nonparametric, multivariate ordination technique that is well-suited for ecological data with non-normal or unknown distributions (McCune and Grace 2002). As an unconstrained ordination technique, NMS is not dependent on relationships of taxonomic data with a predefined environmental gradient (McCune and Mefford 2006).

NMS uses a matrix of distances among sampling sites and taxonomic data to generate an ordination plot that shows the difference between macroinvertebrate communities at sampling sites visually as distances between points on the plot. I used Sørensen (Bray–Curtis) distance measures in the analysis, as recommended by McCune and Grace (2002) for data sets with numerous zero values, or zero-inflated data sets, such as our macroinvertebrate taxonomic data.

NMS analysis was conducted using PC-ORD version 5 (McCune and Mefford 2006). The analysis parameters were six initial axes, 40 runs with real data, 10 iterations to evaluate stability with 400 maximum iterations, a random seed integer to initiate 50 runs with random data, and to step down in dimensionality to re-evaluate stress as the number of axes used to explain variation decreased. Pearson-product moment correlation analysis (R, version 2.14.1) was used to compare the positions of the sites on the ordination axes to relative abundances of each individual taxon, LRBS scores, and values for each selected sediment metric to determine if these were strong drivers of macroinvertebrate community structure.

Results

Physicochemical Parameters

Parameters describing stream water quality- conductivity, temperature, pH, and dissolved oxygen – generally fell within expected ranges (Mulholland and Lenat 1992) with a few exceptions for conductivity and dissolved oxygen (Table 3). Two instances of high conductivity (1221 $\mu\text{S}/\text{cm}$ and 1240 $\mu\text{S}/\text{cm}$) were recorded in August at sites JA09-02 and JA33-04, respectively and an instance of low conductivity (12 $\mu\text{S}/\text{cm}$) was recorded at site JA04-02 in October. Field notes do not indicate an obvious source for these extreme values. There were two instances of low dissolved oxygen levels (3.45 mg/L and 2.8 mg/L) (Table 3), recorded at sites JA19-02 and site JA33-04, respectively. Both sites were sampled in August when water temperatures were above 20°C.

Biological Parameters

A total of 167 macroinvertebrate taxa were identified (Table 4) and the scores of 31 metrics describing various aspects of community composition were calculated (Table 5, see Table 1 for metric descriptions). The mean number of taxa in each sample was 23, with the pollution-intolerant Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa making up, on average 42% of the total taxa richness (range of percent EPT taxa: 10-70%, Table 5). Often, one taxon dominated the invertebrate sample at the study sites (mean percent dominance: 50%; range: 10-80%, Table 5). Chironomidae were generally the most common invertebrates at the study sites (mean percentage of sample: 40%; range: 0-80%, Table 5). In general, habit groups (e.g., burrower, clingers) had more frequent and stronger correlations with fine sediment than did functional feeding groups.

Selection of macroinvertebrate metrics

The tiered correlation analysis procedure eliminated 12 of the original 31 macroinvertebrate metrics from further analysis based on failure to meet the established relationship criteria with sediment stability ($r \geq 0.4$, $p < 0.05$, Table 6).

Physical Parameters

Overall, streams were dominated by sand (size 0.06-2 mm) and were highly embedded (mean embeddedness: 70%, Table 7). Fine sediment was present at all 49 sites and at site JA27-03, the substrate was composed entirely of fine particles (Table 8). At nine sites, no large particles (bedrock, boulders, cobbles) were encountered in the stratified particle size assessment process for collection of Relative Bed Stability (RBS) data.

As expected, log-transformation of explanatory variables tended to linearize relationships with macroinvertebrate metrics (Figure 3, Figure 5). As such, observed median sediment size (OBS_MSS) was expressed as LOBS_MSS (\log_{10} observed median sediment size) and RBS scores were expressed as LRBS scores. Stable, naturally low-sediment sites were rare, with only one site (JA01-02) classified as not impacted by anthropogenic sedimentation (LRBS score = 0, Table 8). The majority of the study sites were impaired due to excess anthropogenic sedimentation (Figure 6).

The mean LRBS score was -1.52 and the range was -2.69 to 0.01 (Table 7). This range was limited, covering mainly the negative portion of the possible spectrum of scores, from stable to highly impaired due to excess sedimentation (Figure 4). The lack of positive LRBS scores signifies that there were no under-sedimented or armored streams in this study. A map of the study sites symbolized by LRBS score shows that there does not appear to be a pattern in the geographic distribution of LRBS scores (Figure 7).

LRBS scores were significantly ($p < 0.05$) correlated with the sediment composition metrics: LOBS_MSS ($r = -0.59$), percent sand ($r = 0.56$), percent fines ($r = 0.61$), and percent mean embeddedness ($r = 0.58$, Figure 8). These relatively high correlations confirmed a suspected confounding relationship between LRBS and sediment size composition metrics.

Selection of sediment composition metrics

The tiered correlation analysis procedure described above eliminated one sediment composition metric, percent silt, from further analysis based on failure to meet the established relationship criteria ($r \geq 0.4$, $p < 0.05$, Table 9) with macroinvertebrate metrics. Thus, the four remaining sediment composition metrics were LOBS_MSS, percent sand, percent fines, and percent mean embeddedness.

Relationships between sediment size, LRBS, and macroinvertebrate communities

The final list of 19 macroinvertebrate metrics, one sediment stability metric, and four sediment composition metrics is shown in Tables 6 and 9. Macroinvertebrate metrics that were highly correlated with LRBS were often highly correlated with sediment composition metrics (Table 10). An example is given in Figure 9, which shows the correlation of EPT-Hydropsychidae Richness with LRBS score, percent sand, percent fines, and percent mean embeddedness.

In some instances, metrics were correlated with either LRBS or sediment composition metrics, but not with both (Table 10). For example, percent partially armored taxa was correlated with LRBS ($r = 0.28$, $p < 0.05$) but not with any of the sediment composition metrics, while percent Ephemeroidea was correlated with all LOBS_MSS, percent sand, percent fines, and percent mean embeddedness ($r = -0.32, 0.39, 0.40$, and 0.35 , respectively, $p < 0.05$) but not with LRBS (Table 10).

The independence of the macroinvertebrate – sediment stability relationship

The relationship between a macroinvertebrate metric and LRBS was accepted as independent only if all four partial correlation relationships (one for each sediment composition metric) were significant at $p < 0.05$. None of the 19 selected macroinvertebrate metrics met this criterion (Table 11). However, when the significance criterion was relaxed to $p < 0.1$, percent Ephemeridae (a family of burrowing mayflies in the order Ephemeroptera), although they were not abundant in the samples (mean metric score = 0.001, Table 5), was related to LRBS even after independently removing the influence of each sediment composition metric (Table 11). Three other macroinvertebrate metrics were also related to LRBS, but not in a completely independent (i.e. across all four sediment composition metrics) and significant ($p < 0.1$) manner: EPT-Hydropsychidae richness, proportion of EPT-Hydropsychidae, and percent burrowers (Table 11).

Identifying the major drivers of macroinvertebrate community composition

The NMS ordination analysis produced a 2-dimensional solution with a final stress of 16, which represents a moderate amount of distortion of the original Sorenson distance matrix (McCune and Mefford 2006; Figure 10). The 2-dimensional solution explained 86% of the original Sorenson distance matrix (r^2 for linear correlations of axes 1 and 2: 0.37 and 0.50, respectively) (Figure 10).

The importance of taxa as drivers of the final ordination configuration depended on the axis (Table 12). Axis 2 was strongly correlated with the dipteran family Chironomidae ($r = -0.85$) (Figure 10) and the mayfly *Maccaffertium* spp. ($r = 0.70$, Table 12). Correlations of individual taxa with axis 1 were relatively weaker than with axis 2. The strongest taxa

correlations with axis 1 were with the order Hemiptera ($r = -0.62$) and the mayfly *Caenis* spp. ($r = -0.59$, Table 12).

The environmental variables (sediment composition and LRBS) were not strongly correlated with the ordination axes, but were relatively more strongly correlated with axis 2 than with axis 1 (Table 13). For example, the relationship between percent sand and axis 2 ($r = -0.46$) was stronger than percent sand and axis 1 ($r = -0.10$, Table 13). Ordination axes were more strongly correlated with sediment composition metrics than with LRBS, particularly with percent sand (Figure 10). For example, the strongest sediment correlations with axis 2 were with percent sand ($r = -0.46$) and percent fines ($r = -0.45$); for axis 1 the strongest correlation was with percent embeddedness ($r = -0.19$, Table 13). In comparison, LRBS exhibited the weakest correlation with overall community structure as evidenced by the lowest correlations with the ordination axes of all the sediment metrics ($r = 0.29$ for axis 2 and $r = 0.03$ for axis 1, Table 13).

Discussion

Sediment issues in the Piedmont region

The frequency of negative LRBS scores (indicating excess anthropogenic sedimentation) and the comparative lack of positive LRBS scores (which would have indicated bed armoring) suggest that Virginia's Piedmont streams typically lack stable sediment. Many streams were classified as unstable due to over-fining of the streambed and we did not encounter any streams with naturally high amounts of stable sediment. The highly sedimented stream conditions can be explained by the erosional geology and soil conditions of the region (Wiken et al. 2011, The College of William and Mary 1999) and by the history of land use conversions in this traditionally forested eco-region (Omernik 1987, Cole and Ware 1997, Gellis et al. 2009, Wiken et al. 2011).

Because of the extent of sedimentation-impacted stream miles, the random site selection scheme used in this study may not have captured the full picture of sediment issues in the region. Increasing the sample size by including additional streams may have increased the chance of showing stronger relationships between Relative Bed Stability and macroinvertebrate metrics. Also, specifically including known under-sedimented or armored systems and additional stable systems at equilibrium in the dataset would have increased the length of the Relative Bed Stability gradient and may have provided a more complete picture of sedimentation across the piedmont.

Sediment composition and macroinvertebrate communities

Sediment composition, in particular the proportion of fine sediment, was an important driver of macroinvertebrate community composition. Sediment composition is a well-known determinant of potential macroinvertebrate communities (Cummins and Lauff 1969, Minshall & Minshall 1977, Mebane 2001) and increasing amounts of fine sediment have been shown to have a range of impacts on macroinvertebrate communities (Angradi 1999, Bond and Downes 2003), typically resulting in decreased faunal abundance and diversity (Chou et al. 2004).

However, given the wide variation in tolerances, habitats, and modes of feeding among taxa, the effects of sedimentation are not observed universally, but are greater for some taxa than others (Richards et al. 1993). In this study, half of the original 31 macroinvertebrate metrics tested were related to the amount of fine sediment measured in streams, generally in a graded linear fashion similar to that reported by Angradi (1999).

The strongest relationships to sediment composition were seen in EPT taxa (a negative association) and burrowers (a positive association). EPT taxa are generally dependent on a heterogeneous, well-sorted substrate and intolerant of pollution and disturbance, and have been

identified as a reliable metric for their predictable declines in response to increasing fine sediment (Waters 1995, Angradi 1999, Mebane 2001, Freeman and Schorr 2004). Despite broad intolerance, some EPT families respond positively to increasing fine sediment (e.g., some taxa in the mayfly family Baetidae, Angradi 1999). In this study, individuals of the burrowing mayfly family Ephemeridae, although not abundant, responded positively to increasing fine sediment because they have morphological adaptations to cope with fine sediment. The low abundance of this taxon, and potentially other taxa naturally associated with fine sediment, may be confounded by the rapid sampling approach, which typically does not target low diversity areas like pools and backwater zones.

The dipteran family Chironomidae dominated most samples but was weakly, albeit significantly, positively correlated with fine sediment. This may be because the family Chironomidae is a large, taxonomically diverse group with a wide range of pollution tolerance that varies among different genera and species. Thus, the family-level identification may result in a loss of ecological information associated with lower levels of identification and obscure relationships to fine sediment resulting in difficulty detecting trends (Lenat 1990, Freeman and Schorr 2004). For example, Angradi (1999) found opposite trends at the sub-family level – a decrease in % Chironominae and an increase in % Orthoclaadiinae in response to increasing fine sediment. Relyea et al. (2000) also detected species-level responses to fine sediment, which would have been obscured by leaving identifications at higher taxonomic levels.

Overall, habit groups (e.g., burrowers and clingers) were more related to increasing fine sediment than feeding groups (e.g., scrapers and collector-gatherers). This finding was the opposite of a study by Rabeni et al. (2005) which suggested that sedimentation had stronger effects on individuals' method of food acquisition than on habit. This contrasting result may have

arisen because my study examined only two feeding groups while the study by Rabeni et al. (2005) examined a more complete assemblage (gatherers, predators, scrapers, shredders and filterers).

