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Macroinvertebrate Sensitivity Thresholds for Sediment in Virginia Streams

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ABSTRACT

Sediment is the most commonly identified pollutant associated with macroinvertebrate community impairments in freshwater streams nationwide. Management of this physical stressor is complicated by the multiple measures of sediment available (e.g., suspended, dissolved, bedded) and the variability in natural "healthy" sediment loadings across ecoregions. Here we examine the relative importance of 9 sediment parameters on macroinvertebrate community health as measured by the Virginia Stream Condition Index (VSCI) across 5 ecoregions. In combination, sediment parameters explained 27.4% of variance in the VSCI in a multiregion data set and from 20.2% to 76.4% of variance for individual ecoregions. Bedded sediment parameters had a stronger influence on VSCI than did dissolved or suspended parameters in the multiregion assessment. However, assessments of individual ecoregions revealed conductivity had a key influence on VSCI in the Central Appalachian, Northern Piedmont and Piedmont ecoregions. In no case was a single sediment parameter sufficient to predict VSCI scores or individual biological metrics. Given the identification of embeddedness and conductivity as key parameters for predicting biological condition, we developed family-level sensitivity thresholds for these parameters, based on extirpation. Resulting thresholds for embeddedness were 68% for combined ecoregions, 65% for the Mountain bioregion (composed of Central Appalachian, Ridge and Valley, and Blue Ridge ecoregions), and 88% for the Piedmont bioregion (composed of Northern Piedmont and Piedmont ecoregions). Thresholds for conductivity were 366 μS/cm for combined ecoregions, 391 μS/cm for the Mountain bioregion, and 136 μS/cm for the Piedmont bioregion. These thresholds may help water quality professionals identify impaired and at-risk waters designated to support aquatic life and develop regional strategies to manage sediment-impaired streams. Inclusion of embeddedness as a restoration endpoint may be warranted; this could be facilitated by application of more quantitative, less time-intensive measurement approaches. We encourage refinement of thresholds as additional data and genus-based metrics become available. *Integr Environ Assess Manag* 2019;15:77–92. Published 2018. This article has been contributed to by US Government employees and their work is in the public domain in the USA.

Keywords: Sediment Macroinvertebrate bioassessment Species sensitivity distribution Conductivity Embeddedness

INTRODUCTION

Human manipulation of the landscape through agriculture, urbanization, and resource extraction continues to increase exponentially with population growth to support societal needs (Hooke 2000). These activities involve substantial earthmoving. Estimates suggest that humans move an average of 5443 kg (6 tons) of sediment annually per person, that is, 4.0–4.5 × 10^{13} kg/yr (40–45 Gt/yr) collectively, arguably making them the greatest living agent of geomorphic change on Earth (Hooke 1994). These landscape manipulations lead to large-scale erosion and accompanying inputs of sediments into freshwater systems, which markedly affect beneficial uses (e.g., recreation, navigation, and reservoir efficiency) and reduce biological integrity (Waters 1995). Perhaps not surprisingly, there is increasing recognition of the importance of addressing physical stressors such as sediment in addition to managing chemical stressors in aquatic systems (Burton 2017). In the United States, sediment has been identified as a significant cause of freshwater river and stream impairments for a variety of designated uses and is second only to bacterial impacts in 303(d) listings under the Clean Water Act (US Environmental Protection Agency [USEPA] 2016a). In the majority of cases, total maximum daily load (TMDL) development is required to address impairments, which involves the identification of the quantity of a pollutant that can enter a receiving water without causing

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harm and the development of an accompanying watershed remediation plan.

Bioassessments of macroinvertebrate communities are used by the majority of states in the United States to assess attainment of the "protection of aquatic life" designated use, which is most often expressed as narrative water quality criteria (USEPA 2002; Govenor et al. 2017). States assess a variety of biological metrics related to macroinvertebrate communities, and many have developed macroinvertebrate-based indices particular to their unique bioregions. Sediment and siltation are most commonly determined to be the primary pollutants of concern in TMDL reports for waters with aquatic life use impairments that were identified via macroinvertebrate bioassessments (Govenor et al. 2017). These sediment effects are physical in nature and are distinct from the potential effects from contaminants or nutrients that may adsorb to sediment particles.

Quantification and management of sediment can be complex because a stream's sediment load consists of dissolved, suspended, and bedded (i.e., deposited) components (Gerhard 2000), and sediment can change form in response to natural or anthropogenic shifts in physical and chemical conditions (e.g., flow, temperature, pH; see Lane 1955). Excess sediment in each of its varied forms can affect aquatic life; however, the relative influence of the various sediment parameters on biological communities has not been explicitly examined. Conventionally, water quality managers have focused primarily on measures of suspended sediment (Jones et al. 2012), with a more recent focus on dissolved solids (i.e., salts; Pond 2012; Cormier et al. 2013; Boehme et al. 2016). Suspended particulates can be quantified as total suspended solids (TSS), suspended solids concentration, and turbidity. Dissolved sediments can be quantified as total dissolved solids (TDS) or estimated with conductivity. Both suspended and dissolved measures of sediment have been associated with behavioral changes (Gammon 1970; Wood and Armitage 1997; Berry et al. 2003; Gibbins et al. 2007; Larsen and Ormerod 2010; Jones et al. 2012), reductions in growth and survival (Berry et al. 2003; Kennedy et al. 2005), and shifts in macroinvertebrate community structure (Pond 2010; Timpano et al. 2015; Boehme et al. 2016).

Despite the traditional focus on suspended sediments, increasing evidence suggests aquatic life effects from excess bedded sediments can exceed those of suspended sediments (Jones et al. 2012; Gordon et al. 2013). Bedded sediments can be measured in terms of the grain-size distribution of the stream bed, percent cover of particular size classes, and embeddedness (i.e., the extent to which gravel, cobble, and boulders are buried by silt, sand, or mud in the stream bottom; Barbour et al. 1999). An increase in bedded sediments has been linked to shifts in community composition and decreased macroinvertebrate abundance (Sorensen et al. 1977; Waters 1995; Wood and Armitage 1997; Berry et al. 2003; Kaller and Hartman 2004; Cormier et al. 2008; Benoy et al. 2012; Jones et al. 2012; Sutherland et al. 2012; Burdon et al. 2013; Vadher et al. 2015).

The USEPA distinguishes between "sediment" (which encompasses suspended and bedded forms) and "salinity/total dissolved solids/chlorides/sulfates" (which encompasses dissolved sediment forms) when identifying causes of stream impairment in the TMDL process. Herein, suspended, bedded, and dissolved sediment-associated parameters are uniformly referred to as "sediment." This general usage is consistent with geomorphological terminology (Gerhard 2000).

Because of the widespread effect of sediment on water quality, and key gaps in the knowledge of sediment-induced impairment, the USEPA has identified the development of numeric criteria for suspended and bedded sediment as a top-10 priority in terms of the tools needed for improving national water quality management outcomes (USEPA 2003) and has provided a framework document for this purpose (USEPA 2006a). Natural sediment regimes vary widely among waterbody forms, sizes, and ecological regions, necessitating that criteria be region specific (USEPA 2006a). In addition, appropriate criteria will need to vary by the designated use of a water body (e.g., aquatic life use, public water supply). As benthic macroinvertebrate taxa can vary widely in their sensitivity to sediment, with morphological, physiological, and behavioral traits influencing sensitivity (Extence et al. 2013), criteria derived to be protective of this community need to account for taxon-specific effects. In a recent summary of numeric sediment criteria in the United States, criteria were available in 32 states, tribal lands, or territories. Most were developed for turbidity or suspended solids (USEPA 2006a). VA has a 500 000 μg/L total dissolved solids criteria for waters designated as public water supply (9VAC25-260-140) but no quantitative sediment-related criteria for aquatic life use.

