ESTIMATING EMBEDDEDNESS FROM BANKFULL SHEAR VELOCITY IN GRAVEL STREAMBEDS TO ASSESS SEDIMENT IMPACTS ON AQUATIC BIOTA

Sierra Smith

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Biological Systems Engineering

Jonathan A. Czuba
Tess W. Thompson
Kyle Strom

May 4, 2023
Blacksburg, VA

Keywords: embeddedness, fine sediment, shear velocity, remote sensing

ESTIMATING EMBEDDEDNESS FROM BANKFULL SHEAR VELOCITY IN GRAVEL STREAMBEDS TO ASSESS SEDIMENT IMPACTS ON AQUATIC BIOTA

Sierra Smith

ABSTRACT

Previous research efforts have shown that fish and macroinvertebrates are responsive to fine sediment in streambeds. Excess fine sediment (<2mm in diameter) impairs over 40,000 miles of streams in the U.S., degrading habitat quality for many aquatic species. Embeddedness (*emb, %*), a measure of fine sediment in gravel bed streams, is negatively correlated with bankfull shear velocity (u_*, *m/s*). This relationship can be modeled by $emb = au_*^b$, with baseline coefficient values of a = 10 and b = –1. The purpose of this thesis was to investigate the applicability of this relationship across the U.S., to begin to quantify the variation of embeddedness in time, and to determine the applicability of embeddedness as a habitat metric for lotic biota. The areas that were studied included Stroubles Creek at the Virginia Tech Stream Lab, the Upper Roanoke River Basin in southwest Virginia, and Level II and III ecoregions nationwide with the U.S. EPA National Rivers and Streams Assessment dataset. Nationally, measurements of embeddedness were higher than modeled in areas with higher sediment supply, and lower than modeled in regions with low fine sediment supply. By calculating shear velocity through remotely sensed channel geometry metrics, embeddedness may be predicted throughout a stream network. Various biotic metrics were found to be correlated to embeddedness, with regional variation. Burrowing macroinvertebrate taxa, which may use increased sand to escape predation, increased with increasing embeddedness while the number of Ephemeroptera, Plecoptera, Trichoptera (EPT) taxa, the number of lithophilic spawning fish, and the number of salmonid taxa decreased with increasing embeddedness. Highly embedded substrate is generally considered poor habitat, which was supported by a trend of decreasing intolerant fish taxa with increasing embeddedness. Richness (total number of taxa) did not show a significant correlation, indicating that embeddedness, and fine sediment in general, is not necessarily an impairment to all stream habitat, but is impactful for particular taxa.

ESTIMATING EMBEDDEDNESS FROM BANKFULL SHEAR VELOCITY IN GRAVEL STREAMBEDS TO ASSESS SEDIMENT IMPACTS ON AQUATIC BIOTA

Sierra Smith

GENERAL AUDIENCE ABSTRACT

Previous research has shown that fish and macroinvertebrates are responsive to fine sediment in streambeds. Excess fine sediment (sand, silt, and clay) impairs over 40,000 miles of streams in the U.S., degrading habitat quality for many aquatic species. Embeddedness (*emb, %*), a measure of fine sediment in gravel bed streams, decreases with increasing bankfull shear velocity (*u*, m/s*), a measure of a stream's ability to move a particular size of sediment. The purpose of this thesis was to investigate the relationship between embeddedness and shear velocity in varying areas, to begin to quantify the variation of embeddedness in time, and to determine the applicability of embeddedness as a habitat metric for stream biota. The areas that were studied included Stroubles Creek at the Virginia Tech Stream Lab, the Upper Roanoke River Basin in southwest Virginia, and Level II and III ecoregions nationwide with the U.S. EPA National Rivers and Streams Assessment dataset. Nationally, measurements of embeddedness were higher in areas that may have higher sediment supply, and lower in regions with low fine sediment supply. By calculating shear velocity with remotely available stream data, embeddedness may be predicted throughout a stream network and compared with biota in those locations. Various biotic metrics were found to be correlated to embeddedness, with regional variation. Burrowing macroinvertebrate taxa, which may use increased sand to escape predation, increased with increasing embeddedness while the number of Ephemeroptera, Plecoptera, Trichoptera (EPT) taxa, the number of lithophilic spawning fish, and the number of salmonid taxa decreased. Highly embedded substrate is generally considered poor habitat, which was supported by a trend of decreasing intolerant fish taxa with increasing embeddedness.

Acknowledgements

Thank you to my advisor, Dr. Jon Czuba and my committee members Dr. Tess Wynn Thompson and Dr. Kyle Strom for your thoughtful instruction, support and interest. Thank you to Nicholas Christensen for your persistent enthusiasm. Thanks to Diana Schmidt for being my Bollos buddy. Thank you to the many people who helped me collect and measure rocks: Ellie Buehrer, Reilly Oare, Amara Shareef, Shashwat Dhanuka, Natty Abrahams, Sam Weatherly, Nathan Michaelson, and Justus Hargett within the Czuba group as well as Simone Gibson, Griffin Brandstetter, and Mr. Tim Smith. Thank you to Iris and Paula Smith for fielding phone calls at any hour of the day, and for your continuous love and support. Thank you to Sally Entrekin and Paul Angermeier for your consultation on the biotic aspects of this research. Thank you to the Stream Team for welcoming me into discussions about biology, forecasting, and communication. Thanks to the patrons of the Rivermill Bar and Grill for being additional communication sounding boards. Thank you to Laura Lehmann, for construction of the randomizer and assistance in data acquisition at the StREAM Lab. This work was partially supported by the National Science Foundation (NSF-EAR 2243003). This work would not have been made possible without Sakura, the best field dog in the business.