Sediment stability and macroinvertebrate communities

Macroinvertebrate community composition was also responsive to sediment stability as measured by LRBS scores. The strongest relationships to LRBS were again seen in EPT taxa (a positive association) and burrowers (a negative association). In all cases, those macroinvertebrate metrics that were related to LRBS were also moderately- to strongly-correlated with one or more sediment composition variables. Sediment composition is ecologically tied to macroinvertebrate community composition and mathematically integrated in the calculation of LRBS scores. Thus, it is not surprising that metrics that responded to fine sediment size also responded to the consequences of fine sediment such as inherent substrate instability. My primary objective however, was to determine if macroinvertebrate metrics were responsive specifically to excess fine sediment due to human activity and not just natural variation in fine sediment loads.

This study did not show any significant relationships between macroinvertebrate community metrics and sediment stability that were completely independent of all of the sediment composition metrics. This indicates that the macroinvertebrate community appears to be very responsive to the amount of fine sediment present in the stream system and that sediment composition is a strong driver of community structure – perhaps stronger than sediment stability. Rempel et al. (2000) also found that although mean sediment grain size (used in the calculation of the LRBS score) was identified as an important factor driving variation in taxonomic diversity, it did not affect taxa when the effects of all other physical variables (including percent fines) were held constant.

Despite the lack of significant independent relationships from the partial correlation analysis, there were some metrics that hold promise for future studies. The most promising metrics was percent Ephemeridae (order Ephemeroptera), which was significantly ($p < 0.1$) correlated with LRBS after removing the influence of sediment size. Given the unique response to LRBS, this and other potentially important metrics (EPT-Hydropsychidae and percent burrowers) may be valuable for managers as a proxy tool to make important distinctions about the anthropogenic origin of fine sediment pollution in streams.

Conclusion

Many streams in the Virginia Piedmont are impacted by human-induced sedimentation, as quantified by measurements of streambed stability. Sediment size composition (e.g. proportion of the substrate composed of sand-sized particles) and sediment stability are both important factors influencing benthic macroinvertebrate communities, but of the two, sediment composition was the stronger driver of community composition for our study sites. This finding is likely due to an overall lack of variability in bed sediment stability conditions in the region, rather than a lack of responsiveness of macroinvertebrate metrics to bed sediment stability. A non-random approach to adding more stable and under-sedimented stream channels would have increased the length of the Relative Bed Stability gradient and may have increased the strength of the macroinvertebrate – sediment stability relationships.

The use of macroinvertebrates to distinguish between natural and anthropogenic sedimentation is a promising area for future research. The most promising community metric to accomplish this distinction – the burrowing mayfly family Ephemeridae - was also one of the least collected taxa in the samples. I suggest using a macroinvertebrate sampling protocol that targets sedimented areas such as pools and backwater zones to capture natural-sediment dwellers

present in those areas that may not be captured by a rapid assessment sampling approach. Also, I recommend the identification of individuals to lower taxonomic levels; subfamily or genus-level identifications of Chironomidae in particular should be explored as potential indicators of human-induced fine sedimentation.

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Table 1. List and descriptions of macroinvertebrate community metrics describing overall community richness, pollution tolerance and sensitivity, diversity, and various ecological traits and their expected response to sedimentation.

Metric	Description	Response to Sedimentation
Richness & Tolerance		
Taxa Richness	Total number of taxa found in sample	(-)
EPT Richness	Number of Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa	(-)
Percent EPT	Proportion of the total number of taxa that are EPTs	(-)
EPT-Hydropsychidae Richness	Combined number of EPT taxa excluding Family Hydropsychidae	(-)
Percent EPT-Hydropsychidae	Proportion taxa that are EPT taxa excluding Family Hydropsychidae	(-)
Hilsenhoff Biotic Index	Average Hilsenhoff Biotic Index, a measure of pollution tolerance	(+)
Evenness & Diversity		
Percent Dominance	Proportion of the total number of individuals that are in the sample's most abundant family	(+)
Shannon Diversity Index	Diversity index that accounts for species richness and relative abundance.	(-)
Functional Feeding Group		
Scraper Richness	Number of taxa that feed by scraping substrate algae	(-)
Percent Scraper	Proportion of taxa that feed by scraping substrate algae	(-)
Collector-Gatherer Richness	Number of taxa that feed by collecting and/or gathering food particles	Variable
Percent Collector-Gatherer	Proportion of taxa that feed by collecting and/or gathering food particles	Variable
Habitat & Behavior		
Burrower Richness	Number of taxa with morphological adaptations for burrowing in substrate	(+)
Percent Burrower	Proportion of taxa with morphological adaptations for burrowing in substrate	(+)
Clinger Richness	Number of taxa with morphological adaptations for clinging to substrate	(-)
Percent Clinger	Proportion taxa with morphological adaptations for clinging to substrate	(-)
Fixed Retreat Richness	Number of taxa with morphological adaptations for building fixed retreats	(-)
Percent Fixed Retreat	Proportion of taxa with morphological adaptations for building fixed retreats	(-)
Sprawler Richness	Number of taxa with morphological adaptations for sprawling	(-)
Percent Sprawler	Proportion of taxa with morphological adaptations for building fixed retreats	(-)

Table 1 continued.

Morphology		
Fully Armored Richness	Number of taxa with hard shells or full-body sclerotization or other physically-armoring protection	(+)
Percent Fully Armored	Proportion of the total number of taxa with hard shells or full-body sclerotization or other physically-armoring protection	(+)
Partially Armored Richness	Number of taxa with partial sclerotization (e.g. covered gills) or other physically-armoring protection	Variable
Percent Partially Armored	Proportion of the total number of taxa with partial sclerotization (e.g. covered gills) or other physically-armoring protection	Variable
Associated with Sediment		
Percent Ceratopogonidae	Proportion of taxa in the family Ceratopogonidae (Order Diptera)	(+)
Percent Chironomidae	Proportion of taxa in the family Chironomidae (Order Diptera)	Variable
Percent Oligochaeta	Proportion of taxa in the subclass Oligochaeta	Variable
Percent Sphaeridae	Proportion of taxa in the family Sphaeridae (Class Bivalvia)	(+)
Percent Gomphidae	Proportion of taxa in the family Gomphidae (Order Odonata)	(+)
Percent Ephemeridae	Proportion of taxa in the family Ephemeridae (Order Ephemeroptera)	(+)
Percent Tipulidae	Proportion of taxa in the family Tipulidae (Order Diptera)	(+)

Table 2. List and descriptions of sediment composition and bedded sediment stability metrics and their expected response to sedimentation.

Variable	Description	Response to Sedimentation
Sediment composition		
OBS_MSS	Observed substrate median diameter (D_{50})	(-)
LOBS_MSS	Log_{10} (Observed substrate median diameter)	(-)
Percent sand	Proportion of particles 0.06-2 mm diameter	(+)
Percent silt	Proportion of particles <0.06 mm diameter	(+)
Percent fines	Proportion of particles <2 mm diameter	(+)
Percent mean embeddedness	Mean embeddedness of measured particles	(+)
Sediment stability		
RBS	Relative Bed Stability = D_{50} / D^*_{cbf}	(-)
LRBS	Log_{10} Relative Bed Stability = $\text{Log}_{10} D_{50} / \text{Log}_{10} D^*_{cbf}$	(-)

Note: D_{50} = observed substrate median diameter, D^*_{cbf} = critical substrate median diameter predicted to be mobilized at bankfull flow

Table 3. Summary statistics for physicochemical parameters. The number of sites (N) used to calculate summary statistics for each parameter varied due to issues with equipment malfunction.

Variable	N	Mean \pm 1 Standard Error	Range
Conductivity ($\mu\text{S}/\text{cm}$)	45	156 \pm 36	12 - 1240
Temperature ($^{\circ}\text{C}$)	45	15.9 \pm 0.8	5.93 - 25.42
pH	38	6.8 \pm 0.1	5.79 - 7.81
Dissolved Oxygen (mg/L)	48	8.4 \pm 0.2	2.8 - 10

Table 4. List of 167 identified taxa.

Ephemeroptera

- Ameletidae
 - Ameletus* sp.
- Baetidae
 - Acentrella* sp.
 - Acerpenna* sp.
 - Baetis* sp.
 - Centroptilum* sp.
 - Heterocleon* sp.
 - Plauditus* sp.
 - Procloeon* sp.
 - Pseudocloeon* sp.
 - Unidentified
- Baetiscidae
 - Baetisca* sp.
- Caenidae
 - Caenis* sp.
 - Cercobraccys* sp.
- Ephemerellidae
 - Attenella* sp.
 - Drunella* sp.
 - Ephemerella* sp.
 - Eurylophella* sp.
 - Seratella* sp.
 - unidentified
- Ephemeridae
 - Hexagenia* sp.
 - unidentified
- Heptageniidae
 - Epeorus* sp.
 - Heptagenia* sp.
 - Leucrocuta* sp.
 - Maccaffertium* sp.
 - Stenacron* sp.
 - unidentified
- Isonychiidae
 - Isonychia* sp.
- Leptophlebiidae
 - Leptophlebia* sp.
 - Paraleptophlebia* sp.
 - unidentified
- Siphonuridae
 - Siphonurus* sp.
- Tricorythidae
 - Tricorythodes* sp.

Plecoptera

- Capniidae
 - Allocapnia* sp.
 - unidentified
- Chloroperlidae
 - Haploperla* sp.
 - unidentified
- Leuctridae
 - Leuctra* sp.
- Nemouridae
 - Amphinemura* sp.
 - Prostoia* sp.
 - unidentified
- Peltoperlidae
 - Tallaperla* sp.
- Perlidae
 - Acroneuria* sp.
 - Eccoptura* sp.
 - Perlesta* sp.
- Perlodidae
 - Cliperla* sp.
 - Isoperla* sp.
 - Remenus* sp.
 - unidentified
- Pteronarcyidae
 - Pteronarcys* sp.

Trichoptera

- Brachycentridae
 - Brachycentrus* sp.
- Goeridae
 - Goera* sp.
- Hydropsychidae
 - Cheumatopsyche* sp.
 - Diplectrona modesta*
 - Hydropsyche* sp.
 - unidentified
- Hydroptilidae
 - Hydroptila* sp.
- Lepidostomatidae
 - Lepidostoma* sp.
- Leptoceridae
 - Nectopsyche* sp.
 - Oecetis* sp.
 - Trianodes* sp.
 - unidentified
- Limnophilidae
 - Ironoquia* sp.

Trichoptera cont.

- Pycnopsyche* sp.
- Philopotamidae
 - Chimarra* sp.
 - Dolophiodes* sp.
 - Wormaldia* sp.
 - unidentified
- Phryganeidae
 - Ptilostomis* sp.
- Planariidae
 - unidentified
- Polycentropodidae
 - Neureclipsis* sp.
 - Polydentropus* sp.
 - unidentified
- Psychomyiidae
 - Lype diversa*
- Rhyacophilidae
 - Rhyacophila* sp.
- Coleoptera**
- Dryopidae
 - Helichus* sp.
- Dytiscidae
 - Neoporus* sp.
 - unidentified
- Elmidae
 - Ancyronyx variegates*
 - Dubiraphia* spp.
 - Macronychus*
 - glabratus*
 - Microcylloepus* sp.
 - Optioservis* sp.
 - Oulimnius*
 - latiusculus*
 - Promeresia* sp.
 - Stenelmis* sp.
- Gyrinidae
 - Dineutes* sp.
 - Gyrinus* sp.
- Haliplidae
 - Peltodytes* sp.
- Hydrophilidae
 - Hydrobius* sp.
- Psephenidae
 - Ectopria nervosa*
 - Psephenus* sp.
- Ptilodactylidae
 - Anchytarsus bicolor*

Megaloptera

- Corydalidae
Corydalus cornutus
Nigronia fasciatus
Sialidae
Sialis sp.

Diptera

- Athericidae
Atherix sp.
Ceratopogonidae
Atrichopogon sp.
Bezzia sp.
Culicoides sp.
Probezzia sp.
Sphaeromias sp.
Chironomidae
unidentified
Culicidae
Aedes sp.
Anopheles sp.
Dixidae
Dixa sp.
Dixella sp.
Empididae
Hemerodromia sp.
Psychodidae
Pericoma sp.
Simuliidae
unidentified
Tabanidae
Chrysops sp.
Tipulidae
Antocha sp.
Dicranota sp.
Hexatoma sp.
Ormosia sp.
Pilaria sp.
Pseudolimnophila sp.
Tipula abdominalis
Tipula spp.
unidentified

Odonata

- Aeshnidae
Basiaeschna sp.
Boyeria vinosa
Calopterygidae
Calopteryx sp.
unidentified
Coenagrionidae
Argia sp.
Enallagma sp.
Ischnura sp.
Cordulegastridae
Cordulegaster sp.
Corduliidae
Epicordulia sp.
unidentified
Gomphidae
Dromogomphus sp.
Gomphus sp.
Hagenius brevistylus
Lanthus sp.
Ophiogomphus spp.
Progomphus sp.
Stylogomphus sp.
unidentified
Lestidae
Lestes
Libellulidae
Pachydiplax
longipennis
Perithemis sp.
unidentified
Macromiidae
Macromia sp.

Hemiptera

- Corixidae
unidentified

Isopoda

- Asellidae
Caecidotea sp.