Our goal was to determine sediment-based sensitivity thresholds for occurrence of benthic macroinvertebrates in Virginia noncoastal streams that would help water quality professionals identify impaired and at-risk waters that are designated to support aquatic life and develop regional strategies to manage sediment-impaired streams. To that end, our objectives were to

1) Identify the sediment parameters most strongly associated with stream condition as measured by the Virginia benthic macroinvertebrate index; and
2) Determine associated thresholds of effect on taxon occurrence for these sediment parameters.

MATERIALS AND METHODS

VDEQ probabilistic monitoring program data

We used surface water quality monitoring data provided by the Virginia Department of Environmental Quality (VDEQ) Probabilistic Monitoring Program (ProbMon), which are publicly available on the department's website (www.deq.virginia.gov; *ProbMon Data Set* 2001–2014, updated March 2017 and *Family Macroinvertebrate Ecological Data*

Application System Database, updated March 2017). ProbMon monitoring stations are randomly located with the USEPA's probability survey design program (Stevens 1997; VDEQ 2003; USEPA 2006b). VDEQ samples approximately 5% of ProbMon sites in multiple years to establish trends in water quality condition over time. Data collected from 2001 through 2014 were available at the time of our study.

At each station, VDEQ conducts physical habitat assessments by using USEPA Rapid Bioassessment Protocols (RBP II) during the fall (Barbour et al. 1999; VDEQ 2003). VDEQ quantifies 9 sediment parameters: specific conductance (conductivity), TDS, turbidity, TSS, particle size (%Fines, %Sand, and median particle size [logD50]), embeddedness, and the log of relative bed stability (LRBS; "Estimate 2" from the report by Kaufmann et al. [1999]). The definitions and methods used to quantify these sediment parameters are described further in Table 1.

VDEQ collects benthic macroinvertebrate community data at wadable ProbMon sites during spring (March 1 through May 31) and fall (September 1 through November 30) index periods. One of 2 sampling approaches (single habitat [riffles] or multihabitat) is used as determined by local stream geomorphology and instream characteristics (VDEQ 2008). Sampling methods follow the state's biological monitoring program standard operating procedures (VDEQ 2008), which are based on RBP II and regional guidelines (USEPA 1997; Barbour et al. 1999).

To evaluate biological condition in noncoastal streams, VDEQ calculates the Virginia Stream Condition Index (VSCI) with benthic macroinvertebrate community data (Burton and Gerritsen 2003). The VSCI, which ranges from 1 to 100, is calculated by summing scores on 8 biological metrics representing taxonomic richness, composition, diversity, pollution tolerance, and trophic composition (Table 2). VDEQ calculates VSCI for spring and fall index periods and provides an average annual score for each site. Stations with scores less than 61 are designated as impaired upon verification of the regional biologist, and the associated reach is placed on the Virginia 303(d) list of impaired waters (VDEQ and VDCR 2014).

Analysis of these data has broad applicability to the eastern United States because (1) the data represent multiple ecoregions that extend well beyond VA, (2) most taxa here have extensive geographic ranges, (3) the anthropogenic effects being assessed (e.g., urbanization, agriculture, mining) are widespread, and (4) sampling protocols and biotic metrics used here are commonly used in other states.

Data selection

We restricted our analysis to the data we believed to be most instructive relative to our objectives. We excluded observations collected (a) prior to 2004 because they did not contain a full suite of sediment parameters and (b) in 2004 or later that were missing one or more of the evaluated parameters. Our data represent 5 of the 7 level III ecoregions in Virginia (Omernik and Griffith 2014). We did not include data from the Middle Atlantic Coastal Plain or Southeastern Plains regions because stream condition in these regions is assessed with the Virginia Coastal Plain Macroinvertebrate Index (VDEQ 2013) and our focus was on noncoastal streams. The unique hydrology and ecology of coastal regions renders the 2 indices nonequivalent. For stations measured in multiple years, we included only the first year in which both invertebrate and full sediment data were available. In total, the data set meeting all study criteria comprised 374 stations (Figure 1).

Identification of Sediment Parameters Associated with Stream Condition

We designed our analyses to identify which sediment parameters are most strongly associated with macroinvertebrate community response. We chose the annual average of the 2 seasonal VSCI scores (calculated by VDEQ) as the primary response variable when identifying sediment parameters associated with stream condition on the basis of data availability. Each of the 9 sediment parameters discussed above, which are typical parameters measured during habitat evaluations and stream assessments in Virginia and other states that use RPB II protocols, was included as an independent variable: conductivity, TDS, turbidity, TSS, %Sand, %Fines, logD50, embeddedness, and LRBS. We used R version 3.1.2 (R Development Core Team 2016) for data analyses. Normality of sediment parameters was checked with Shapiro–Wilks tests, and data were transformed to improve normality. TDS, conductivity, TSS, and turbidity data were log transformed, while embeddedness, %Sand, and %Fines data were arcsine square root transformed. We used the *glmnet* package in R (Friedman et al. 2010) to conduct elastic net regression to determine the sediment parameters most strongly associated with the VSCI response. Elastic net regression is a regularized regression approach that accounts for both collinearity among input parameters (i.e., grouping) and minimization of parameters included in the model (Zou and Hastie 2005). The output includes coefficients for the sediment parameters, the y intercept, and a deviance ratio, which is the fraction of (null) deviance explained (equivalent to R^2; Friedman et al. 2010). The elastic net approach may drop predictor variables from the model in cases where they do not significantly explain the response, consistent with least absolute shrinkage and selection operator (LASSO) regression (Bardsley et al. 2015). Model coefficients with the largest absolute values indicate parameters with the strongest influence on the response variable.

Development of sensitivity thresholds for sediment parameters

On the basis of the results of the elastic net regression, we identified embeddedness and conductivity as the strongest predictors of stream condition. Family-level invertebrate classification data from the fall index period and corresponding embeddedness and conductivity data were then used to determine separate sensitivity thresholds for both these parameters. Fall invertebrate data were used rather than spring data because fall data were collected concurrently