Table of Contents

Acknowledgements iv

List of Figures vii

List of Tables x

1. Introduction 1

1.1 Streambed sediments and biota 1

1.2 Study objectives 3

1.3 Theoretical underpinnings relating physical stream characteristics to embeddedness 4

2.1 Stream Lab 8

2.2 Upper Roanoke River Basin 9

2.3 National scale 10

3.1 General field methods for measuring embeddedness 11

3.2 Stroubles Creek Field Methods 12

3.2 Field, Upper Roanoke 13

3.2.1 Repeated embeddedness measurements, Upper Roanoke 13

3.2.2 NRSA method in Upper Roanoke 14

3.2.3 Surveying for channel dimensions 14

3.2.4 Sand collection, Upper Roanoke 16

3.3 Remotely sensed methods, Upper Roanoke 16

3.4 NRSA analysis 17

3.4.1 NRSA physical habitat 17

3.4.2 NRSA biotic metrics 18

4 Results 19

4.1 Stream lab 19

4.2 Upper Roanoke 20

4.3 National scale 25

4.3.1 National scale embeddedness and shear velocity 25

4.3.2 National scale embeddedness and biotic metrics 29

5. Discussion 40

5.1 Temporal variability in embeddedness 40

5.2 Regional variability in model fit 41

5.3 Functional relationships between macroinvertebrates and embeddedness 42
5.4 Fish metrics and embeddedness 42
5.5 Regional variability in relationship between embeddedness and biotic metrics 43
5.6 General limitations of model 43
5.7 Biotic applicability 44
6. Future Work 45
7. Conclusions 46
References 47

List of Figures

Figure 1. Embeddedness is a spatial average of the vertical extent to which a particle is surrounded by a finer (< 2 mm) substrate…….……..1

Figure 2. Diagram of embeddedness predicted from shear velocity (Czuba et al. 2022) ……5

Figure 3. Conceptual diagram of the relationship between embeddedness and other physical parameters……6

Figure 4. Conceptual diagram relating mobile bed conditions and embeddedness.……7

Figure 5. Map of Stream Lab study sites for repeated measurements of embeddedness……9

Figure 6. Upper Roanoke River Basin study sites in southwest Virginia……10

Figure 7. Map of 2,804 sites from the U.S. EPA NRSA dataset (2008/09, 2013/14, and 2018/19) where embeddedness, bankfull depth, and slope were measured……11

Figure 8. 0.6 m by 0.6 m aluminum pipe and string quadrant used to randomly select pebbles for embeddedness measurements…….12

Figure 9. Diagram of two quadrat placements, one adjacent to the cross section and one offset in the downstream direction by 1 m……13

Figure 10. Representative cross section from site 1……15

Figure 11. Longitudinal profile from site 1……15

Figure 12. Embeddedness measurements at Stroubles Creek and stage measured at Bridge 1 near site 1, April to November 2022……..19

Figure 13. Paired measurements of embeddedness at Stroubles Creek…….20

Figure 14. Measured embeddedness and reach-averaged shear velocity calculations……21

Figure 15. Modeled and measured embeddedness in the Upper Roanoke River Basin……22

Figure 16. Comparison of average embeddedness measured with Czuba et al. (2022) and with NRSA methods……...23

Figure 17. Comparison of embeddedness measurement methods in the Upper Roanoke River Basin……..24

Figure 18. Embeddedness measurements and discharge measurements at sites 15, 17, and 18 on the Roanoke River in Glenvar (site 15) and Lafayette VA (sites 17 & 18)……...24

Figure 19. Predicted embeddedness and Upper Roanoke River Basin sites…….25

Figure 20. Selected Level III ecoregions. (A) range of values for selected ecoregions, (B) shear velocity vs. embeddedness for all NRSA sites, with selected ecoregions highlighted, (C) deviation

of measured embeddedness from modeled, where positive values are more embedded than modeled and negative values are less, (D) map of selected ecoregions……...26

Figure 21. Modeled and measured embeddedness for selected Level III ecoregions: Klamath Mountains (6.2.11), Central Basin and Range (10.1.5), Chihuahuan Desert (10.2.4), Driftless Area (8.1.5), and the Valley and Ridge (8.4.1). Regressions for individual ecoregions are displayed with colored dotted lines and the 1:1 line where the measured embeddedness is equal to modeled embeddedness is displayed with black dashed lines……...27

Figure 21. Median deviations by Level III ecoregion from modeled embeddedness……27

Figure 23. Median deviations by Level II ecoregion from modeled embeddedness…….28

Figure 24. Relationship between two fine sediment metrics included in the NRSA dataset…….29

Figure 25. Impact of bedrock on embeddedness model with NRSA dataset…….29

Figure 26. Positive correlation between embeddedness and % burrower taxa mapped by Level III ecoregion……31

Figure 27. Positive correlation between embeddedness and % burrower taxa mapped by Level II ecoregion……31

Figure 28. Embeddedness and percentage of taxa that are burrowers with points from the Central Basin and Range (10.1.5) and the Ridge and Valley (8.4.1) regions highlighted……..32

Figure 29. Negative correlation between embeddedness and number of EPT taxa mapped by Level III
ecoregion……33

Figure 30. Negative correlation between embeddedness and number of EPT taxa mapped by Level II ecoregion……33

Figure 31. Embeddedness and number of EPT taxa with points from the Central Basin and Range (10.1.5) and Ridge and Valley (8.4.1) regions highlighted……34

Figure 32. Negative correlation between embeddedness and number of lithophilic taxa mapped by Level III ecoregion…….35

Figure 33. Negative correlation between embeddedness and number of lithophilic taxa mapped by Level II ecoregion……..35