Decapoda

- Cambaridae
Cambarus sp.
Orconectes sp.
unidentified

Amphipoda

- Crangonyctidae
Crangonyx sp.
Gammaridae
Gammarus sp.
Hyaellidae (Talitridae)
Hyaella azteca

Annelida

- Lumbriculidae
Oligochaeta

Bivalvia

- Corbiculidae
Corbicula fluminea
Speridae
unidentified
Sphaeriidae
Pisidium sp.
Sphaerium sp.

Gastropoda

- Ancylidae (Planorbidae)
Ferrissia sp.
Hydrobiidae
unidentified
Lymnaeidae
Lymnaea sp.
Physidae
Physella sp.
Planorbidae
Helisoma sp.
Menetus sp.
Leptoxis sp.
Pleurocera sp.
Viviparidae
Campeloma sp.

Nematoda

Table 5. Summary statistics for macroinvertebrate metrics.

Metric	Mean \pm 1 Standard Error	Range
Taxa Richness	23.2 \pm 0.8	14 - 35
EPT Richness*	9.8 \pm 0.5	2 - 22
Percent EPT*	0.4 \pm 0.0	0.1 - 0.7
EPT-Hydropsychidae Richness*	8.4 \pm 0.5	2 - 20
Percent EPT-Hydropsychidae*	0.4 \pm 0.0	0.1 - 0.7
Hilsenhoff Biotic Index*	5.6 \pm 0.1	2.8 - 7.1
Percent Dominance*	0.5 \pm 0.0	0.1 - 0.8
Shannon Diversity Index*	8.2 \pm 0.5	2.6 - 20
Scraper Richness*	3.8 \pm 0.2	1 - 7
Percent Scraper	0.2 \pm 0.0	0.1 - 0.3
Collector-Gatherer Richness	6.7 \pm 0.4	2 - 13
Percent Collector-Gatherer	0.4 \pm 0.0	0.1 - 0.8
Burrower Richness*	7.7 \pm 0.4	3 - 14
Percent Burrower*	0.3 \pm 0.0	0.2 - 0.7
Clinger Richness*	12.8 \pm 0.6	3 - 23
Percent Clinger*	0.6 \pm 0.0	0.2 - 0.8
Fixed Retreat Richness	0.8 \pm 0.1	0 - 3
Percent Fixed Retreat	0.01 \pm 0.0	0 - 0.1
Sprawler Richness	2.6 \pm 0.2	0 - 6
Percent Sprawler	0.1 \pm 0.0	0 - 0.2
Fully Armored Richness	5.9 \pm 0.3	2 - 11
Percent Fully Armored	0.3 \pm 0.0	0.1 - 0.4
Partially Armored Richness*	13.2 \pm 0.6	6 - 27
Percent Partially Armored*	0.6 \pm 0.0	0.3 - 0.8
Percent Ceratopogonidae*	0.01 \pm 0.0	0 - 0.1
Percent Chironomidae*	0.4 \pm 0.0	0.0 - 0.8
Percent Oligochaeta	0.02 \pm 0.0	0 - 0.3
Percent Sphaeridae*	0.01 \pm 0.0	0 - 0.2
Percent Gomphidae*	0.01 \pm 0.0	0 - 0.1
Percent Ephemerae*	0.001 \pm 0.0	0 - 0.01
Percent Tipulidae	0.008 \pm 0.0	0 - 0.03

* These metrics were selected for inclusion in the analysis based on the tiered correlation analysis described in the methods.

Table 6. Macroinvertebrate metrics were excluded from the analysis if their relationship to LRBS scores was nonlinear, weak ($r < 0.4$), or not significant (p -value > 0.05). Metric descriptions are given in Table 1.

Metric	Reason(s) for Exclusion
Richness & Tolerance	
Taxa Richness	Weak, non-significant relationship
EPT Richness	n/a
Percent EPT	n/a
EPT-Hydropsychidae Richness	n/a
Percent EPT-Hydropsychidae	n/a
Hilsenhoff Biotic Index	n/a
Evenness & Diversity	
Percent Dominance	n/a
Shannon-Wiener Diversity Index	n/a
Functional Feeding Group	
Scraper Richness	n/a
Percent Scraper	Weak relationships
Collector-Gatherer Richness	Weak, non-significant relationship
Percent Collector-Gatherer	Weak, non-significant relationship
Habitat & Behavior	
Burrower Richness	n/a
Percent Burrower	n/a
Clinger Richness	n/a
Percent Clinger	n/a
Fixed Retreat Richness	Weak relationships
Percent Fixed Retreat	Weak relationships
Sprawler Richness	Weak, non-significant relationship
Percent Sprawler	Weak relationships
Morphology	
Fully Armored Richness	Weak, non-significant relationship
Percent Fully Armored	n/a
Partially Armored Richness	n/a
Percent Partially Armored	n/a
Associated with Sediment	
Percent Ceratopogonidae	n/a
Percent Chironomidae	Weak relationships
Percent Oligochaeta	Weak relationships
Percent Sphaeridae	n/a
Percent Gomphidae	n/a
Percent Ephemeridae	n/a
Percent Tipulidae	Weak relationships

Table 7. Summary statistics for sediment stability and sediment composition metrics.

Variable	Mean \pm 1 Standard Error	Range
RBS	0.07 \pm 0.02	0.00 - 1.02
LRBS*	-1.52 \pm 0.08	-2.69 - 0.01
Log (Observed Median Sediment Size) (m) *	0.31 \pm 0.11	-1.41 - 2.33
Percent sand (size 0.06-2 mm) *	0.46 \pm 0.03	0.08 - 0.95
Percent silt (size <0.06 mm)	0.10 \pm 0.02	0.00 - 0.58
Percent fines (size <2 mm) *	0.56 \pm 0.04	0.08 - 1.00
Percent mean embeddedness*	0.70 \pm 0.03	0.27 - 1.00

* These metrics were selected for inclusion in the analysis based on the tiered correlation analysis described in the methods.

Table 8. Stream bed sediment composition, sediment stability and stream slope by site. For site location, refer to map in Figure 2.

Site	Slope	LRBS	% Bedrock	% Boulder	% Cobble	% Coarse Gravel	% Fine Gravel	% Sand	% Silt	% Mean embedded.
JA01-02	1.19	0.01	0.37	0.09	0.19	0.14	0.14	0.08	0.00	26.9
JA02-02	0.40	-0.90	0.11	0.01	0.11	0.25	0.20	0.30	0.01	64.5
JA04-02	0.35	-0.97	0.08	0.04	0.13	0.26	0.13	0.27	0.11	56.5
JA05-03	0.48	-1.29	0	0.01	0.03	0.35	0.08	0.52	0.01	70.8
JA07-01	0.41	-2.28	0	0.02	0.03	0.03	0.14	0.61	0.17	76.1
JA09-02	0.78	-2.22	0	0.01	0.03	0.05	0.17	0.62	0.12	81.3
JA10-04	0.82	-1.65	0	0.01	0.03	0.22	0.22	0.42	0.10	56.4
JA13-04	0.35	-2.69	0	0.01	0	0	0.03	0.77	0.19	97.3
JA15-02	2.77	-2.43	0	0	0	0.01	0.09	0.75	0.15	98.0
JA16-03	0.40	-1.99	0	0	0	0.02	0.26	0.68	0.04	88.2
JA18-01	0.20	-2.08	0	0	0	0	0.01	0.95	0.04	96.9
JA19-02	0.30	-1.82	0	0	0.06	0.07	0.16	0.64	0.07	88.7
JA22-03	0.77	-2.03	0	0	0.01	0.05	0.02	0.55	0.37	98.2
JA24-01	0.22	-1.24	0	0	0	0	0.03	0.78	0.18	97.8
JA25-02	0.50	-1.19	0	0.06	0.07	0.10	0.14	0.44	0.20	78.4
JA26-03	0.27	-1.87	0	0.01	0.01	0.01	0.27	0.60	0.09	79.6
JA27-03	0.16	-2.54	0	0	0	0	0	0.42	0.58	100.0
JA30-04	0.25	-1.76	0	0	0	0.04	0.35	0.57	0.05	72.0
JA31-02	0.71	-1.74	0	0	0	0.14	0.31	0.49	0.05	74.5
JA32-03	0.21	-2.06	0.11	0	0.01	0	0.01	0.53	0.33	86.4
JA33-04	0.43	-1.21	0	0	0.21	0.30	0.08	0.30	0.11	64.5
JM07-01	2.21	-1.83	0.05	0.10	0.12	0.07	0.10	0.57	0	66.0
JM12-04	0.40	-0.85	0.05	0.07	0.19	0.15	0.32	0.22	0	33.5
JM13-01	1.50	-1.37	0.03	0.22	0.11	0.07	0.18	0.39	0	58.4
JM17-03	1.11	-1.89	0	0	0.12	0.20	0.12	0.38	0.19	64.0
JM18-03	1.04	-1.23	0	0.00	0.13	0.31	0.32	0.22	0.02	33.7
JM19-02	0.28	-0.72	0.06	0.10	0.17	0.24	0.17	0.26	0.01	58.3
JM20-01	0.77	-0.85	0.15	0.13	0.13	0.17	0.18	0.18	0.07	44.7
JM23-04	1.42	-1.62	0	0.08	0.24	0.16	0.09	0.44	0	53.5
JM26-02	0.53	-0.90	0.21	0.01	0.13	0.12	0.09	0.44	0	57.5
JM27-02	0.63	-2.03	0.01	0.04	0.11	0.05	0.02	0.75	0.03	86.7
JM31-02	2.74	-0.53	0.19	0.42	0.15	0.07	0	0.17	0.00	31.7
JM37-01	0.79	-0.86	0.03	0.19	0.35	0.19	0.04	0.19	0.02	42.0
JM42-02	0.52	-0.87	0.01	0.13	0.19	0.29	0.05	0.31	0.02	60.7
JM48-03	0.67	-1.36	0	0	0.19	0.31	0.01	0.43	0.06	68.0
JM50-01	0.45	-1.20	0.02	0.04	0.22	0.22	0.20	0.24	0.07	63.4
JM51-03	0.95	-0.74	0.05	0.12	0.17	0.29	0.22	0.14	0.00	43.0
JM52-01	0.34	-1.14	0.05	0.02	0.10	0.36	0.03	0.30	0.13	59.8
JM53-01	0.15	-1.97	0	0	0.04	0.15	0.12	0.31	0.39	84.9
JM55-03	0.34	-0.87	0.08	0.05	0.19	0.22	0.15	0.23	0.08	51.0
JM58-03	0.82	-1.92	0.02	0.16	0.21	0.10	0.09	0.11	0.31	62.3
JM64-02	0.10	-1.67	0	0.02	0.02	0.02	0.10	0.75	0.08	82.6
JM65-01	0.37	-1.85	0	0	0.14	0.16	0.06	0.43	0.21	75.3
JM66-02	1.31	-0.69	0.10	0.29	0.16	0.06	0.18	0.21	0.00	46.3
JM70-02	0.19	-1.45	0	0	0	0.08	0.39	0.49	0.04	70.0
JM71-05	0.27	-1.60	0	0	0.01	0.11	0.25	0.59	0.04	80.1
JM74-01	0.49	-2.20	0	0.03	0	0	0.02	0.92	0.03	92.9
JM75-01	0.37	-1.78	0.04	0.01	0.02	0.13	0.20	0.49	0.12	72.4
JM77-02	0.12	-1.62	0.01	0.02	0.01	0.00	0.16	0.63	0.17	86.2
JM82-01	0.29	-1.73	0	0	0.05	0.09	0.17	0.61	0.09	82.4

Table 9. Sediment composition metrics metrics were excluded from the analysis if their relationship to the selected macroinvertebrate metrics (see Table 5) were nonlinear, weak ($r < 0.4$), or not significant ($p\text{-value} > 0.05$). Metric descriptions are given in Table 1.

Metric	Reason(s) for Exclusion
Sediment composition	
OBS_MSS	non-linear relationships
LOBS_MSS	n/a
Percent sand	n/a
Percent silt	Weak relationships
Percent fines	n/a
Percent mean embeddedness	n/a
Sediment stability	
RBS	non-linear relationships
LRBS	n/a

Table 10. Pairwise correlations of macroinvertebrate metrics with sediment stability (LRBS) and sediment composition metrics. Metrics are listed in order of strongest correlations with LRBS.