Table 1. Sediment parameters evaluated and methods of determination

Sediment parameter	Abbreviation	Units	Definition	Method	Notes
Dissolved sediment parameter					
Total dissolved solids	TDS	mg/L	Dry weight of material dissolved in a measured volume of water, generally the sum of cations and anions in the water; will pass through standard filter	DCLS; Standard Methods 2540 C-11	
Conductivity	conductivity	µS/cm	Ability of the solution to conduct electricity, a reflection of dissolved ion concentrations	Field-measured with multimeter, pre- and postchecked to within 5% of calibration standards	Pre- and postchecked to within ±5% of calibration standards (147 µS/cm or 1413 µS/cm)
Suspended sediment parameter					
Total suspended solids	TSS	mg/L	Dry weight of material removed from a measured volume of water passed through a standard filter (in VA 1.5-micron filter)	DCLS; Method USGS I-3765-85	
Turbidity	turbidity	NTU	Intensity of light passing through a water sample	DCLS; Standard Methods 2130 B-11	
Bedded sediment parameter					
Embeddedness	embeddedness	%	Percent burial of gravel and larger particles by sand and fines	In field with RBP	Mean of 55 measurements (5 at each of 11 reach cross-sections); visual estimate by trained field personnel categorized into 1 of 10 equal percentage bins (0%–10%, 10%–20%, … 90%–100%)
Percent sand	%Sand	%	Percent of particles 0.06–2 mm	In field with RBP	Pebble count of 55 samples (5 at each of 11 reach cross-sections)
Percent fines	%Fines	%	Percent of particles <0.06 mm	In field with RBP	Pebble count of 55 samples (5 at each of 11 reach cross-sections)
Median particle size	logD50	log(mm)	Log (base 10) of median grain size	In field with RBP	Median from pebble count of 55 samples (5 at each of 11 reach cross-sections)
Log relative bed stability	LRBS	unitless	Log of ratio of observed substrate median diameter to average critical diameter at bankfull flow	Calculated with field-measured metrics	"Estimate 2" including considerations for reach roughness (Kaufmann et al. 1999)

DCLS = testing conducted by Virginia Division of Consolidated Laboratory Services; LRBS = log of relative bed stability; NTU = nephelometric turbidity units; RBP = Rapid Bioassessment Protocols (Barbour et al. 1999); TDS = total dissolved solids; TSS = total suspended solids; USGS = United States Geological Survey.

Table 2. Coefficients of elastic net regression—combined ecoregional assessment[a]

Metric	VSCI	EPT Taxa	Total taxa	%E	%PT-H	% Chironomidae	% Top 2 Dom	HBI	% Scrapers
Biological representation	Biological condition	Taxonomic richness	Taxonomic richness	Composition	Composition	Composition	Diversity	Tolerance	Trophic group
Dissolved									
Conductivity (log)	−9.69	−2.49	−2.10	**−5.41**	**−5.42**	2.12	8.16	**0.40**	2.15
TDS (log)	0.61	0.01	−0.36	0.02	—	−1.77	0.52	−0.04	4.14
Suspended									
TSS (log)	−0.57	−0.10	−0.76	0.09	—	—	0.89	−0.04	0.21
Turbidity (log)	−4.72	−1.13	0.53	−3.44	**−3.17**	5.08	0.33	0.27	−8.56
Bedded									
Embeddedness (asin sqrt)	**−20.56**	**−2.92**	**−2.49**	**−13.11**	**−12.76**	**20.57**	**14.81**	**0.73**	**−30.28**
%Fines (asin sqrt)	**14.10**	**2.51**	**3.84**	—	—	**−4.14**	**−15.71**	0.00	**24.52**
%Sand (asin sqrt)	**15.07**	**3.61**	**5.23**	**3.57**	2.60	**−2.73**	**−13.41**	**−0.35**	**13.46**
Relative bed stability (log)	−1.10	−1.04	0.00	−0.47	—	0.90	−1.26	0.17	3.06
Median particle size (log)	4.50	1.83	1.48	0.82	0.39	−1.11	−3.41	−0.21	−2.66
Deviance ratio	*0.274*	*0.371*	*0.172*	*0.120*	*0.118*	*0.190*	*0.167*	*0.246*	*0.230*
Intercept	86.2	11.59	17.38	50.5	51.2	−0.62	35.88	3.37	35.04

[a]Bold red font indicates the 3 most influential sediment parameters in each model. Deviance ratio indicates the proportion of variance in the metric explained by the model.
%E = percent of individuals belonging to Ephemeroptera; EPT Taxa = number of distinct taxa belonging to Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies); HBI = Hilsenhoff Biotic Index which is an abundance-weighted average pollution tolerance at the family level; %Scrapers = percent abundance of individuals whose primary functional mechanism for feeding is to graze on substrate- or periphyton-attached algae and associated material; Total Taxa = total number of distinct taxa; VSCI = Virginia Stream Condition Index; % Chironomidae = percent of individuals belonging to Chironomidae; %PT-H = percent of individuals belonging to Plecoptera plus Trichopera minus Hydropsychidae; % Top 2 Dom = percent abundance of individuals in the 2 most abundant taxa.

with sediment parameters. Burton and Gerritsen (2003) found negligible differences in VSCI scores between the fall and spring index periods and noted that the fall index period had slightly lower variability in VSCI scores, based on repeated sampling at individual sites.

We developed macroinvertebrate community sensitivity thresholds separately for embeddedness and conductivity for the combined multiregion data set (n = 373; one station of the 374 evaluated above did not have fall insect data and was excluded from further evaluation). In addition, we developed thresholds for each of 2 larger biological regions. We grouped the Blue Ridge, Ridge and Valley, and Central Appalachian ecoregions, which are subdivisions of the Ozark, Ouachita-Appalachian Forests level II ecoregion (Omernick and Griffith 2014), into the "Mountain bioregion" (n = 164). And we grouped the Northern Piedmont and Piedmont ecoregions, which are subdivisions of the Southeastern US Plains level II ecoregion, into the "Piedmont bioregion" (n = 209). We did not develop threshold values for each of the 5 ecoregions individually because of the limited sample sizes in some regions, which would result in increased uncertainty in the threshold.

We selected extirpation as the response to develop the thresholds, following the approach used by Cormier et al. (2013) to develop a benchmark for freshwater ionic strength with field data (USEPA 2011). Extirpation is "the depletion of a population to the point that it is no longer a viable resource or is unlikely to fulfill its function in the ecosystem" (USEPA 2016b). Here we define extirpation as the level of embeddedness or conductivity at which there is a 5% or lower probability of observing a family at a given site (i.e., the 95th percentile of the cumulative distribution function [CDF] of probability of occurrence for a given family [XC95]). We identified the response threshold as the level of the sediment parameter at which 5% of the families in the community are extirpated (i.e., effects concentration for the fifth percentile [EC05]). This corresponds to the embeddedness or conductivity level considered protective of 95% of macroinvertebrate families. The EC05 protectiveness level is consistent with levels used in laboratory-based methods to determine effects thresholds for water quality criteria (Stephen et al. 1985).

The threshold development process comprised 3 major phases, each with multiple steps (Figure 2). We included macroinvertebrate families in the sensitivity analysis if they were detected at 15 or more sample stations. This number was chosen to allow potential identification of trends in relations between sediment parameters and extirpation. Based on these criteria, we included 63 of 114 detected