Figure 34. Embeddedness and number of lithophilic taxa with points from the Columbia Plateau (10.1.2) and the North Central Hardwood Forests (8.1.4) regions highlighted…….36

Figure 35. Negative correlation between embeddedness and number of intolerant fish taxa mapped by Level III ecoregion……37

Figure 36. Negative correlation between embeddedness and number of intolerant fish taxa mapped by Level II ecoregion…….37

Figure 37. Embeddedness and number of intolerant fish taxa with points from the Central Basin and Range and Columbia Plateau regions highlighted……..38

Figure 38. Negative correlation between embeddedness and number of salmonid taxa mapped by Level III ecoregion…….39

Figure 39. Negative correlation between embeddedness and number salmonid taxa mapped by Level II ecoregion……..39

Figure 40. Embeddedness and number of salmonid taxa with points from the Central Basin and Range (10.1.5) region highlighted…….40

List of Tables

Table 1: Regional curve equations used to determine bankfull characteristics from drainage area in Upper Roanoke River Basin……...17

1. Introduction

1.1 Streambed sediments and biota

Excess fine sediment (<2mm in diameter) impairs over 40,000 miles of streams in the U.S. (USEPA, 2022), degrading habitat quality for many aquatic species (Kemp et al., 2011; Wharton et al., 2017; Wood & Armitage, 1997). Sediment may enter waterways through erosion of hillslopes or streambanks. Fine sediments may move through streams at higher flows as wash load or suspended load, or they might settle within streams, increasing fine sediment in the bed. Macroinvertebrate communities and some species of fish are known to be responsive to various metrics of sedimentation, especially fine sediment in the benthos (Govenor et al. 2019).

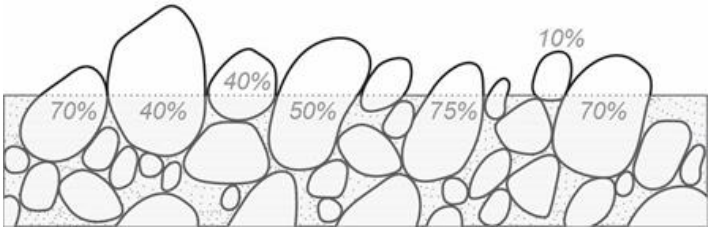

Figure 1. Embeddedness is a spatial average of the vertical extent to which a particle is surrounded by a finer (< 2 mm) substrate.

Embeddedness, or the degree to which gravel and larger particles are surrounded by sand and silt, can be an important habitat parameter for aquatic biota (Figure 1). Embeddedness decreases surface area available to benthic macroinvertebrates and fish, and therefore has been negatively correlated to general habitat suitability (Barbour et al. 1999). Sediment size controls the pore space in the bed, which influences which macroinvertebrates can live in the bed. When embeddedness is high, pore spaces between gravel and cobbles are filled with sand. Due to the filling of interstitial spaces with fine sediment, embeddedness has been found to reduce the availability of refugia used by invertebrates to avoid 'wash-out' during high flow events, affecting invertebrate distribution (Jones et al. 2011). In addition to direct habitat impacts, embeddedness or presence of sand in the bed impacts sediment transport. The grain size distribution of sediment on the bed affects transport of that sediment, with increased sand in the bed increasing the transport of gravel and cobbles (Wilcock and Crowe 2003). Juvenile salmonids have been found to have a decreasing growth rate and increasing mortality with increasing fine sediment loading, specifically measured via embeddedness (Suttle et al. 2004). Burrowing macroinvertebrate taxa, which are

unavailable as prey to salmon, have been found to have a significant positive linear relationship with embeddedness (Suttle et al. 2004).

Studies in Virginia and West Virginia have found embeddedness to be a significant factor for local endangered fish populations. Roanoke logperch (*Percina rex*) are an endangered fish in the North Fork Roanoke River where *P. rex* habitat is impaired by high sediment and embeddedness (Roberts et al 2016). Adults and juveniles preferentially use habitat with lower silt cover and embeddedness (Roberts et al. 2016). As lithophilic spawners, they lay their eggs in gravel or cobble. If the gravel is highly embedded, eggs are more likely to be flushed away due to decreased hiding effects. Alternatively, eggs might be buried and not receive the oxygen they require if there is excess fine sediment. For Candy Darters, *Etheostoma osburni*, an endangered fish in the New River basin, habitat selection has been characterized by shifts from the low-velocity, slightly embedded areas used by juvenile Candy Darters to the swift, shallow areas with little fine sediment and complex substrate, used by adults. Adult Candy Darters have been found to avoid areas with greater than 25% embeddedness (Dunn & Angermeier 2016).

Embeddedness is one of many habitat factors impacting these two species of fish and biota more generally. As such, embeddedness is generally measured along with other parameters to assess habitat available to fish or aquatic macroinvertebrates (Fitzpatrick et al. 1998; Sutherland et al. 2010) . While the pathways of embeddedness impacts on macroinvertebrates have been studied (Wood & Armitage 1997; Jones et al. 2011), there are multiple methods of obtaining embeddedness values that require varying amounts of time and expense. These range from quick visual estimation to determining a reach-averaged embeddedness by direct measurement of randomized pebbles. One common measure is a visual estimate as part of a Rapid Bioassessment Protocol (RBP) which rates embeddedness from 0-20 with 0 being 100% embedded and 20 being 0% embedded (Barbour et al. 1999). This method ranks 0-25% embeddedness as optimal and greater than 75% embeddedness as poor habitat, assuming a negative correlation between biota and fine sediment. Embeddedness of individual pebbles (as indicated by a percent in Figure 1) may be measured along specified cross sections and averaged to estimate percent embeddedness for the reach of stream (Fitzpatrick et al. 1998).