		LRBS	Log Obs. Sed. Size	Percent Sand	Percent Fines	Percent Mean Embeddedness
Percent Burrower	r	-0.54	-0.59	0.56	0.61	0.58
	p-value	0.00006*	0.00001*	0.00003*	0.00000*	0.00001*
EPT-Hydropsychidae		0.46	0.46	-0.44	-0.49	-0.52
Richness		0.00075*	0.00077*	0.00177*	0.00036*	0.00013*
EPT Richness		0.45	0.46	-0.47	-0.49	-0.53
		0.00119*	0.00091*	0.00072*	0.00032*	0.00008*
Percent EPT- Hydropsychidae		0.44	0.45	-0.39	-0.45	-0.48
		0.00146*	0.00123*	0.00509*	0.00103*	0.00042*
Percent EPT		0.43	0.45	-0.44	-0.46	-0.51
		0.00210*	0.00125*	0.00153*	0.00084*	0.00016*
Clinger Richness		0.38	0.46	-0.45	-0.47	-0.47
		0.00656*	0.00083*	0.00112*	0.00068*	0.00057*
Percent Clinger		0.37	0.50	-0.44	-0.46	-0.48
		0.00970*	0.00027*	0.00158*	0.00097*	0.00044*
Hilsenhoff Biotic Index		-0.37	-0.43	0.51	0.49	0.49
		0.00928*	0.00230*	0.00020*	0.00031*	0.00040*
Shannon Diversity Index		0.35	0.35	-0.40	-0.42	-0.39
		0.01240*	0.01392*	0.00405*	0.00254*	0.00560*
Partially Armored Richness		0.33	0.27	-0.28	-0.31	-0.33
		0.01927*	0.05928	0.04852*	0.03229*	0.01919*
Burrower Richness		-0.33	-0.40	0.36	0.39	0.39
		0.01938*	0.00423*	0.01141*	0.00554*	0.00625*
Percent Ceratopogonidae		-0.32	-0.31	0.40	0.33	0.29
		0.02390*	0.03253*	0.00487*	0.02014*	0.04229*
Percent Partially Armored		0.28	0.21	-0.22	-0.22	-0.27
		0.04662*	0.14977	0.13270	0.12590	0.06427
Percent Dominance		-0.28	-0.25	0.35	0.33	0.28
		0.05039	0.08581	0.01237*	0.02136*	0.04873*
Percent Chironomidae		-0.27	-0.31	0.38	0.38	0.34
		0.05688	0.02897*	0.00668*	0.00719*	0.01851*
Scraper Richness		0.25	0.30	-0.45	-0.35	-0.33
		0.08291	0.03398*	0.00116*	0.01497*	0.02235*
Percent Sphaeridae		-0.20	-0.27	0.33	0.30	0.31
		0.16495	0.05864	0.02017*	0.03739*	0.02891*
Percent Gomphidae		-0.18	-0.30	0.32	0.31	0.26
		0.21637	0.03563*	0.02625*	0.02790*	0.07180*
Percent Ephemeridae		-0.11	-0.32	0.39	0.40	0.35
		0.45569	0.02561*	0.00628*	0.00483*	0.01305*

*Significant at $\alpha = 0.05$

Table 11. Partial correlations of the relationships between macroinvertebrate metrics and LRBS holding constant each of the sediment composition metrics. The notation "LRBS | Percent Sand" means LRBS partialing out the effect of percent sand.

LRBS		Log Obs. Sed. Size	Percent Sand	Percent Fines	Percent Mean Embeddedness
Percent Burrower	r	-0.06	-0.25	-0.06	-0.15
	p	0.66195	0.08362†	0.69164	0.28825
EPT-Hydropsychidae Richness		0.14	0.25	0.10	0.09
		0.34676	0.08609†	0.47287	0.52459
EPT Richness		0.11	0.19	0.06	0.04
		0.44370	0.18809	0.66307	0.77996
Percent EPT-Hydropsychidae		0.12	0.25	0.12	0.10
		0.43064	0.08075†	0.42448	0.48610
Percent EPT		0.09	0.19	0.08	0.03
		0.55730	0.20296	0.60807	0.82380
Clinger Richness		-0.05	0.10	-0.04	0.00
		0.74223	0.48683	0.80074	0.97852
Percent Clinger		-0.17	0.09	-0.05	-0.04
		0.25247	0.55129	0.72265	0.77842
Hilsenhoff Biotic Index		0.01	-0.02	0.12	0.04
		0.94820	0.91692	0.41577	0.77426
Shannon Diversity Index		0.11	0.11	-0.01	0.08
		0.45848	0.46177	0.93678	0.60534
Partially Armored Richness		0.21	0.20	0.14	0.12
		0.15629	0.17675	0.32086	0.42486
Burrower Richness		0.04	-0.12	0.00	-0.04
		0.77845	0.40907	0.99596	0.76912
Percent Ceratopogonidae		-0.12	-0.07	-0.08	-0.16
		0.41694	0.65386	0.58115	0.28717
Percent Partially Armored		0.22	0.19	0.19	0.12
		0.13383	0.18917	0.19112	0.39240
Percent Dominance		-0.14	-0.05	0.00	-0.09
		0.34873	0.75357	0.98881	0.51987
Percent Chironomidae		0.00	-0.01	0.10	-0.01
		0.99036	0.96950	0.47836	0.95460
Scraper Richness		-0.03	-0.11	-0.09	-0.02
		0.82151	0.46112	0.52975	0.89106
Percent Sphaeridae		0.08	0.05	0.11	0.09
		0.59409	0.74133	0.46516	0.48862
Percent Gomphidae		0.18	0.07	0.18	0.05
		0.21474	0.65116	0.21876	0.73552
Percent Ephemeridae		0.37	0.25	0.48	0.31
		0.00900*†	0.08368†	0.00049*†	0.02941*†

*Significant at $\alpha = 0.05$, †Significant at $\alpha = 0.1$

Table 12. Pearson product moment correlations between NMS ordination axes and macroinvertebrate taxa (N=49).

Taxa	Axis 1		Taxa	Axis 2	
	r	r ²		r	r ²
Hempitera	-0.62	0.39	Chironomidae	-0.85	0.72
Caenis sp.	-0.59	0.35	Maccaffertium spp.	0.70	0.49
Tipulidae	-0.56	0.32	Chimarra sp.	0.56	0.31
Oligochaetae	-0.56	0.31	Isonychia sp.	0.50	0.25
Dubiraphia spp.	-0.55	0.30	Cheumatopsyche sp.	0.47	0.22
Pisidium sp.	-0.54	0.29	Leucocuta sp.	0.45	0.20
Macromia sp.	-0.54	0.29	Pteronarcys sp.	0.45	0.20
Aedes sp.	-0.49	0.24	Oulimnius latiusculus	0.43	0.19
Menetus sp.	-0.48	0.24	Neureclipsis sp.	0.40	0.16
Ephemerella spp.	0.44	0.19	Orconectes sp.	0.39	0.15
Dolophiodes sp.	0.42	0.18	Dicranota sp.	0.39	0.15
Lymnaea sp.	-0.42	0.18	Optioservis sp.	0.38	0.14
Peltodytes sp.	-0.41	0.17	Hydropsyche sp.	0.36	0.13
Nectopsyche sp.	-0.41	0.17	Acroneuria sp.	0.35	0.12
Hyaella azteca	-0.41	0.17	Leuctra sp.	0.34	0.12
Helisoma sp.	-0.41	0.17	Wormaldia sp.	0.33	0.11
Argia sp.	-0.39	0.15	Ephemerellidae	0.33	0.11
Atrichopogon sp.	-0.38	0.15	Corydalus cornutus	0.31	0.10
Pericoma spp.	-0.38	0.15	Polycentropus sp.	0.31	0.10
Drunella sp.	0.37	0.13	Nigronia fasciatus	0.30	0.09
Chloroperlidae	0.37	0.13	Bezzia spp.	-0.30	0.09
Epicordulia sp.	-0.36	0.13	Psephenus sp.	0.28	0.08
Lestes sp.	-0.36	0.13	Amphinemura sp.	-0.24	0.06
Hydrobius sp.	-0.36	0.13	Gammarus sp.	0.23	0.05
Simuliidae	0.36	0.13	Anopheles sp.	-0.23	0.05
Ephemerellidae	0.36	0.13	Dineutes sp.	-0.22	0.05
Ptilostomis sp.	-0.36	0.13	Centroptilum sp.	-0.22	0.05
Wormaldia sp.	0.36	0.13	Epeorus sp.	0.22	0.05
Ischnura sp.	-0.35	0.12	Calopteryx sp.	-0.22	0.05
Leptoceridae	-0.35	0.12	Eurylophella temporalis	-0.22	0.05
Acentrella sp.	0.34	0.12	Hemerodromia sp.	0.21	0.05
Heptageniidae	0.34	0.11	Allocapnia sp.	0.21	0.05
Tipula abdominalis	0.32	0.10	Probezzia sp.	-0.21	0.05
Stylogomphus sp.	0.29	0.08	Hexatoma sp.	-0.21	0.04
Planariidae	-0.29	0.08	Corixidae	0.20	0.04
Enallagma sp.	-0.28	0.08	Antocha sp.	0.19	0.04
Pteronarcys sp.	0.28	0.08	Oligochaetae	-0.19	0.04
Microcyloepus sp.	-0.27	0.07	Calopterygidae	0.19	0.04

Epeorus sp.	0.26	0.07	Nemouridae	0.19	0.04
Corduliidae	-0.26	0.07	Lype diversa	-0.19	0.04
Procloeon spp.	0.26	0.07	Tipula abdominalis	0.19	0.04
Ancyronyx variegatus	-0.25	0.06	Dolophiodes sp.	0.19	0.04
Eccoptura xanthenes	0.24	0.06	Ectopria nervosa	0.18	0.03
Amphinemura sp.	0.23	0.05	Baetis sp.	0.18	0.03
Paraleptophlebia sp.	-0.21	0.05	Ironoquia sp.	-0.18	0.03
Nematoda	0.22	0.05	Seratella sp.	0.18	0.03
Dixa sp.	0.20	0.04	Progomphus obscurus	-0.18	0.03
Leptophlebiidae	0.20	0.04	Crangonyx sp.	-0.17	0.03
Taeniopteryx sp.	-0.19	0.04	Culicoides sp.	-0.17	0.03
Polycentropodidae	-0.19	0.04	Gomphus sp.	-0.17	0.03
Cambaridae	0.19	0.03	Hydroptila sp.	-0.17	0.03
Baetisca sp.	-0.18	0.03	Pisidium sp.	-0.17	0.03
Attenella sp.	-0.18	0.03	Tallaperla sp.	0.17	0.03
Dineutes sp.	-0.17	0.03	Diplectrona modesta	0.17	0.03
Leucrocuta sp.	-0.17	0.03	Plauditus spp.	-0.16	0.03
Calopteryx sp.	-0.16	0.03	Drunella sp.	0.16	0.03
Nemouridae	-0.16	0.02	Chloroperlidae	0.16	0.03
Anopheles sp.	-0.15	0.02	Speridae	-0.16	0.03
Sialis sp.	-0.15	0.02	Basiaeschna sp.	-0.16	0.03
Calopterygidae	-0.15	0.02	Leptoceridae	-0.16	0.03
Acroneuria sp.	0.14	0.02	Gomphidae	-0.16	0.02
Clioperla clio	0.15	0.02	Heterocleon sp.	-0.15	0.02
Chironomidae	0.14	0.02	Heptageniidae	0.15	0.02
Ophiogomphus spp.	0.14	0.02	Dubiraphia spp.	-0.15	0.02
Hemerodromia sp.	-0.14	0.02	Pilaria sp.	-0.15	0.02
Sphaerium sp.	0.13	0.02	Brachycentrus sp.	-0.15	0.02
Isonychia sp.	0.14	0.02	Tricorythodes sp.	0.14	0.02
Hagenius brevistylus	0.13	0.02	Physella sp.	-0.14	0.02
Philopotamidae	0.13	0.02	Prostoia sp.	-0.14	0.02
Ferrissia sp.	-0.13	0.02	Helichus sp.	-0.13	0.02
Maccaffertium spp.	0.13	0.02	Hydrobius sp.	-0.13	0.02
Probezzia sp.	-0.12	0.02	Ameletus sp.	-0.13	0.02
Plauditus spp.	0.12	0.02	Ophiogomphus spp.	0.13	0.02
Centropilum sp.	-0.11	0.01	Sphaeromias sp.	-0.13	0.02
Perlesta sp.	0.12	0.01	Stenacron sp.	0.13	0.02
Lepidostoma sp.	-0.12	0.01	Siphonurus sp.	-0.13	0.02
Oecetis sp.	-0.11	0.01	Campeloma sp.	-0.13	0.02
Physella sp.	-0.11	0.01	Perithemis sp.	-0.13	0.02
Caacidotea sp.	-0.11	0.01	Chrysops sp.	0.13	0.02
Tricorythodes sp.	-0.10	0.01	Heptagenia sp.	-0.13	0.02
Pycnopsyche sp.	0.10	0.01	Paraleptophlebia sp.	0.13	0.02