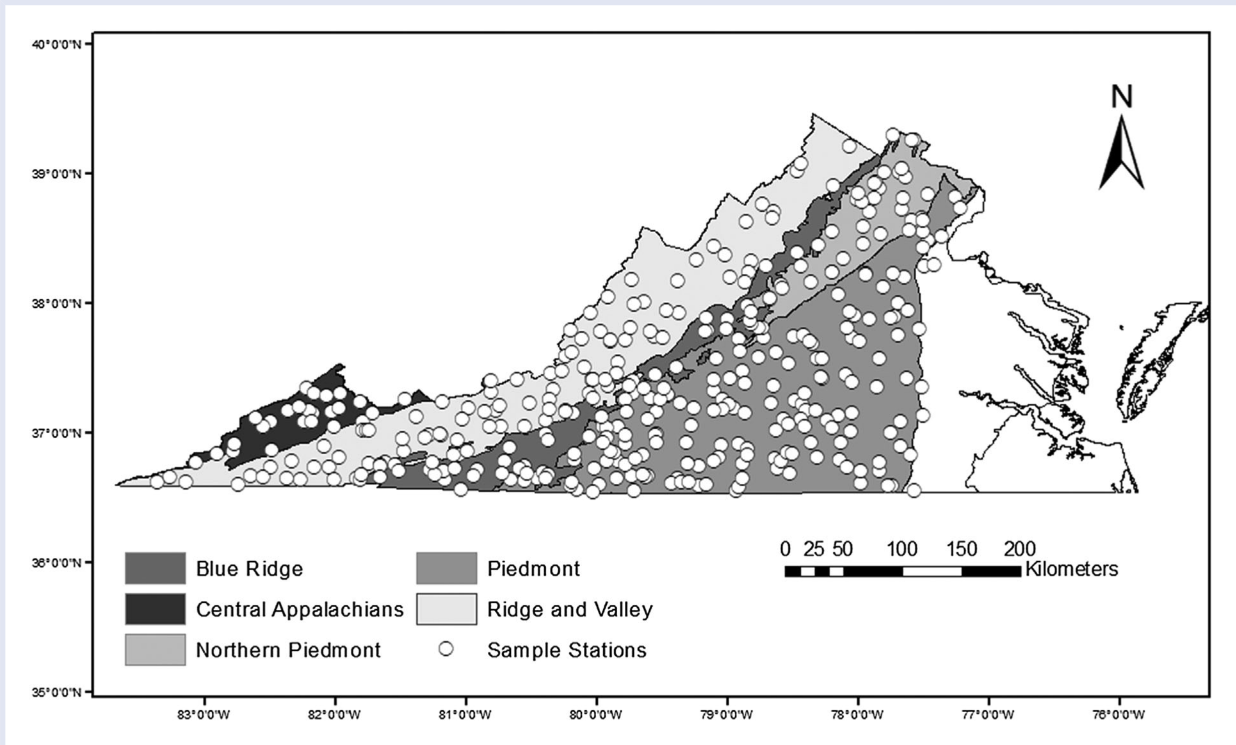

Figure 1. Sampling locations included in the assessment and associated level III ecoregions.

families in the sensitivity analysis for the combined-region threshold, 41 families for the Mountain bioregion, and 49 families for the Piedmont bioregion.

Although observed embeddedness values ranged from 0% to 100%, observations were not uniformly distributed across this range. Under this condition, we may be more likely to observe a family at a given embeddedness value simply because there were more stations with that embeddedness condition rather than because of an embeddedness effect. To account for this potential bias, we used a weighted CDF to estimate the XC95 for each family. First, the range of embeddedness was divided in to 50 bins, each representing a 2% range. Stations (observations) were classified into bins on the basis of their measured embeddedness, and each station was assigned a weight $w_i = 1/n_i$, where n_i is the number of sites in the i^{th} bin (per USEPA 2011). A similar approach was used to analyze conductivity. We divided the range of observed conductivity values (9.5–1167 μS/cm) into 50 bins, each 23.2 μS/cm in size, and assigned stations weights on the basis of the total number of sites in each bin.

The cumulative probability of detecting a given family F(*x*) at embeddedness (or conductivity) values at or below a given value (*x*), was calculated as follows (adapted from Equation 1 of USEPA 2011):

$$F(x) = \frac{\sum_{i=1}^{N_b} w_i \sum_{j=1}^{M_i} I(x_{ij} < x \text{ and } F_{ij})}{\sum_{i=1}^{N_b} w_i \sum_{j=1}^{M_i} I(F_{ij})} \quad (1)$$

Where x_{ij} is the embeddedness (conductivity) value in the j^{th} sample of bin I; N_b is the total number of bins; $w_i = 1/n_i$, where n_i is the number of sites in the i^{th} bin; M_i is the number of stations in i^{th} bin; F_{ij} is true if the family of interest was observed in the j^{th} sample of bin i; and I is an indicator function that equals 1 if the conditions are true and 0 otherwise.

We used a linear 2-point interpolation to identify the XC95 for each family as the embeddedness (or conductivity) level at which the probability of extirpation was 95%. Confidence in the XC95 value was determined by visual inspection of a plot of the probability of observing the family at a given stressor level. Plots that showed increasing probability of observation or no directional response with increasing stressor were considered to have an undefined XC95 value and were qualified with a ">" (Cormier et al. 2018b). To determine the EC05, we ordered the XC95 values from low to high and generated a CDF of the data. The EC05 was identified as the fifth percentile of this distribution.

We generated a 95% confidence interval for the mean EC05 by using bootstrapping. For each data set (combined ecoregions, Mountain bioregion, Piedmont bioregion), we generated 1000 bootstrap datasets by resampling the original data set *n* times with replacement. Here *n* equals the sample size of the data set (n = 373 for combined ecoregion; n = 164 for Mountain; n = 209 for Piedmont). Each bootstrapped data set was then processed as described above to generate an EC05 for the macroinvertebrate

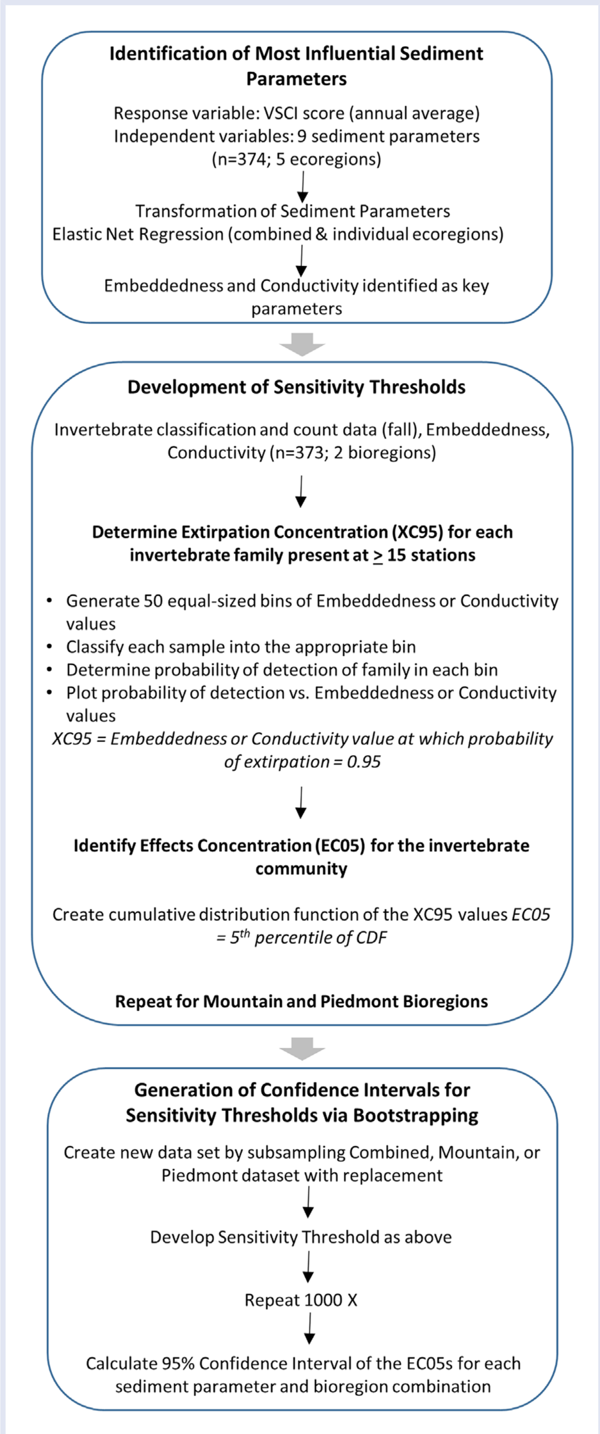

Figure 2. Statistical analysis approach.

community. The 95% confidence interval for the EC05 was determined from the resulting distribution.