There are various field methods for quantifying embeddedness, but few methods of estimating it without direct measurement. Ongoing research indicates that embeddedness can be

predicted from channel geometry available from remotely sensed data (Czuba et al. 2022). Specifically, it has been demonstrated that there is a correlation between bankfull shear velocity and embeddedness in the Dan and Roanoke River Basins in southern Virginia and North Carolina (Czuba et al. 2022). "Bankfull" is the condition when water fills a stream channel to the top of its banks and mobilizes the streambed, is often considered the condition shaping channel form, and generally occurs at a frequency of 1~2 years, varying by region (Lindroth et al. 2020; Parker et al. 2007; Phillips & Jerolmack 2016). Shear velocity is related to the ability of a stream to mobilize a given particle and can be calculated from channel geometry. Further development of this relationship would allow for an alternative method of determining embeddedness. However, this relationship has not been explored outside of these basins, or over time.

1.2 Study objectives

The focus of this thesis is to further investigate the scope of applicability of the relationship between calculations of reach-averaged shear velocity at bankfull discharge and reach-averaged embeddedness as well as the biotic relevance of this relationship. The specific objectives are as follows:

1. Determine temporal variability in embeddedness via repeated measurements at Stroubles Creek and in the Upper Roanoke River Basin.
2. Determine regions nationally where embeddedness is significantly correlated with bankfull shear velocity as calculated by channel geometry.
3. Determine biotic metrics that are significantly correlated with embeddedness and the regional variation of that correlation.

Related to these objectives are the following hypotheses:

1. Because bankfull conditions occur every 1~2 years and stream capacity to mobilize sediment varies between bankfull events, embeddedness is expected to vary over time, with embeddedness measured being closest to embeddedness predicted directly following bankfull events.

2. Because sediment supply, geology, and frequency of bankfull events, etc. varies regionally, the model fits for ecoregions are expected to vary, with higher embeddedness than predicted occurring in higher fine sediment supply areas and lower embeddedness than predicted occurring in low fine sediment supply regions.

3. Because increased embeddedness is related to increased fine sediment generally, and burrowing macroinvertebrate taxa are protected from predation (Suttle et al. 2004) by fine sediment, percent burrower taxa are expected to increase with increasing embeddedness.

4. Because juvenile salmonid growth has been shown to decrease with increasing embeddedness, the number of salmonid taxa are expected to decrease with increasing embeddedness.

5. Because biota respond to a suite of environmental variables of which embeddedness is only one, the strength of correlations between embeddedness and biotic metrics are expected to vary by ecoregion.

6. Because biota have varying positive and negative responses to fine sediment, the total number of taxa for fish and for macroinvertebrates is not expected to be significantly correlated with embeddedness.

1.3 Theoretical underpinnings relating physical stream characteristics to embeddedness

The relationship proposed by Czuba et al. (2022) links embeddedness (*emb, %*) to shear velocity (u_*, *m/s*) with eq. 1, where a and b are empirical coefficients. For the generalized relationship, $a = 10$ and $b = 1$, though these coefficients may be locally calibrated to a region or study basin to account for unaccounted factors such as local sediment supply or sand grain size distribution. This may be used to calculate a baseline level of embeddedness, as illustrated in Figure 2.

$$emb = a\,(u_*)^{-b} \qquad (1)$$

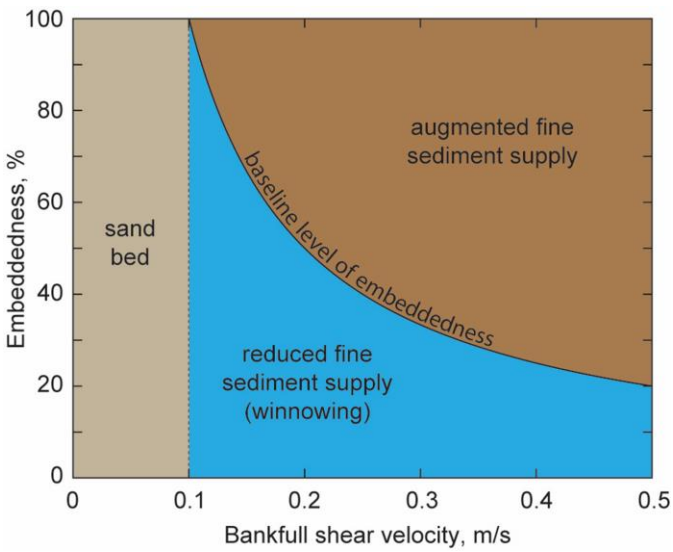

Figure 2. Diagram of embeddedness predicted from shear velocity (Czuba et al. 2022).

Shear velocity is a measure of the strength of turbulence in a stream, which is related to the ability of a stream to mobilize a given particle. Shear velocity can be calculated from channel geometry (eq. 2 & 3).

$$u*^{x} = \sqrt{gR_h S} \qquad (2)$$

$$u*^{\tau} = \left(\frac{\alpha_s}{R\tau_c}\right)^{1/18} \left(\frac{gQ_b}{aK_n B_b}\right)^{1/3} S^{7/18} \qquad (3)$$

Where gravity (g, 9.81 m/s^2), submerged specific gravity (R, 1.65), critical shear stress (τ_c , 0.04), Manning-Strickler log law velocity distribution coefficient (a, 8.1), unit conversion factor (K_n , 1 for SI units, 1.49 for English units), and roughness length scale (α_s , 2) are treated as constants. The 'x' indicates the shear velocity is calculated from a cross section and the τ indicates the shear velocity is calculated from the critical shear stress (Czuba et al., 2022). The hydraulic radius (R_h) can be approximated by depth for wide streams. The site-specific variables are bankfull depth (h), slope (S), and bankfull discharge and top width (Q_b and B_b , respectively). These may be measured in the field or through remote sensing. Bankfull depth, width, and discharge can be found from regional curves, empirical equations based on drainage area (Keaton 2005, Beiger 2015). Drainage area and slope can be calculated from digital elevation models (DEMs), which have been calculated from a 30 m DEM in the National Hydrography Dataset (NHD). Together, shear velocities can be calculated from these values (Figure 3).