Boyeria vinosa	-0.10	0.01	Hexagenia sp.	-0.12	0.02
Orconectes sp.	0.09	0.01	Menetus sp.	-0.12	0.02
Dytiscidae	-0.08	0.01	Haploperla sp.	-0.12	0.02
Anchytarsus bicolor	-0.09	0.01	Stenelmis sp.	0.12	0.01
Chrysops sp.	0.09	0.01	Tipulidae	-0.12	0.01
Seratella sp.	0.09	0.01	Procloeon spp.	0.12	0.01
Stenelmis sp.	-0.08	0.01	Pachydiplax longipenis	-0.11	0.01
Cambarus sp.	0.08	0.01	Libelluliidae/Corduliidae	-0.11	0.01
Hexagenia sp.	-0.08	0.01	Goera sp.	-0.12	0.01
Gomphus sp.	-0.08	0.01	Aedes sp.	-0.11	0.01
Progomphus obscurus	-0.08	0.01	Sialis sp.	-0.11	0.01
Prostoia sp.	0.08	0.01	Pycnopsyche sp.	-0.11	0.01
Ironoquia sp.	0.08	0.01	Cambaridae	0.11	0.01
Stenacron sp.	-0.07	0.01	Pseudolimnophila sp.	0.10	0.01
Atherix sp.	-0.07	0.00	Ephemerella spp.	-0.10	0.01
Dicranota sp.	-0.06	0.00	Stylogomphus sp.	0.11	0.01
Ameletus sp.	0.06	0.00	Dytiscidae	-0.10	0.01
Acerpenna sp.	0.06	0.00	Acentrella sp.	0.10	0.01
Cercobracys sp.	-0.07	0.00	Baetidae	-0.10	0.01
Hydrobiidae	-0.07	0.00	Leptophlebiidae	0.10	0.01
Isoperla sp.	0.06	0.00	Ferrissia sp.	-0.10	0.01
Oulimnius latiusculus	0.05	0.00	Acerpenna sp.	-0.10	0.01
Bezzia spp.	-0.06	0.00	Leptoxis sp.	0.10	0.01
Hexatoma sp.	0.05	0.00	Macronychus glabratus	0.09	0.01
Pilaria sp.	-0.05	0.00	Promeresia sp.	-0.09	0.01
Pleurocera sp.	0.06	0.00	Helisoma sp.	0.09	0.01
Cordulegaster sp.	-0.06	0.00	Simuliidae	-0.09	0.01
Crangonyx sp.	0.05	0.00	Baetisca sp.	0.09	0.01
Corbicula fluminea	0.05	0.00	Hemiptera	0.08	0.01
Sphaeromias sp.	0.05	0.00	Corduliidae	0.09	0.01
Dixella sp.	0.05	0.00	Planariidae	0.08	0.01
Antocha sp.	0.04	0.00	Atrichopogon sp.	0.08	0.01
Pseudocloeon sp.	0.04	0.00	Pericoma spp.	0.08	0.01
Baetidae	-0.04	0.00	Cordulegaster sp.	-0.08	0.01
Ephemeridae	-0.04	0.00	Isoperla sp.	-0.08	0.01
Leptophlebia sp.	0.04	0.00	Corbicula fluminea	-0.07	0.01
Siphonurus sp.	0.05	0.00	Dixa sp.	0.07	0.01
Pachydiplax longipenis	-0.04	0.00	Leptophlebia sp.	-0.07	0.01
Perithemis sp.	0.05	0.00	Lymnaea sp.	-0.07	0.01
Libelluliidae/Corduliidae	-0.04	0.00	Caecidotea sp.	-0.07	0.01
Leuctra sp.	0.05	0.00	Polycentropodidae	0.07	0.01
Trianodes sp.	-0.04	0.00	Gyrinus sp.	-0.07	0.00
Speridae	0.04	0.00	Ormosia sp.	-0.07	0.00

Neoporus sp.	-0.02	0.00	Lanthus sp.	0.06	0.00
Macronychus glabratus	-0.03	0.00	Clioperla clio	-0.07	0.00
Optioservis sp.	-0.03	0.00	Ancyronyx variegatus	-0.05	0.00
Gyrinus sp.	0.03	0.00	Capniidae	-0.06	0.00
Psephenus sp.	0.04	0.00	Perlodidae	-0.05	0.00
Culicoides sp.	-0.04	0.00	Atherix sp.	0.04	0.00
Ormosia sp.	0.03	0.00	Dixella sp.	0.04	0.00
Heterocleon sp.	0.04	0.00	Pseudocloeon sp.	-0.05	0.00
Eurylophella temporalis	0.04	0.00	Attenella sp.	-0.05	0.00
Heptagenia sp.	-0.03	0.00	Hydrobiidae	0.04	0.00
Corydalus cornutus	-0.04	0.00	Argia sp.	-0.05	0.00
Nigronia fasciatus	-0.03	0.00	Epicordulia sp.	-0.04	0.00
Dromogomphus sp.	-0.03	0.00	Ischnura sp.	-0.04	0.00
Lanthus sp.	0.03	0.00	Lestes sp.	-0.04	0.00
Allocapnia sp.	-0.02	0.00	Lepidostoma sp.	-0.04	0.00
Haploperla sp.	-0.03	0.00	Oecetis sp.	0.04	0.00
Perlodidae	-0.03	0.00	Hyaella azteca	-0.03	0.00
Tallaperla sp.	0.03	0.00	Microcyllloepus sp.	-0.03	0.00
Diplectrona modesta	-0.03	0.00	Peltodytes sp.	-0.03	0.00
Hydropsyche sp.	0.04	0.00	Cambarus sp.	-0.04	0.00
Lype diversa	0.04	0.00	Tipula sp.	-0.03	0.00
Polycentropus sp.	-0.04	0.00	Caenis sp.	-0.04	0.00
Gammarus sp.	-0.01	0.00	Nematoda	-0.03	0.00
Helichus sp.	-0.01	0.00	Boyeria vinosa	-0.03	0.00
Promeresia sp.	0.00	0.00	Macromia sp.	-0.03	0.00
Ectopria nervosa	0.02	0.00	Perlesta sp.	0.03	0.00
Pseudolimnophila sp.	0.01	0.00	Hydropsychidae	0.04	0.00
Tipula sp.	0.01	0.00	Nectopsyche sp.	0.03	0.00
Baetis sp.	-0.01	0.00	Ptilostomis sp.	0.03	0.00
Leptoxis sp.	0.02	0.00	Sphaerium sp.	-0.01	0.00
Campeloma sp.	0.01	0.00	Neoporus sp.	-0.01	0.00
Corixidae	-0.02	0.00	Anchytarsus bicolor	-0.02	0.00
Basiaeschna sp.	-0.02	0.00	Cercobracys sp.	0.01	0.00
Gomphidae	0.01	0.00	Ephemeridae	-0.01	0.00
Capniidae	-0.02	0.00	Pleurocera sp.	-0.02	0.00
Brachycentrus sp.	0.00	0.00	Enallagma sp.	-0.01	0.00
Goera sp.	-0.01	0.00	Dromogomphus sp.	0.01	0.00
Cheumatopsyche sp.	-0.01	0.00	Hagenius brevistylus	-0.01	0.00
Hydroptila sp.	0.01	0.00	Eccoptura xanthenes	-0.02	0.00
Hydropsychidae	-0.02	0.00	Taeniopteryx sp.	-0.02	0.00
Chimarra sp.	0.00	0.00	Trianodes sp.	0.02	0.00
Neureclipsis sp.	0.01	0.00	Philopotamidae	-0.01	0.00

Table 13. Pearson product moment correlations between NMS ordination axes and sediment size composition and LRBS (N=49). For explanation of variables see Table 2.

	Axis 1	Axis 2
LRBS	r = 0.03	r = 0.29
LOBS_MSS	0.11	0.39
% Sand	-0.10	-0.46
% Fines	-0.12	-0.45
% Embeddedness	-0.19	-0.41

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Figure 1. Physiographic provinces of Virginia. The Piedmont region (shown in brown) is the primary study area of this investigation.

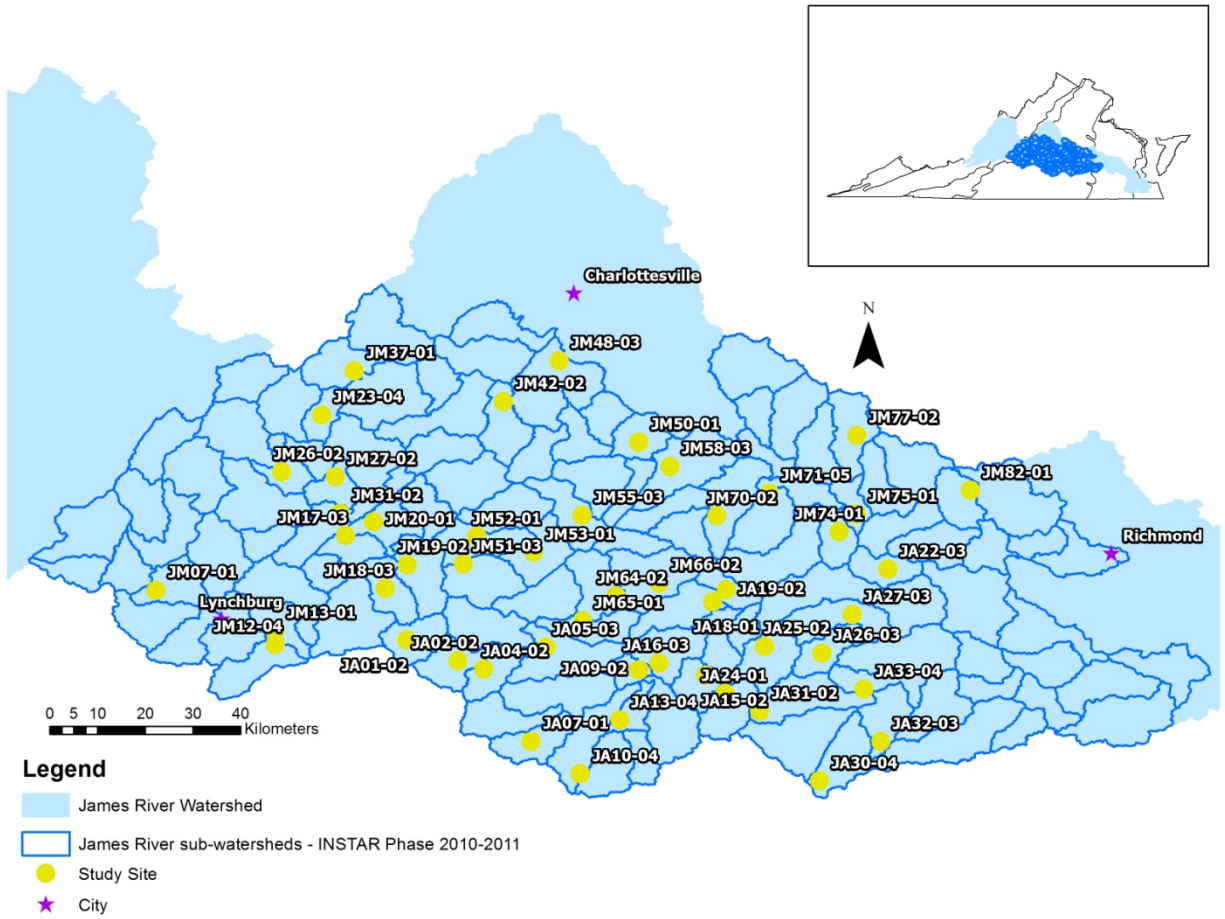
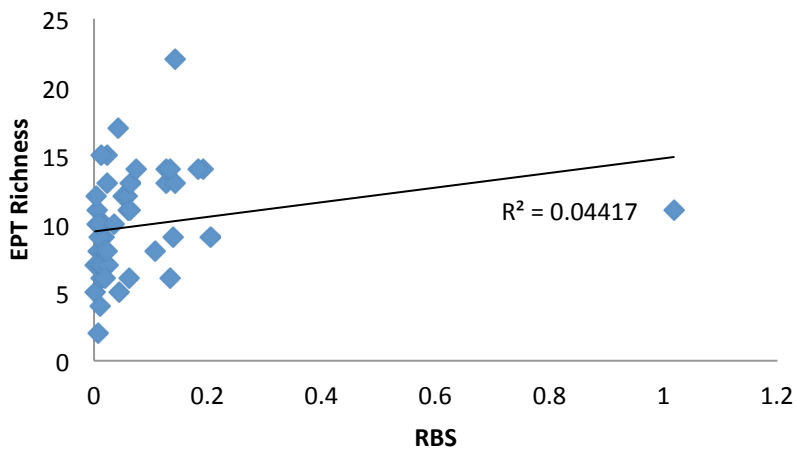
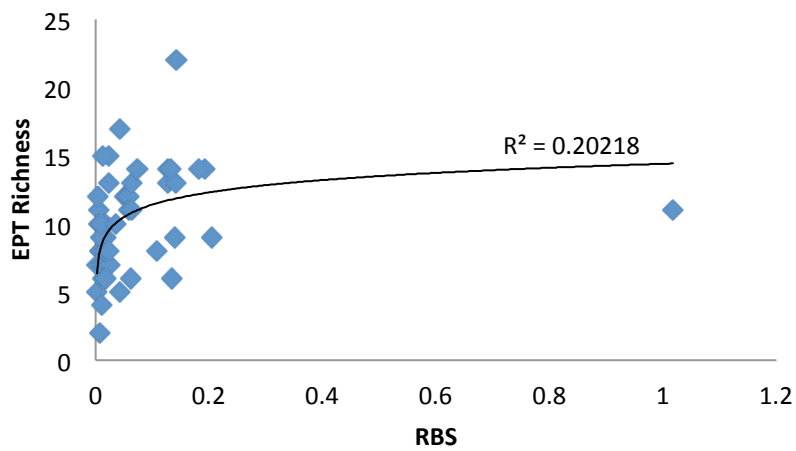


Figure 2. Map of 49 study sites within the middle James River watershed. Inset map shows the study area is located in the central Virginia Piedmont eco-region.