RESULTS AND DISCUSSION

Identification of sediment parameters most strongly associated with stream condition

Observed sediment parameters represented a wide range of stream conditions, with TDS ranging from 1 to 584 mg/L, conductivity ranging from 9.55 to 1167 μS/cm, TSS ranging from 1 to 306 mg/L, and turbidity ranging from 0.50 to 130 NTUs. Bedded traits including embeddedness, %Sand, and %Fines covered the range of possible levels (0%–100%); median particle sizes ranged from very fine silt (0.008 mm) to boulders (661 mm), and LRBS represented conditions from stream degradation (1.48) to aggradation (−3.63).

Combined, the sediment parameters explained 27.4% of the observed variance in the VSCI in the multiregion data set (as indicated by the deviance ratio, Table 2). Sediment explained between 11.8% and 37.1% of variance in the biological metrics included in the VSCI, with EPT Taxa (richness) being the most influenced by sediment. Two measures of community composition (%E and %PT-H) were the least influenced by sediment. The percent of variance in VSCI explained by the combined sediment parameters is lower than expected considering sediment is the most commonly identified stressor of macroinvertebrate communities in VA (Govenor et al. 2017). However, VSCI scores represent the effects of multiple chemical, physical, and biological stressors. These stressors, in addition to sediment-related parameters not analyzed here (e.g., percent organic matter, particle shape, frequency and magnitude of sediment loading events) may account for some of the unexplained variance.

Bedded sediment parameters had a stronger effect on VSCI than did dissolved or suspended parameters, with embeddedness, %Sand, and %Fines being the 3 most influential (Table 2). Bedded parameters also had a stronger influence on the individual biological metrics within the VSCI than did dissolved or suspended parameters. Embeddedness was among the top 3 most influential parameters for each of the 8 biological metrics and was the most influential parameter for %E, %PT-H, %Chironomidae, HBI, and %Scrapers. Other research has shown embeddedness to have a significant positive relationship with modified family biotic index, with larger values indicating lower stream quality, and a significant negative relationship with abundance and richness of sensitive taxa (Mebane 2001; Sutherland et al. 2012). Zweig and Rabeni (2001) developed a Deposited Sediment Biotic Index based on observations in Missouri streams; they demonstrated a positive relationship between biotic impairments and deposited sediment. Embeddedness can also lead to loss of refuges from predators (Jones et al. 2012), which may explain effects on abundance.

Conductivity was among the top 3 most influential sediment parameters for %E, %PT-H, and HBI. Elevated conductivity has been associated with increased invertebrate toxicity in laboratory studies (Kennedy et al. 2005) and with shifts in community structure (Pond 2010; Timpano et al. 2015; Boehme et al. 2016). Effects of conductivity are likely to vary with salt composition and sediment source (Cormier et al. 2013; Cook et al. 2015).

Evaluation of individual ecoregions revealed stronger associations between sediment parameters and VSCI scores than were identified in the combined-region evaluation for each ecoregion except the Piedmont (Table 3). Regression models explained between 20.2% (Piedmont) and 76.4%

Table 3. Coefficients of elastic net regression—individual ecoregional assessments[a]

Metric	Level III ecoregion	Coefficients for VSCI					
			Mountain bioregion (n = 164)			Piedmont bioregion (n = 210)	
		Combined regions n = 374	Blue Ridge n = 37	Ridge and valley n = 102	Central Appalachian n = 25	Northern Piedmont n = 46	Piedmont n = 164
Dissolved							
Conductivity (log)		−9.69	5.86	**−4.62**	**−14.17**	**−18.14**	**−20.16**
TDS (log)		0.61	−0.24	1.67	**−2.18**	−2.27	−0.06
Suspended							
TSS (log)		−0.57	**11.54**	−1.91	−0.29	0.73	−1.16
Turbidity (log)		−4.71	**−17.86**	−1.82	—	2.57	—
Bedded							
Embeddedness (asin sqrt)		**−20.56**	0.57	−3.98	—	**16.58**	**−9.27**
% Fines (asin sqrt)		**14.10**	−3.56	0.14	—	−0.48	6.10
% Sand (asin sqrt)		**15.07**	9.50	**5.94**	—	**6.92**	**9.66**
Relative bed stability (log)		−1.10	−5.74	−2.88	**2.16**	1.88	1.92
Median particle size (log)		4.50	**14.48**	**6.97**	—	6.49	0.42
Deviance ratio		*0.274*	*0.764*	*0.342*	*0.486*	*0.341*	*0.200*
Intercept		86.2	38.3	68.1	96.11	78.46	99.63

[a]Bold red font indicates the top 3 most influential sediment parameters in each model. Deviance ratio indicates the proportion of variance in the metric explained by the model.

(Blue Ridge) of variance in VSCI scores within ecoregions. While bedded sediment traits remained among the top 3 most influential parameters in each ecoregion, conductivity was also important in the Ridge and Valley, Central Appalachian, Northern Piedmont, and Piedmont ecoregions. Suspended sediment traits (both TSS and turbidity) were of primary influence on stream condition in the Blue Ridge ecoregion. The 3 ecoregions within the Mountain bioregion appear to have different responses to the various sediment parameters, while the 2 ecoregions within the Piedmont bioregion are similar to each other in sediment responses. The most influential sediment parameters for a given region may provide insight into the mechanisms driving sediment effect for a majority of macroinvertebrates in that region. Embeddedness suggests mechanisms of effect related to physical habitat, including suitable living space and refuge from predators; conductivity suggests physiological stress; and suspended sediment may indicate effects such as abrasion, clogging of feeding apparatus, or visual impairment. These findings reinforce that sediment is a multifaceted stressor not adequately represented by a single parameter and the importance of regional studies for the derivation of biologically relevant sediment criteria.

Sensitivity thresholds for embeddedness

On the basis of our results, we developed sensitivity thresholds for embeddedness and conductivity for the 5 combined ecoregions, the Mountain bioregion, and the Piedmont bioregion. Family-specific extirpation concentrations (XC95s) for embeddedness ranged from 62% to 99% and varied with bioregion (Table 4). XC95 values for Caenidae (small squaregill mayflies), Capniidae (small winter stoneflies), and Perlidae (common stoneflies) differed by more than 20% between Mountain and Piedmont bioregions. This difference could reflect differences in the genera present between bioregions and associated differences in sensitivities or may indicate regional adaptations to prevailing embeddedness conditions. Instream embeddedness levels were generally greater in the Piedmont bioregion (range, 24.4%–100%) than in the Mountain bioregion (range, 0.73%–95.8%). We identified community sensitivity thresholds for embeddedness at 68% for the combined ecoregions, 65% for the Mountain bioregion, and 88% for the Piedmont bioregion (Figure 3, a–c). This pattern indicates that macroinvertebrate communities in Mountain streams are much more sensitive to embeddedness than communities in Piedmont streams.