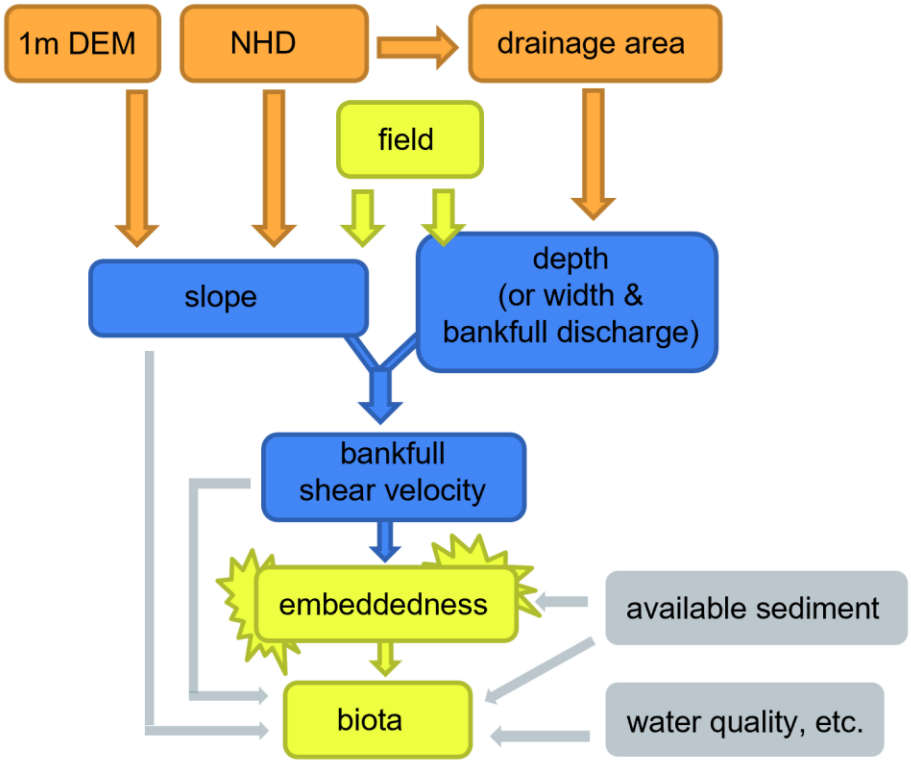

Figure 3. Conceptual diagram of the relationship between embeddedness and other physical parameters. Orange indicates remote sensing including 1-m digital elevation model (DEM) and stream maps available through the National Hydrography Database (NHD), yellow indicates field measurements, blue indicates that these variables can be obtained in multiple ways and gray indicates variables or relationships that are not considered in this study.

Shear velocity relative to fall velocity (w_s, *m/s*) at bankfull stage determines how fine sediment mobilized in the bed will be suspended in the water column. The threshold for particle suspension can be estimated by eq. 4, where α ranges from 0.4 to 1 (Gracia 2008). The fall velocity is calculated by eq. 5 (Ferguson and Church 2004). For this study, the grain size (D, *m*) is considered variable and g, R, and kinematic viscosity of water, ($\nu = 10^{-6}$ m^2/s) are considered constants. The grains are assumed to be spherical and smooth, giving the constants C_1 and C_2 the values 18 and 0.4, respectively.

$$u^*/w_s = \alpha \qquad (4)$$

$$w_s = \frac{RgD^2}{C_1\nu + (0.75\, C_2\, RgD^3)^{0.5}} \qquad (5)$$

As reach-averaged shear velocity increases, sand is increasingly transported higher in the water column, decreasing sand presence in the bed and thus percent embeddedness as the gravel

bed settles into place following a bed-mobilizing (approximated as bankfull) event, illustrated in Figure 4. Under bankfull shear velocities of approximately 0.1 m/s, the bed shifts from gravel to sand, which is equated to 100% embedded (Lamb & Venditti 2016). The value of 0.1 m/s for shear velocity corresponds to a fall velocity of a sand grain of approximately 0.7 mm when $\alpha = 1$ (Garcia 2008). Altering the median sand grain size would alter the threshold for the transition between sand and gravel bed rivers, or the shear velocity at which embeddedness is predicted to be 100% via eq. 1. For a constant α, shear velocity must increase with increasing median sand grain size. For example if the median grain size is 1.0 mm, the shear velocity associated with 100% embeddedness is 0.13 m/s and if the median grain size is 0.4 mm, the shear velocity associated with 100% embeddedness is 0.08 m/s (calculated from eq. 4 and 5).