(A)



(B)



(C)

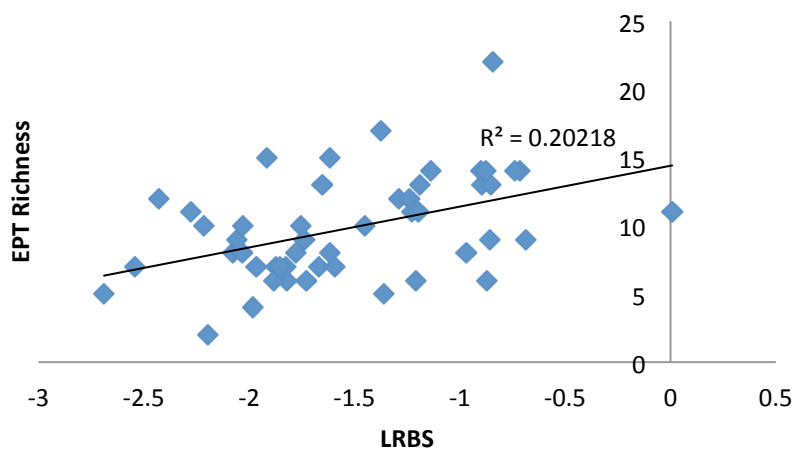


Figure 3. For comparability and to normalize variance, the \log_{10} Relative Bed Stability (RBS) or LRBS is used when relating sediment stability to macroinvertebrate communities. For example, the variation Ephemeroptera, Plecoptera and Trichoptera (EPT) Richness is not as well explained by a linear relationship (A) as it is by a logarithmic relationship (B). The use of LRBS instead of RBS allows for the use of linear relationships with macroinvertebrate community metrics (C).

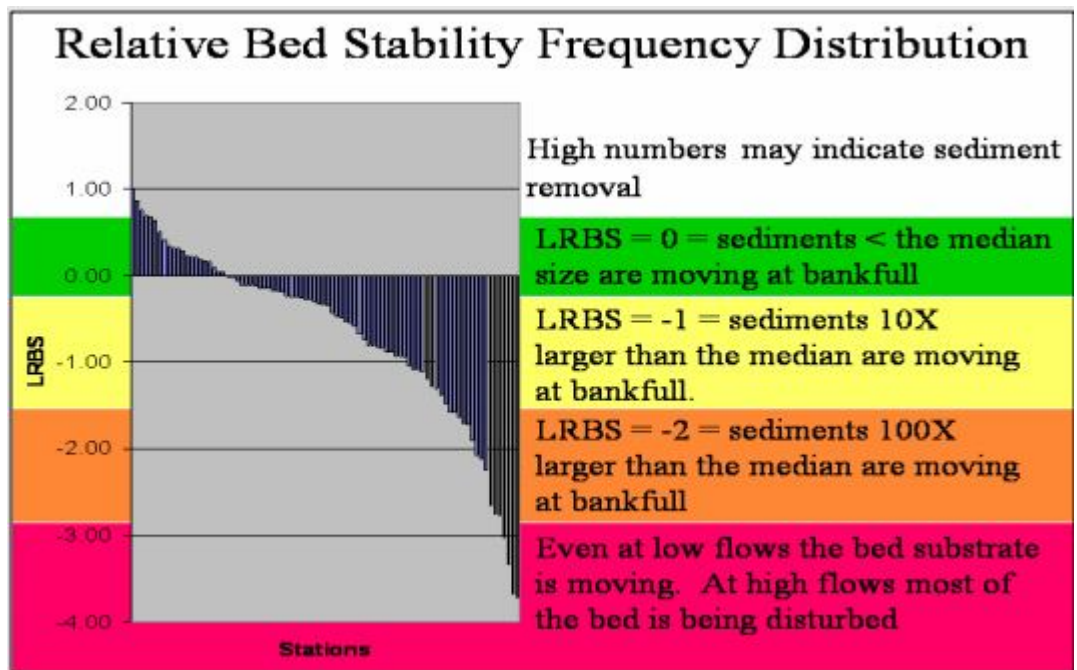


Figure 4. Range of LRBS scores and associated levels of impairment. Image from poster presentation by Virginia Department of Environmental Quality, West Central Regional Office (Willis et al. n.d.).

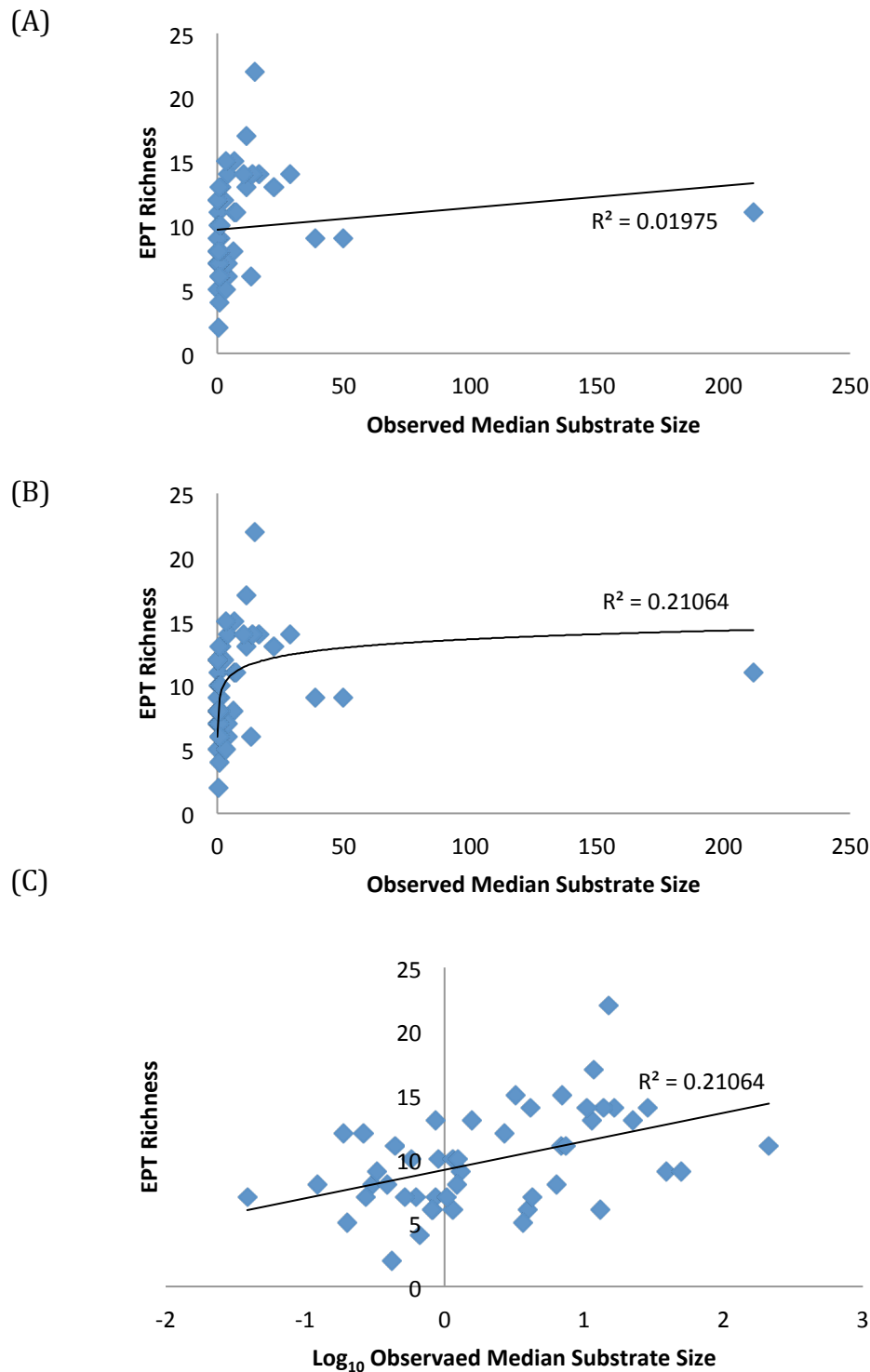


Figure 5. For comparability and to normalize variance, the log_{10} Observed median substrate size ($\text{log}_{10}\text{OBS_MSS}$) or LOBS-MSS is used when relating sediment size composition stability to macroinvertebrate communities. For example, the variation Ephemeroptera, Plecoptera and Trichoptera (EPT) Richness is not as well explained by a linear relationship (A) as it is by a logarithmic relationship (B). The use of LOBS_MSS instead of OBS_MSS allows for the use of linear relationships with macroinvertebrate community metrics (C).

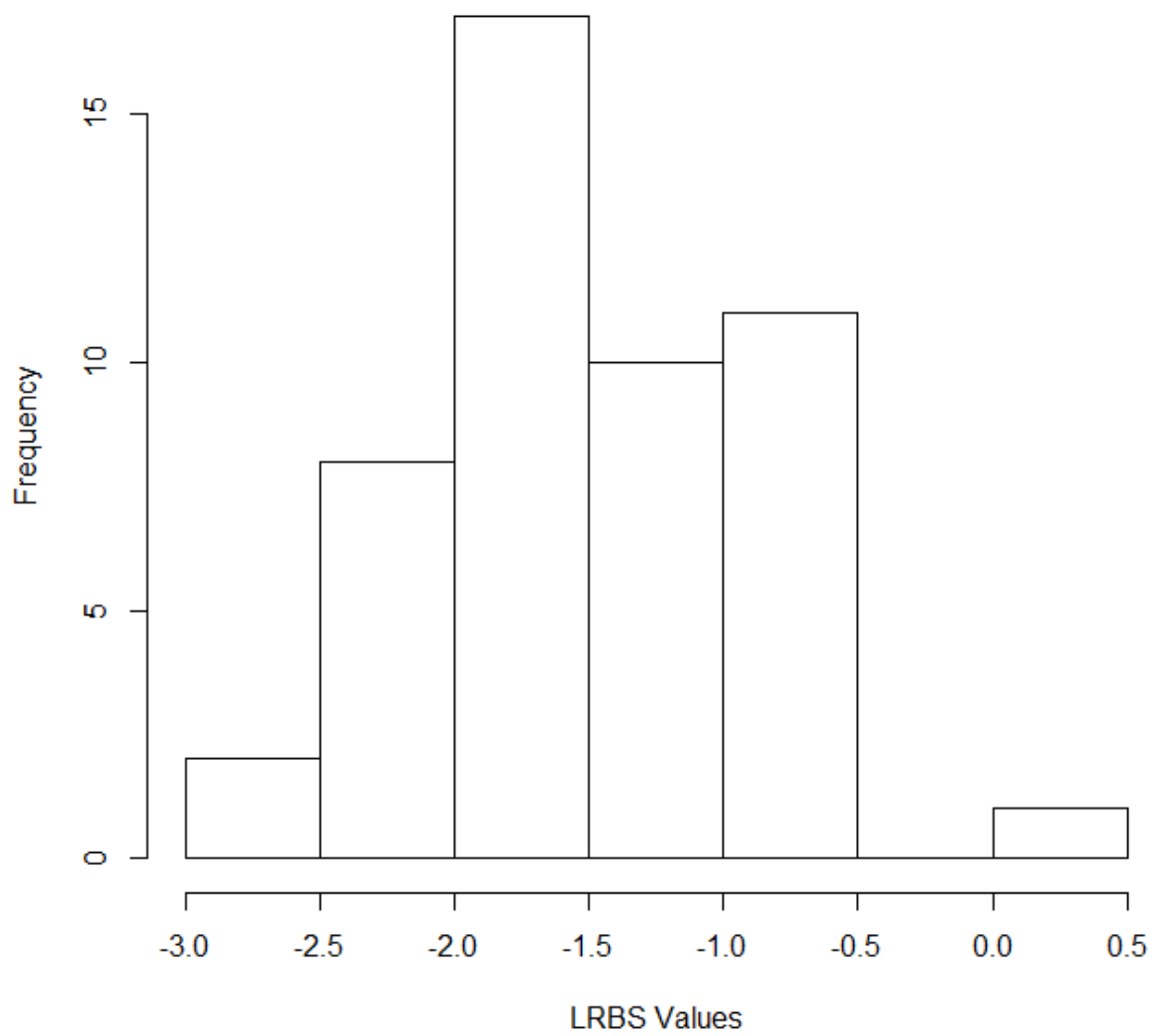


Figure 6. Distribution and frequency of LRBS scores from 49 study sites.