Our findings may be useful to states seeking to set embeddedness standards for stream impairment. We did not identify any states with quantitative benchmarks for embeddedness, although some states have narrative criteria prohibiting "bottom deposits" that adversely affect aquatic life (USEPA 2006a). The Idaho Department of Environmental Quality investigated appropriate sediment targets to aid in

Table 4. Family extirpation concentrations and community effects thresholds for embeddedness and conductivity

Invertebrate family	95th percentile extirpation level [XC95]								
	Combined regions (n = 373)			Mountain bioregion (n = 164)			Piedmont bioregion (n = 209)		
	Nr. stations detected	Embeddedness (%)	Conductivity (µS/cm)	Nr. stations detected	Embeddedness (%)	Conductivity (µS/cm)	Nr. stations detected	Embeddedness (%)	Conductivity (µS/cm)
Aeshnidae	36	> 99	1004	1	—	—	35	> 98	210
Ancylidae	77	> 95	> 773	27	79	773	50	> 95	> 561
Asellidae	25	100	498	10	—	—	15	> 100	176
Athericidae	35	68	> 1004	29	67	> 1004	6	—	—
Baetidae	260	94	> 779	122	82	> 779	138	> 95	> 329
Baetiscidae	25	> 100	277	5	—	—	20	95	127
Brachycentridae	34	93	366	15	82	366	19	100	149
Caenidae	77	98	747	32	73	> 646	45	> 99	> 561
Calopterygidae	40	> 100	754	8	—	—	32	> 100	> 264
Cambaridae	67	96	754	21	87	747	46	96	203
Capniidae	93	91	> 1004	30	65	1004	63	91	231
Ceratopogonidae	54	95	513	25	93	513	29	99	176
Chironomidae	359	> 95	> 910	160	> 87	> 910	199	> 95	> 561
Chloroperlidae	45	68	391	37	64	391	8	—	—
Coenagrionidae	69	99	773	23	92	773	46	> 100	> 561
Corbiculidae	87	> 94	> 997	25	> 92	> 1156	62	> 95	> 561
Corydalidae	154	89	> 839	64	93	> 839	90	90	> 439
Crangonyctidae	16	> 96	747	0	—	—	16	96	> 561
Dixidae	18	95	401	7	—	—	11	—	—
Dryopidae	50	> 96	575	4	—	—	46	94	> 329
Elmidae	346	> 95	> 910	155	> 87	> 910	191	> 95	> 561
Empididae	60	> 96	> 779	24	> 93	779	36	> 95	192
Ephemerellidae	182	> 96	513	93	90	> 513	89	> 98	210
Ephemeridae	16	83	513	12	—	—	4	—	—

(*Continued*)

Table 4. *(Continued)*

	95th percentile extirpation level [XC95]														
	Combined regions (n = 373)					Mountain bioregion (n = 164)					Piedmont bioregion (n = 209)				
Invertebrate family	Nr. stations detected		Embeddedness (%)		Conductivity (μS/cm)	Nr. stations detected		Embeddedness (%)		Conductivity (μS/cm)	Nr. stations detected		Embeddedness (%)		Conductivity (μS/cm)
Ephemeroptera	19		94	>	839	13		—		—	6		—		—
Gammaridae	15	>	100		398	2		—		—	13		—		—
Glossosomatidae	25		82	>	1004	18		86	>	1004	7		—		—
Gomphidae	102	>	95		1004	36		93		1004	66	>	98	>	264
Heptageniidae	335	>	95	>	839	151		85	>	839	184	>	95	>	561
Hydracarina	83	>	94	>	1004	27		80	>	1004	56		94	>	295
Hydropsychidae	348	>	93	>	910	161	>	87	>	910	187		94	>	561
Hydroptilidae	32		92	>	773	14		—		—	18	>	95	>	210
Isonychiidae	194		87	>	839	103		79	>	839	91		92		192
Lepidostomatidae	15		65		401	10		—		—	5		—		—
Leptoceridae	50	>	100		618	5		—		—	45	>	99		210
Leptohyphidae	15	>	100		646	3		—		—	12		—		—
Leptophlebiidae	135	>	96		528	72		92		513	63	>	100		200
Leuctridae	48		95		513	29		92		513	19		98		86
Limnephilidae	39		93		453	21		92		453	18		96		94
Lumbriculidae	48		87		646	20		82		646	28		89	>	439
Naididae	39		94	>	997	24	>	93	>	997	15		94	>	561
Oligochaeta	95	>	98	>	839	37		92	>	839	58	>	95		200
Peltoperlidae	35		76		401	25		69		401	10		—		—
Perlidae	167		89		498	74		65		498	93	>	92	>	329
Perlodidae	62		98		453	29	>	93		453	33		98		231
Philopotamidae	214	>	93		531	90		87		747	124		95	>	439
Physidae	35	>	98		747	5		—		—	30	>	98	>	561

Planorbidae	44	>	100		747	2		—		—	42	>	100	>	561
Plecoptera	30		95		466	17		93		466	13		—		—
Pleuroceridae	112		92	>	485	64	>	83	>	485	48		93		200
Polycentropodidae	35		96		618	16		92	>	618	19		99		200
Psephenidae	175		78	>	1004	119		79	>	910	56		83	>	329
Psychomyiidae	15	>	95		366	5		—		—	10		—		—
Pteronarcyidae	40		87		329	22		79		329	18		87		206
Ptilodactylidae	31		95		317	6		—		—	25		95		—
Rhyacophilidae	64		69		1156	47		82		1156	17		75		—
Simuliidae	203	>	93	>	997	86	>	87	>	997	117		94		—
Sphaeriidae	41	>	100	>	646	8		—		—	33	>	100		—
Taeniopterygidae	97	>	98	>	1156	36		92		1156	61	>	98		—
Talitridae	18	>	100		747	0		—		—	18	>	100		—
Tipulidae	221	>	94	>	910	92	>	90	>	910	129		95		—
Trichoptera	15		62		618	12		—		—	3		—		—
Tricladida	24		83	>	747	12		—		—	12		—		—
EC05 community sensitivity threshold			**68**		**366**			**65**		**391**			**88**		**136**
Bootstrapping mean			72		269			62		360			87		122
95% confidence interval			64–80		176–356			54–68		311–400			81–90		94–156
Range of sediment parameter			0.74–100		9.55–1167			0.73–95.8		9.55–1167			24.4–100		18.00–753.5

— = Family was detected in less than 15 samples and was excluded from threshold assessment. 95% confidence interval on the mean EC05 generated via bootstrapping. XC95 values that are undefined are indicated by ">". EC05 = effects concentration for fifth percentile of macroinvertebrate community; XC95 = extirpation levels as percent of embeddedness.