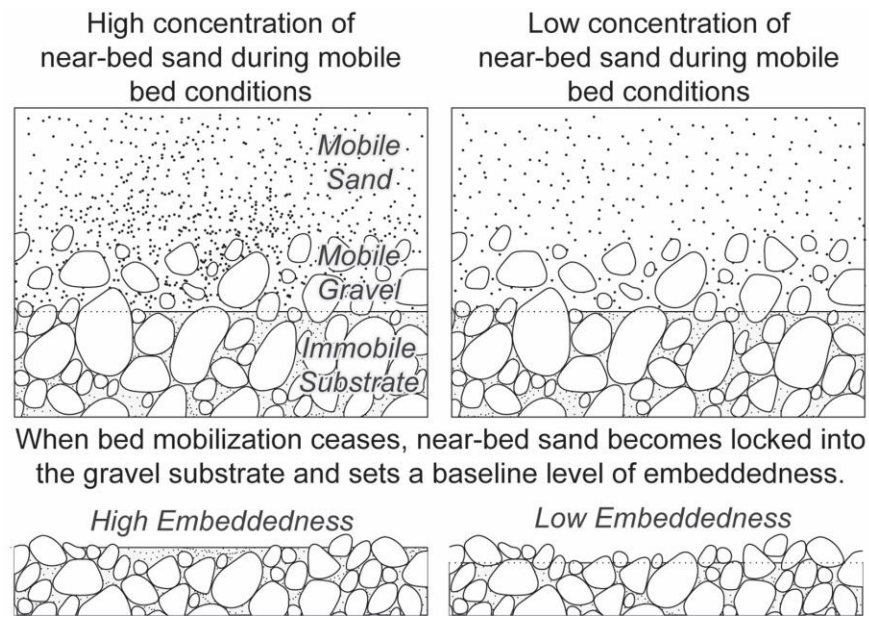

Figure 4. Conceptual diagram relating mobile bed conditions and embeddedness.

The model proposed by Czuba et al. (2022) and illustrated in Figure 2 is constrained to single thread gravel bed streams. In the characterizations of Montgomery and Buffington (1993), gravel bed streams can be characterized as either riffle-pool or plane bed. Riffle-pool streams have a typical slope of 0.001–0.02 and plane bed streams have a typical slope of 0.01–0.03 (Montgomery and Buffington 1993) indicating that the model (eq. 1) is most applicable for slopes ranging 0.001–0.03 (m/m). Cascade or step-pool systems may also contain significant amounts of gravel, but this model is not applicable for those stream types as these stream types have significant drag introduced by channel form (steps or large boulders) such that the reach averaged shear

velocity is not necessarily the shear velocity applied to gravel and sand grains. Additionally, these methods are also only relevant for urban streams when bankfull depth (or width and discharge) are directly measured as regional curves were developed in rural areas (Beiger 2015).

2. Study area

The scope of applicability and variation within the proposed embeddedness-shear velocity relationship was investigated over the span of three study areas. Work in the first study area, Stroubles Creek at the Virginia Tech StREAM Lab, focused on the temporal variability of embeddedness. The second study area, the Upper Roanoke River Basin, was used for a field-based assessment to assess spatial and temporal variability. The third study area was an analysis of embeddedness across the contiguous U. S. with data from the U.S. Environmental Protection Agency's National River and Stream Assessment (NRSA).

2.1 Stream Lab

The Virginia Tech StREAM Lab is a reach of Stroubles Creek in Blacksburg Virginia, 1.5 km long, with an average slope of 0.0023 m/m, a drainage area of 13.5 km^2, and a wetted width of approximately 2-3 m. Pressure transducers at two bridges measure the water stage. This existing instrumentation made this site ideal for repeated measurements of embeddedness in individual riffles and runs. Site 1 is situated in a riffle approximately 10 m upstream of Bridge 1, the location of one of the pressure transducers and one of the velocity sensors. Site 2 and 3 are located in runs upstream of Bridge 2, on either side of one of the velocity sensors. Site 4 is located in a riffle downstream of Bridge 2.