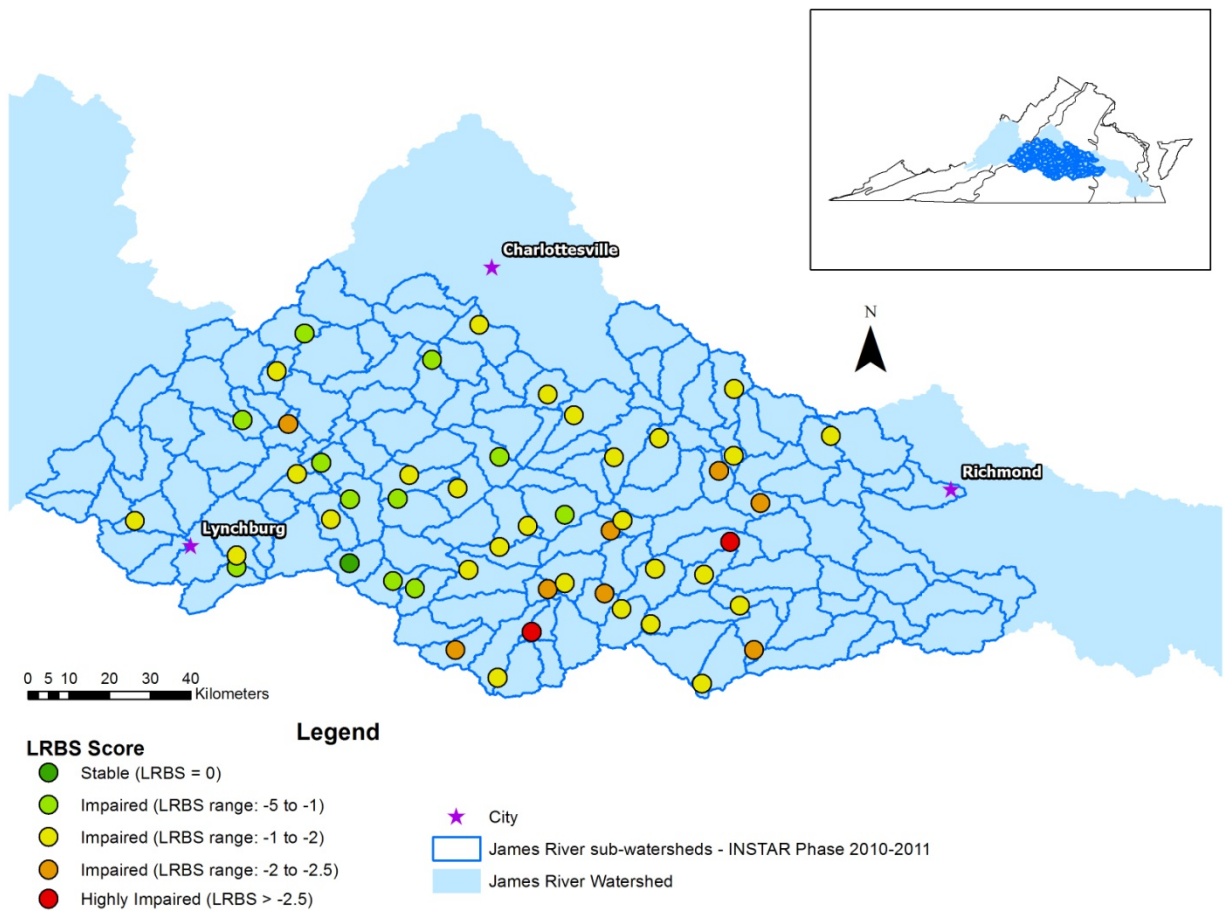


Figure 7. Map of the 49 study sites symbolized by LRBS score. The majority of sites were classified as “impaired” (LRBS score between -0.5 and -2.5) so to illustrate where these sites fell with the “impaired” range, those sites were sub-divided and symbolized in three colors (light green, yellow, and orange) all of which indicate impairment due to excess fine sediment. Inset map shows the study area is located in the central Virginia Piedmont eco-region.

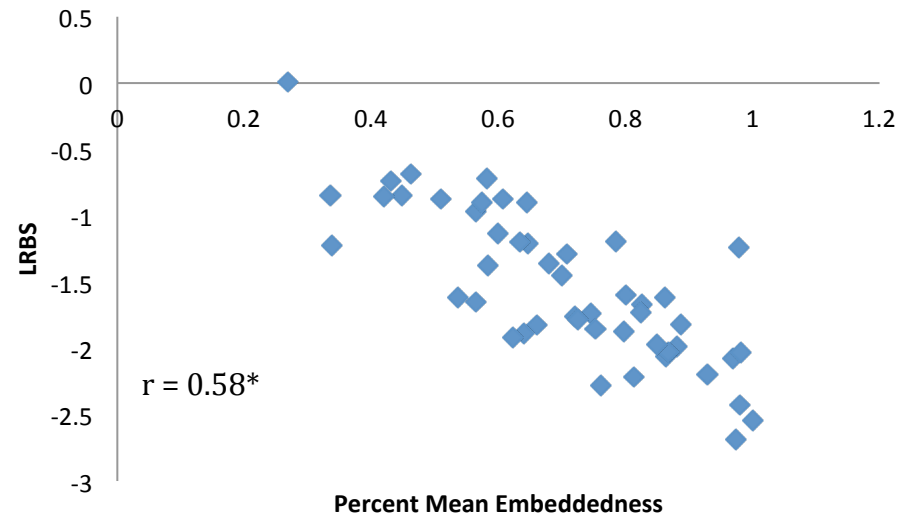
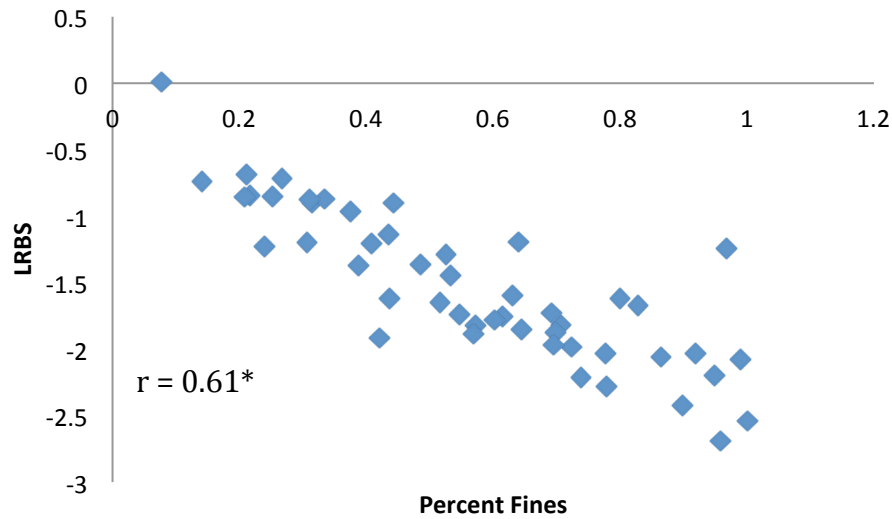
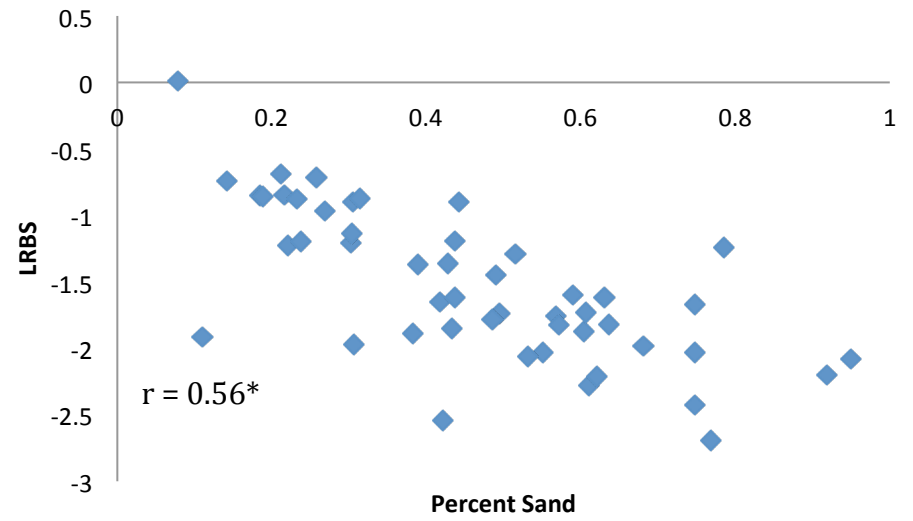
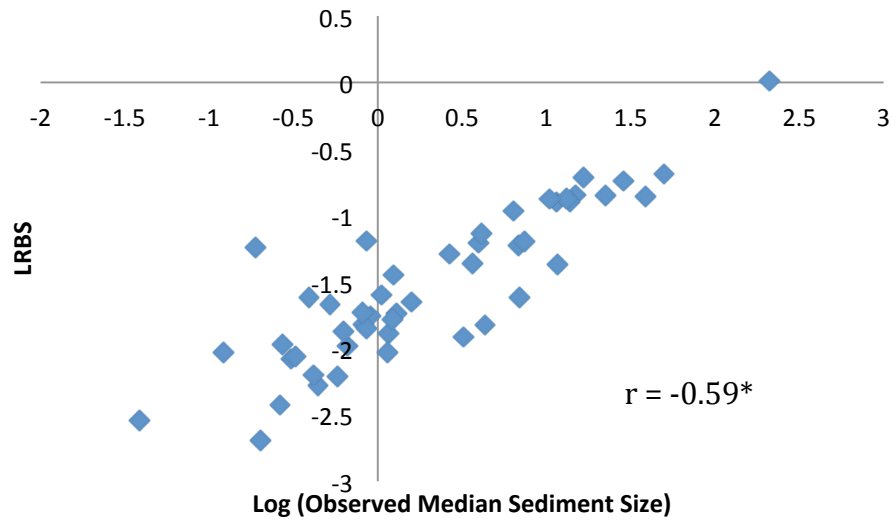


Figure 8. Pairwise correlations between each of the four sediment composition metrics and LRBS. *Denotes significance ($p < 0.05$)

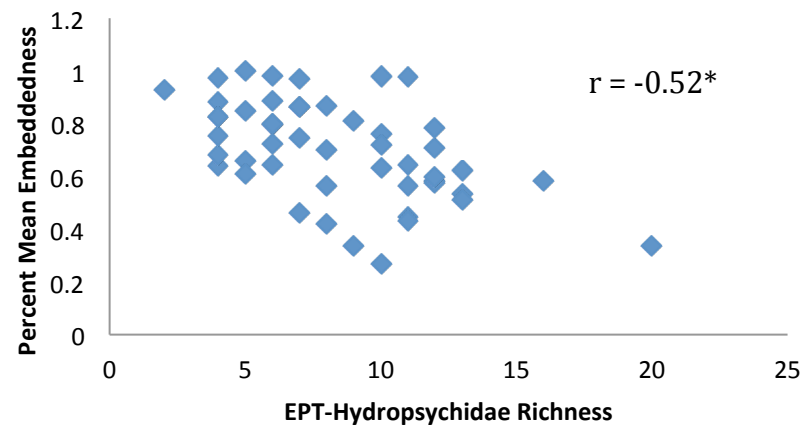
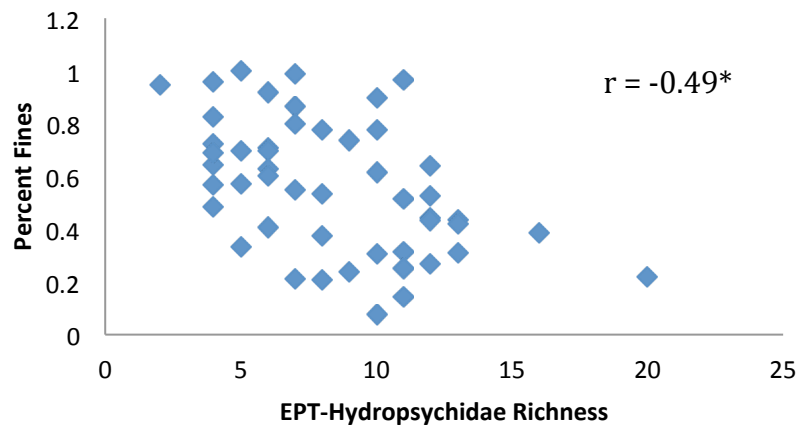
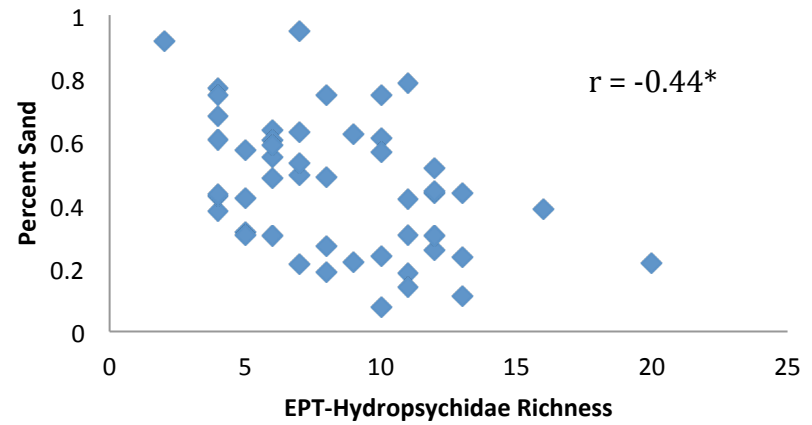
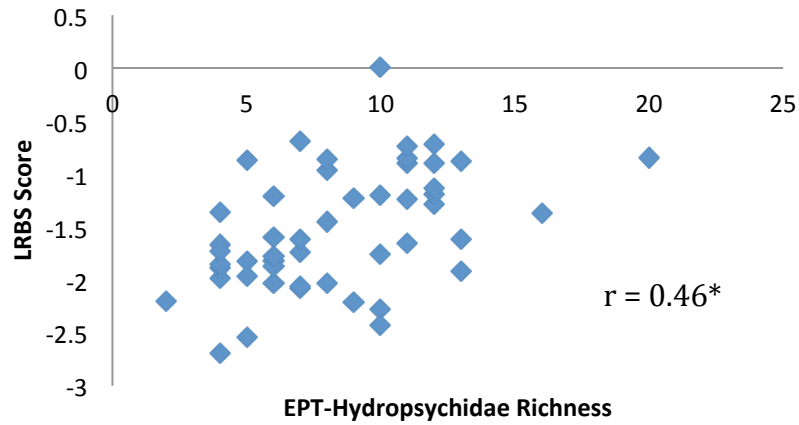