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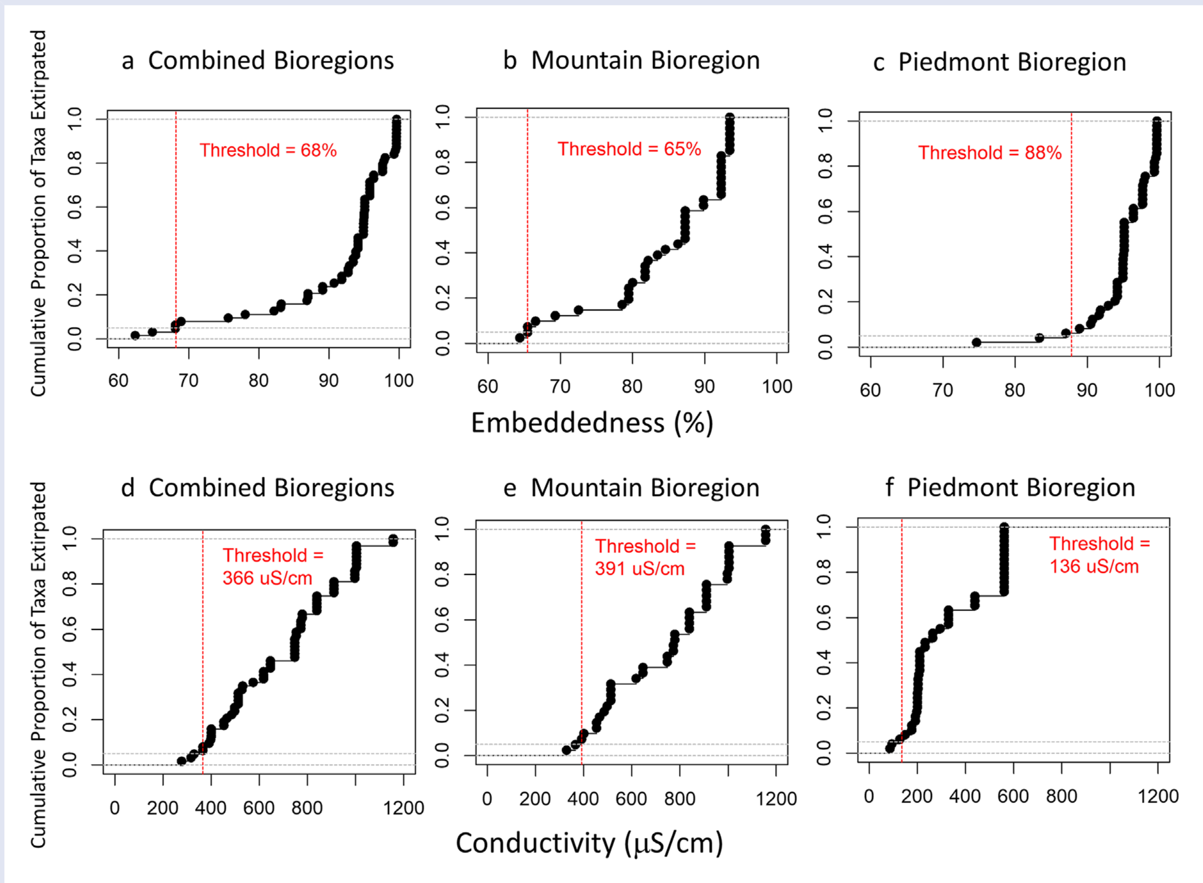

Figure 3. Macroinvertebrate community sensitivity thresholds for embeddedness and conductivity. Red vertical dashed line indicates threshold at which 5% of the community is extirpated.

gauging the attainment of their narrative criteria ("sediment. . .shall not exceed quantities. . .which impair beneficial uses"). They concluded that they could not recommend a specific target for embeddedness and instead recommended that reference streams be used to establish appropriate levels (Rowe et al. 2003). Zheng et al. (2015) report a RBP embeddedness score (*sensu* Barbour et al. 1999) stressor response threshold for West Virginia of less than 13 (corresponding to 25%–50% embeddedness) for "plausible effects" on the West Virginia Biological Stream Condition Index and a score of less than 9 (corresponding to 50%–75% embeddedness) for "substantial effects." These values are slightly lower than the response threshold identified in this study, likely reflecting regional differences in background embeddedness condition. No quantitative or narrative criteria for embeddedness have been established in VA.

Considering the potentially significant effect of embeddedness on macroinvertebrate communities indicated here, embeddedness may warrant inclusion as a monitoring and restoration endpoint (see also Wharton et al. 2017). Many approaches to measure embeddedness are time intensive and subjective, and the approach used may affect resulting estimates (McHugh and Budy 2005). Further, embeddedness measurements can be influenced by interactions between inorganic and organic matter (Jones et al. 2014) and in such cases may represent more than inorganic sediment condition alone. The embeddedness parameter evaluated here is the mean of 55 observations (Table 1), and VDEQ field biologists are specially trained to not let organic matter drive embeddedness scores and to reduce overall subjectivity of this measure. Still, the thresholds developed here should be interpreted and applied with caution. Less subjective, quantitative methods exist that can be used to provide more automated and repeatable embeddedness estimates (Descloux et al. 2010); for example, streambed hydraulic conductivity is a particularly promising approach that shows high correlation to fine sediment measures from frozen sediment cores (Descloux et al. 2010; Datry et al. 2015).

Sensitivity thresholds for conductivity

Family-specific extirpation concentrations for conductivity ranged from 86 to 1156 μS/cm and varied with bioregion (Table 4). The largest variation in XC95 values between Mountain and Piedmont bioregions were found in Capniidae, Gomphidae (clubtail dragonflies), and unidentified families in the clade Hydracarina (water mites). Again, this could reflect differences in the genera present between bioregions and associated differences in sensitivities or may indicate regional adaptations to prevailing conductivity conditions. The upper bound of instream conductivity levels was greater in the Mountain bioregion (range, 9.55–1167 μS/cm) than in the Piedmont bioregion (range, 18.0–753.5 μS/cm). It should be noted that the range of conductivity observed here is much lower than the range reported for Central Appalachian streams influenced by surface mining, which had an upper bound of 11 646 μS/cm (USEPA 2011). Effects of conductivity on invertebrates can be influenced by salt composition