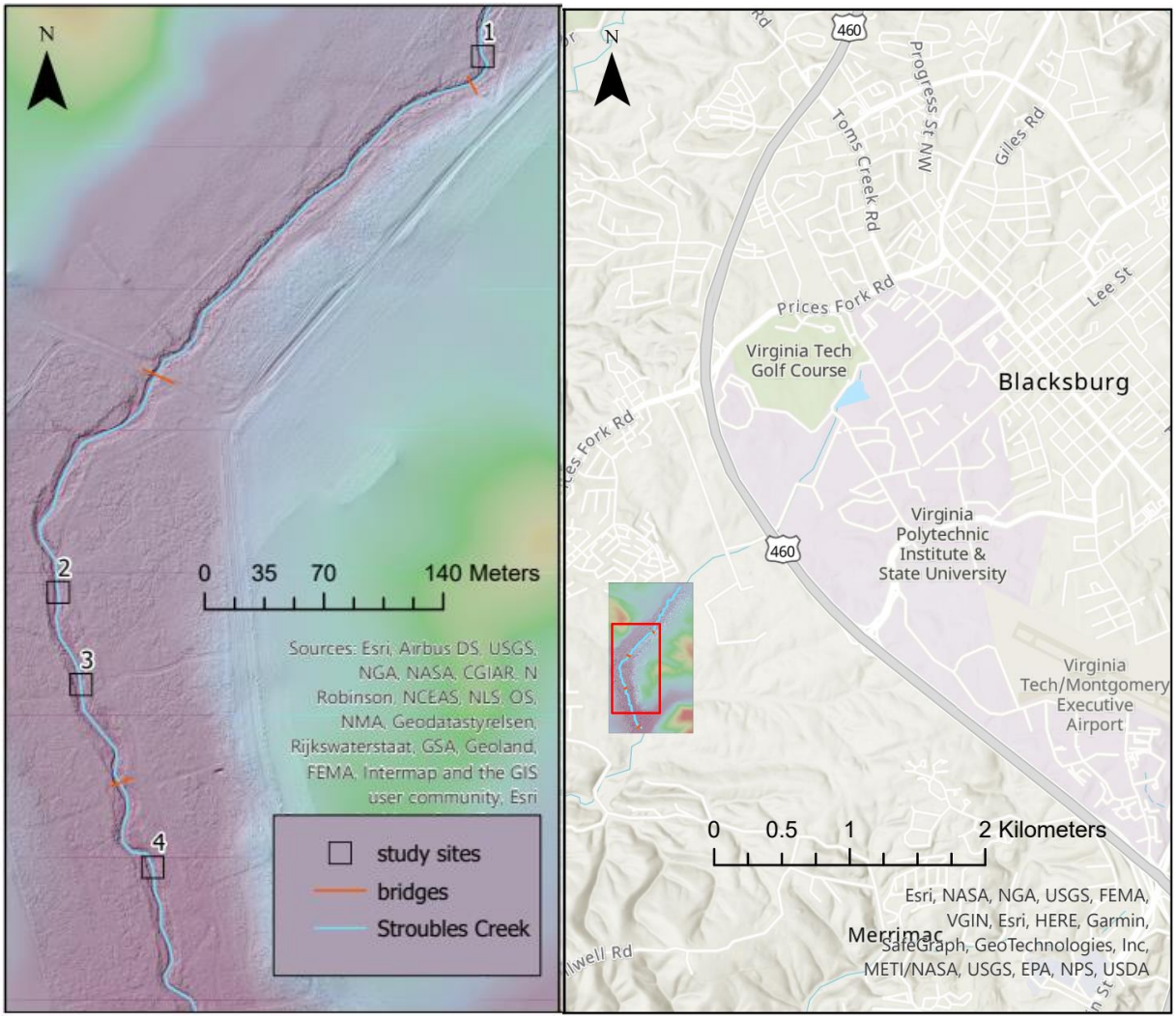

Figure 5. Map of Stream Lab study sites for repeated measurements of embeddedness, May-November 2022.

2.2 Upper Roanoke River Basin

Sites in the Upper Roanoke study area in Southwest Virginia were selected to span a range of slopes (0.0014 – 0.044 m/m) and drainage areas (3.8 – 728 km^2) and based on their accessibility, which included proximity to roads and bridges. This resulted in us identifying 21 sites (Figure 6). There are three sets of paired sites, where one site is upstream and the other is downstream of a proposed crossing of the Mountain Valley Pipeline. The intention with these paired sites was to be able to compare the difference between the measured and predicted embeddedness, upstream and immediately downstream to see if there was a difference on average and at specific times if construction (and associated increased sediment input) was ongoing. Additionally, three of the

sites are located near USGS gages that measure stage and discharge and two sites are located at USGS gages that are in place to measure water quality parameters.

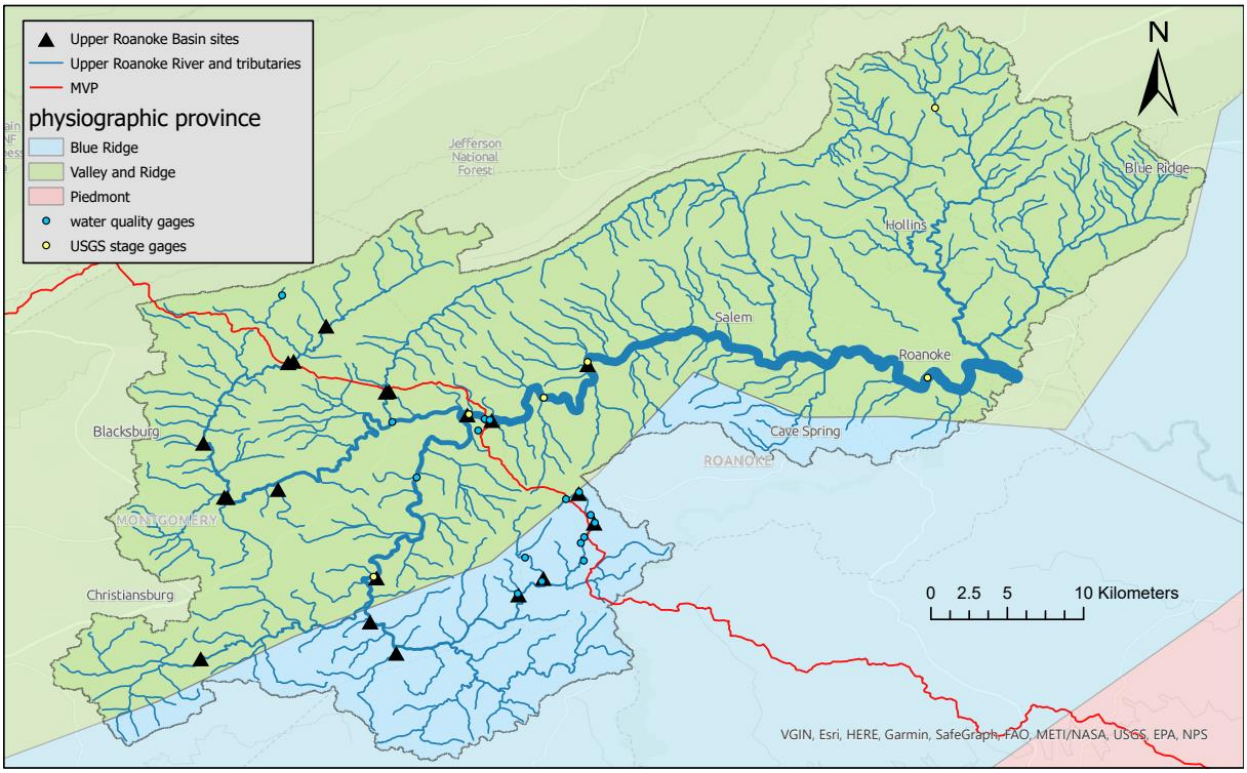

Figure 6. Upper Roanoke River Basin study sites in southwest Virginia, with proposed Mountain Valley Pipeline (MVP) pathway, water quality gages where turbidity is measured, USGS gages where stage and discharge are reported, and physiographic provinces.