Figure 9. An example of a macroinvertebrate metric selected by the tiered correlation analysis (Ephemeroptera, Plecoptera, and Trichoptera (EPT) – Hydropsychidae Richness) for moderate to strong, significant and linear correlations with sediment stability and composition metrics also selected by the tiered correlation analysis*Denotes significance ($p < 0.05$)

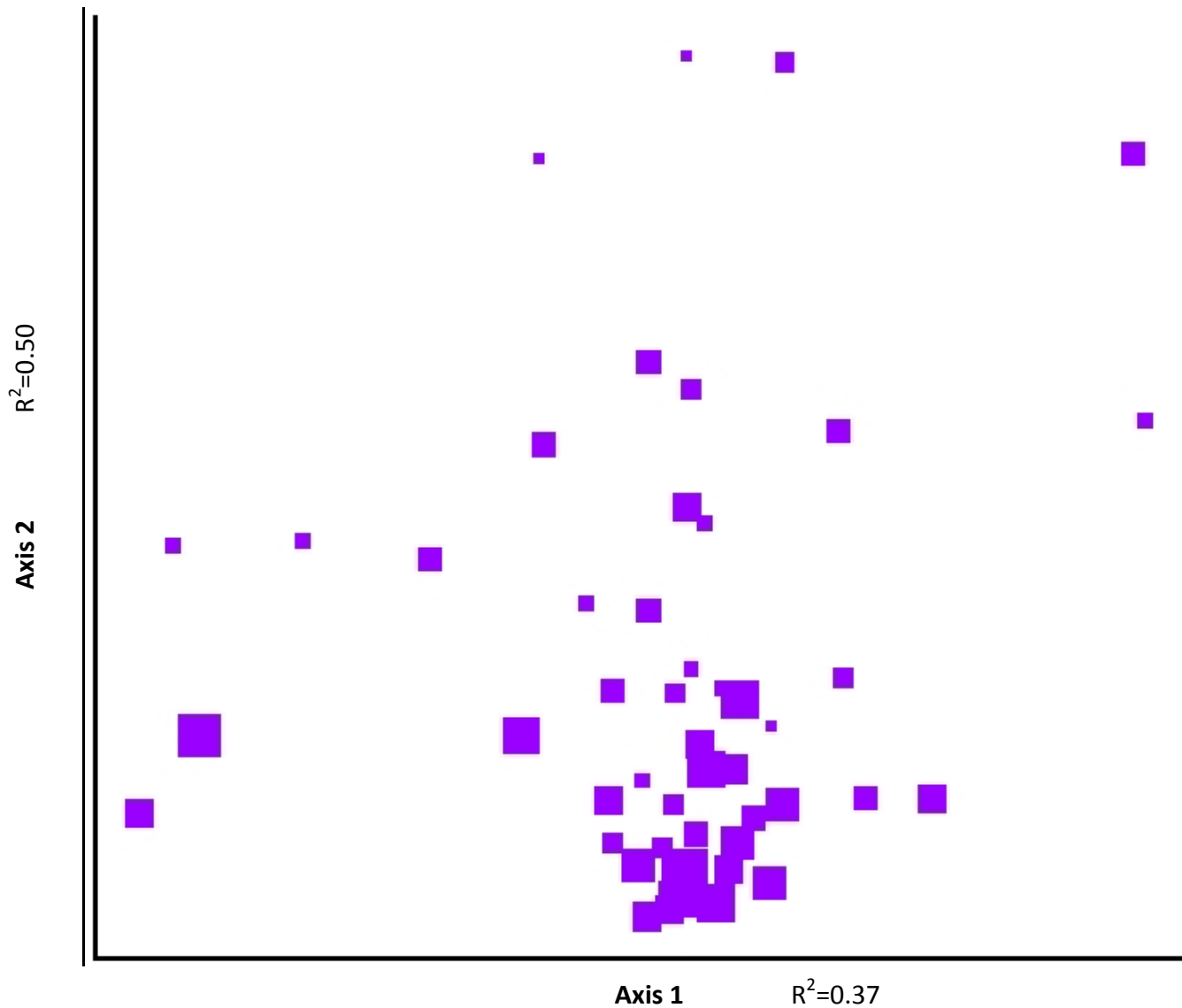


Figure 10. Non-metric multidimensional scaling (NMS) ordination diagram. Squares represent sites. The size of the squares in the figure is proportional to the percentage of sand substrate present. Distance between sites approximates the amount of dissimilarity to one another along two extracted axes of variation. The cumulative proportion of variance in the data explained by both axes is 0.87. Stress in the final solution = 16.

Appendix A. Relative Bed Stability field form and notes.

Relative Bed Stability Form

Station INSTAR ID	DATE
Stream Name	County
Observers	Location

WATER CHEMISTRY		At downstream end of reach					
Cond. (μ S)		Temp ($^{\circ}$ C)		pH		DO (mg/L)	

MEAN WIDTH		TOTAL REACH LENGTH	TRANSECT INCREMENT			THALWEG INCREMENT	SLOPE rise over run				
Cross section Substrate Depth, Size Embeddedness											
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)
A	Depth cm										
A	Size	>2.5 m width = 10 thalwegs, <2.5m = 15 thalwegs									
A	Embed						A10	A11	A12	A13	A14
Thalweg (cm)	A	A1	A2	A3	A4	A5	A6	A7	A8	A9	
Amid	Size										
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)
B	Depth cm										
B	Size	>2.5 m do 10 thalwegs, 1<2.5m do 15 thalwegs									
B	Embed						B10	B11	B12	B13	B14
Thalweg (cm)	B	B1	B2	B3	B4	B5	B6	B7	B8	B9	
Bmid	Size										
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)
C	Depth cm										
C	Size	>2.5 m do 10 thalwegs, 1<2.5m do 15 thalwegs									
C	Embed						C10	C11	C12	C13	C14
Thalweg (cm)	C	C1	C2	C3	C4	C5	C6	C7	C8	C9	
Cmid	Size										
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)
D	Depth cm										
D	Size	>2.5 m do 10 thalwegs, 1<2.5m do 15 thalwegs									
D	Embed						D10	D11	D12	D13	D14
Thalweg (cm)	D	D1	D2	D3	D4	D5	D6	D7	D8	D9	
Dmid	Size										
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)
E	Depth cm										
E	Size	>2.5 m do 10 thalwegs, 1<2.5m do 15 thalwegs									
E	Embed						E10	E11	E12	E13	E14
Thalweg (cm)	E	E1	E2	E3	E4	E5	E6	E7	E8	E9	
Emid	Size										

LARGE WOODY DEBRIS , D >10 cm small end, L >1.5m											All or partially in Bankful channel			
Total LWD A-E	SDSL	SDML	SDLL	MSL	D	MDML	MDLL	LDL	LDML	LDLL	XDSL	D	XDML	XDLL
	D 0.1-0.3M L 1.5-5M	D 0.1-0.3M L 5-15M	D 0.1-0.3M L >15M	0.3-0.6M 1.5-5M	L	D 0.3-0.6M L 5-15M	D 0.3-0.6M L >15M	D 0.6-0.9M L 1.5-5M	D 0.6-0.9M L 5-15M	D 0.6-0.9M L >15M	>0.9M 5M	L 1.5	D >0.9M L 5-15M	D >0.9M L >15M

Station						Date							
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)		
F	Depth cm												
F	Size						>2.5 m width = 10 thalwegs, <2.5m = 15 thalwegs						
F	Embed						F10	F11	F12	F13	F14		
Thalweg (cm)	F	F1	F2	F3	F4	F5	F6	F7	F8	F9			
Fmid	Size												
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)		
G	Depth cm												
G	Size						>2.5 m do 10 thalwegs, 1<2.5m do 15 thalwegs						
G	Embed						G10	G11	G12	G13	G14		
Thalweg (cm)	G	G1	G2	G3	G4	G5	G6	G7	G8	G9			
Gmid	Size												
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)		
H	Depth cm												
H	Size						>2.5 m do 10 thalwegs, 1<2.5m do 15 thalwegs						
H	Embed						H10	H11	H12	H13	H14		
Thalweg (cm)	H	H1	H2	H3	H4	H5	H6	H7	H8	H9			
Hmid	Size												
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)		
I	Depth cm												
I	Size						>2.5 m do 10 thalwegs, 1<2.5m do 15 thalwegs						
I	Embed						I10	I11	I12	I13	I14		
Thalweg (cm)	I	I1	I2	I3	I4	I5	I6	I7	I8	I9			
Imid	Size												
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)		
J	Depth cm												
J	Size						>2.5 m do 10 thalwegs, 1<2.5m do 15 thalwegs						
J	Embed						J10	J11	J12	J13	J14		
Thalweg (cm)	J	J1	J2	J3	J4	J5	J6	J7	J8	J9			
Jmid	Size												
		LEFT	LEFT MIDDLE	MIDDLE	RIGHT MIDDLE	RIGHT	BANKFULL HEIGHT (m)	INCISED HEIGHT (m)	WETTED WIDTH (m)	BANKFULL WIDTH (m)	BAR WIDTH (m)		
K	Depth cm												
K	Size												
K	Embed												
LARGE WOODY DEBRIS , D >10 cm small end, L >1.5m							All or partially in Bankful channel						
Total LWD F-K	SDSL D 0.1-0.3M L 1.5-5M	SDML D 0.1-0.3M L 1.5-5M	SDLL D 0.1-0.3M L >15M	MSL D 0.3-0.6M L 1.5-5M	D DMSL D 0.3-0.6M L 1.5-15M	MSLL D 0.3-0.6M L >15M	LDL D 0.6-0.9M L 1.5-5M	LDML D 0.6-0.9M L 1.5-15M	LDLL D 0.6-0.9M L >15M	KDSL D 0.9M 5M	D L 1.5	KDML D >0.9M L 1.5-15M	KDLL D >0.9M L >15M

SLOPE

A **B** **C** **D** **E** **F** **G** **H** **I** **J** **K**

Original form available at:

<http://www.deq.state.va.us/Programs/Water/WaterQualityInformationTMDLs/WaterQualityMonitoring/ProbabilisticMonitoring/ProbMonDatashets.aspx>

Appendix A (continued). Substrate Classification for Relative Bed Stability Form “Size” cells

Substrate Type	Size		Code	Embedded
Bedrock Smooth	>4000 mm	Bigger than a Small Car	RS	0
Bedrock Rough	>4000 mm	Bigger than a Small Car	RR	0
Concrete or Asphalt			RC	
Hardpan		Firm Consolidate	HP	0
Large Boulder	1000-4000 mm	Meter stick to Small Car	XB	
Small Boulder	250-1000 mm	Basketball to Meter Stick	SB	
Cobble	64-250 mm	Tennisball to basketball	CB	
Coarse Gravel	16-64 mm	Marble to tennisball	GC	
Fine Gravel	2-16 mm	Ladybug to marble	GF	
Sand	0.06-2 mm	Gritty to Ladybug	SA	100
Fines	<0.06 mm	Smooth, not gritty	FN	100
Wood			WD	
Other write comment			OT	

Vita

Amanda Elizabeth Schutt was born on April 5, 1988, in Washington, D.C. She graduated from Fairfax High School, Fairfax, Virginia in 2006. She received her Bachelor of Science in Environmental Studies from Virginia Commonwealth University, Richmond, Virginia in 2010, and subsequently worked as a Research Assistant in the Virginia Commonwealth University Aquatics Lab for two years.