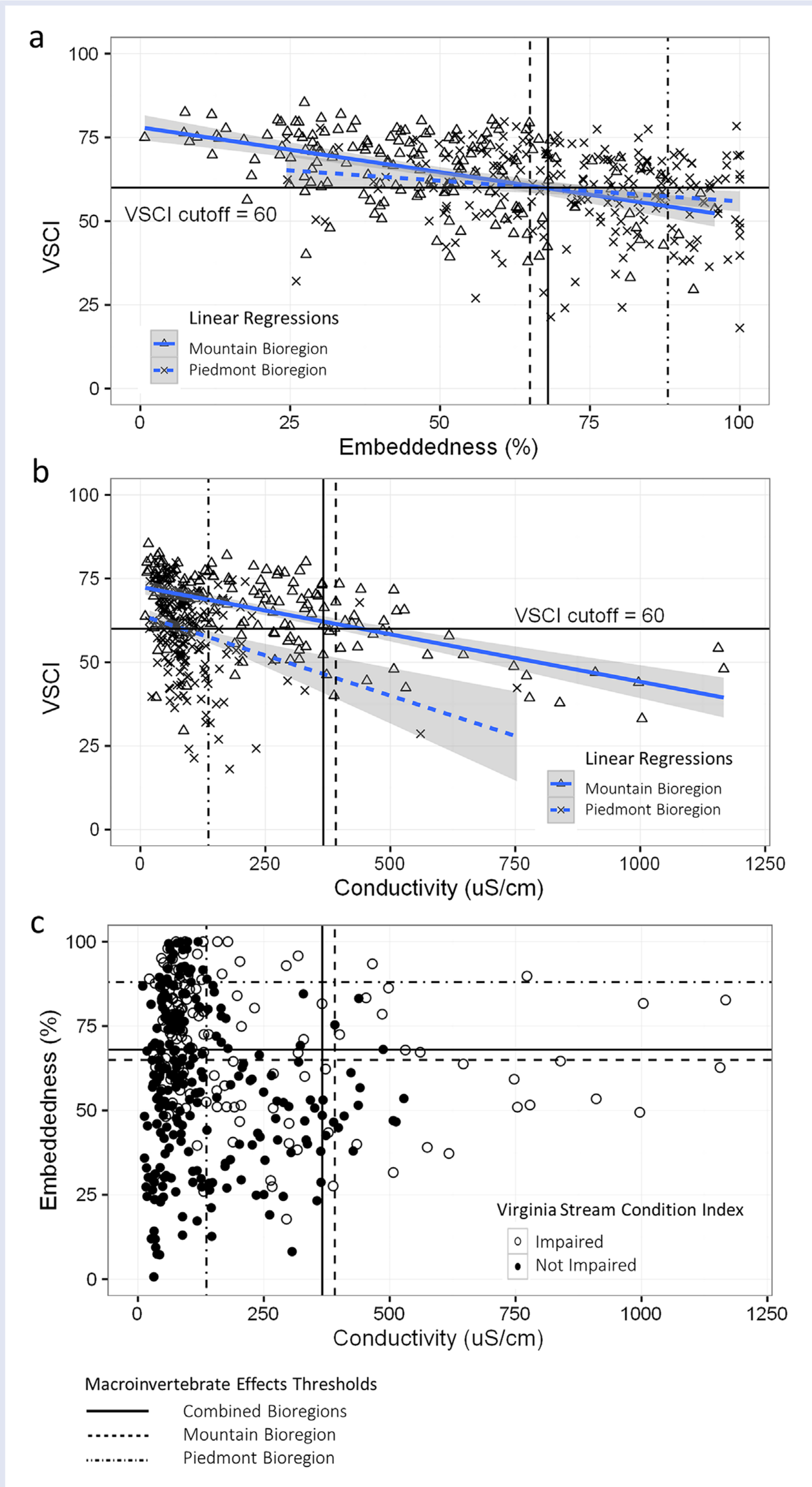

Figure 4. Relationships between embeddedness, conductivity, and virginia stream condition index (VSCI). VSCI response to (a) embeddedness and (b) conductivity in Mountain versus Piedmont bioregions. Shading indicates 95% confidence interval of simple linear regression. (c) Combined embeddedness and conductivity data space and stream impairment status: impaired streams VSCI < 60 (open circles) and nonimpaired streams VSCI > 60 (closed circles).

(Clements and Kotalik 2016), which can vary with source areas (e.g., mining, agricultural, or urban landscapes and varying underlying geologies). We identified community sensitivity thresholds for conductivity at 366 μS/cm for the combined ecoregions, 391 μS/cm for the Mountain bioregion, and 136 μS/cm for the Piedmont bioregion (Figure 3, d–f). This pattern indicates that macroinvertebrate communities in Piedmont streams are much more sensitive to conductivity than communities in Mountain streams.

Our findings may be useful to states seeking to set or refine conductivity standards for stream impairment. VDEQ has determined that dissolved sulfate, chloride, sodium, and potassium are ions that have an effect on benthic communities in the state (VDEQ 2017). VDEQ identified 4 categories of conductivity and associated probability of stress to aquatic life based on odds ratios and VSCI scores: less than 250 μS/cm = "none"; 250–350 μS/cm = "low"; 350–500 μS/cm = "medium"; and more than 500 μS/cm = " high" (VDEQ 2017). Our multiregion threshold of 366 μS/cm aligns with VDEQ's low-to-medium stress threshold, while our estimated mean EC05 derived from bootstrapping (269 μS/cm; Table 4) is closer to VDEQ's more conservative none-to-low stress boundary. Both measures (366 μS/cm and 269 μS/cm) are similar to the USEPA's benchmark of 300 μS/cm for neutral to alkaline waters predominated by sulfate salts (USEPA 2011; Cormier et al. 2013; USEPA 2016c). Our Piedmont bioregion threshold (136 μS/cm) is generally consistent with genus-based thresholds for the Piedmont and Northern Piedmont ecoregions estimated by Cormier et al. (2018a; 138 μS/cm and 227 μS/cm, respectively). However, our Mountain bioregion threshold (391 μS/cm) indicates a lower community-level sensitivity to conductivity than reported by Cormier et al. (2018a) in the Blue Ridge, Ridge and Valley, and Central Appalachian ecoregions (69 μS/cm, 154 μS/cm, and 305 μS/cm, respectively).

Multiple stressor effects

Macroinvertebrates in the Piedmont bioregion were less sensitive to embeddedness and more sensitive to conductivity than macroinvertebrates in the Mountain bioregion (Figure 3). These findings may reflect the differential adaptive pressures on invertebrate populations in these ecoregions. Observed instream embeddedness in the Piedmont bioregion is greater than that in the Mountain bioregion (Table 4, Figure 4a), likely reflecting the Piedmont's naturally sandier habitats. Similarly, surface waters in the Piedmont are less likely to exhibit high conductivity levels (Table 4, Figure 4b). Population sensitivities in both regions are greater for the stressor less commonly encountered in the region. Differences in relative sensitivities are also evident by comparison of simple linear regressions between VSCI scores and stressors for each region, with steeper slopes indicating greater sensitivity (Figure 4, a and b).

Visualization of the combined embeddedness-conductivity data space (Figure 4c) reveals that while both stressors influence biological condition, passing (not impaired) VSCI scores are more limited by high conductivity than by high embeddedness. Streams with both high conductivity and high embeddedness are the least likely to support healthy macroinvertebrate communities; this result reflects the multiple stressor effects. Awareness of the potential additive, antagonistic, or synergistic effects of stressors is necessary both for accurate stressor identification and for effective design of remediation plans.

CONCLUSIONS

The work presented herein provides new insights into the complex relation between instream sediment and macroinvertebrate community composition. This study is the first to quantitatively determine the sediment parameters most strongly associated with benthic macroinvertebrate community responses across regional contexts. It is also the first to develop quantitative thresholds for macroinvertebrate community-level sensitivity to embeddedness. This work suggests that embeddedness may warrant closer consideration as a monitoring or restoration endpoint, including development of more standardized methods for measuring embeddedness. In addition, our work reaffirms the importance of conductivity to stream macroinvertebrates and identifies bioregion-specific thresholds for family-level occurrences in VA. Distinct differences in macroinvertebrate sensitivity to both embeddedness and conductivity between Mountain and Piedmont bioregions (and among montane ecoregions) highlight the importance of studies based on biologically relevant spatial units rather than on political boundaries and suggest that effective management of sediment requires region-specific approaches. We encourage refinement of the sensitivity thresholds identified herein as additional stations are sampled and as sufficient genus-level data become available. Further, we suggest that coordination between states to develop sediment-sensitivity thresholds for shared ecoregions will enhance states' efficacy in managing excess sediment and attaining water quality goals.

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Data Accessibility—Data are publicly available at the Virginia Department of Environmental Quality website: www.vdeq.gov; ProbMon Data Set 2001–2014, updated March 2017 and Family Macroinvertebrate EDAS Database,

updated March 2017. Data selected for evaluation from the VDEQ database using the criteria explained herein are available on request from the corresponding author, Heather Govenor, at hgovenor@vt.edu.

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