2.3 National scale

Since 2008, the U.S. EPA has surveyed stream sites nationwide every five years during a two-year period. For wadeable streams, these surveys include measurements of slope, water depth, bankfull depth, and embeddedness. Most sites have macroinvertebrate and fish surveys as well as physical habitat. Some sites were surveyed only once, and some sites were repeated. For the repeated sites, average values of the relevant metrics were used for regression. The 2,804 wadeable sites ranged in slope from 0.0000011 m/m to 0.47 m/m, in bankfull depth from 0.15 to 17 m, and in bankfull width from 0.65 to 300 m (Figure 7).

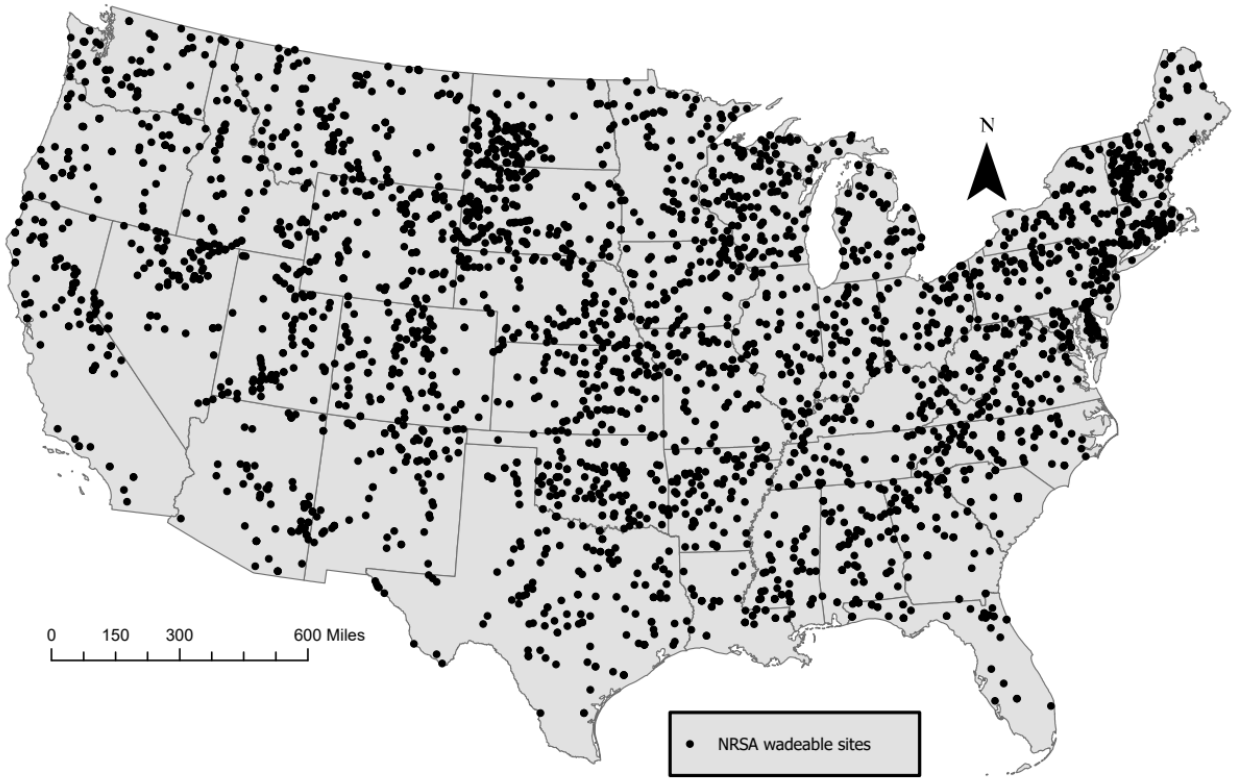

Figure 7. Map of 2,804 sites from the U.S. EPA NRSA dataset (2008/09, 2013/14, and 2018/19) where embeddedness, bankfull depth, and slope were measured.

3. Methods

3.1 General field methods for measuring embeddedness

The general quantitative approach of measuring embeddedness involves selecting pebbles and measuring the percent of the pebble that is submerged in the vertical plain (Fitzpatrick et al., 1998). One method of randomization for which pebbles are selected is to use a 0.6-m by 0.6-m or 1-m by 1-m aluminum quadrat with intersecting strings indicating locations to select pebbles from (Figure 8). Particle-size distributions obtained from grid samples such as this are comparable with pebble counts (Bunte and Abt 2001).

For each pebble, the height of the pebble in its position in the bed (h), the depth of embeddedness (z), and the intermediate diameter (b), which provides a grain size distribution, were measured (Figure 8). Where possible, bedrock and boulders too large to move were avoided. In some cases this was unavoidable. In this case, either ‘bedrock’ or ‘boulder’ were recorded. Boulders were included in the grain size distribution as >256 mm, but were not included in calculating the average embeddedness. Bedrock was not included in the grain size distribution but

did count toward the embeddedness average, as bedrock is considered 0% embedded (Fitzpatrick et al. 1998). Similarly, if the strings cross over sand, the grain is considered < 2 mm in the grain size distribution and 100% embedded. The embeddedness for the site is calculated by taking an average of the percent embeddedness for the measured particles (eq. 6).

$$emb = \frac{z}{h} \times 100\% \qquad (6)$$

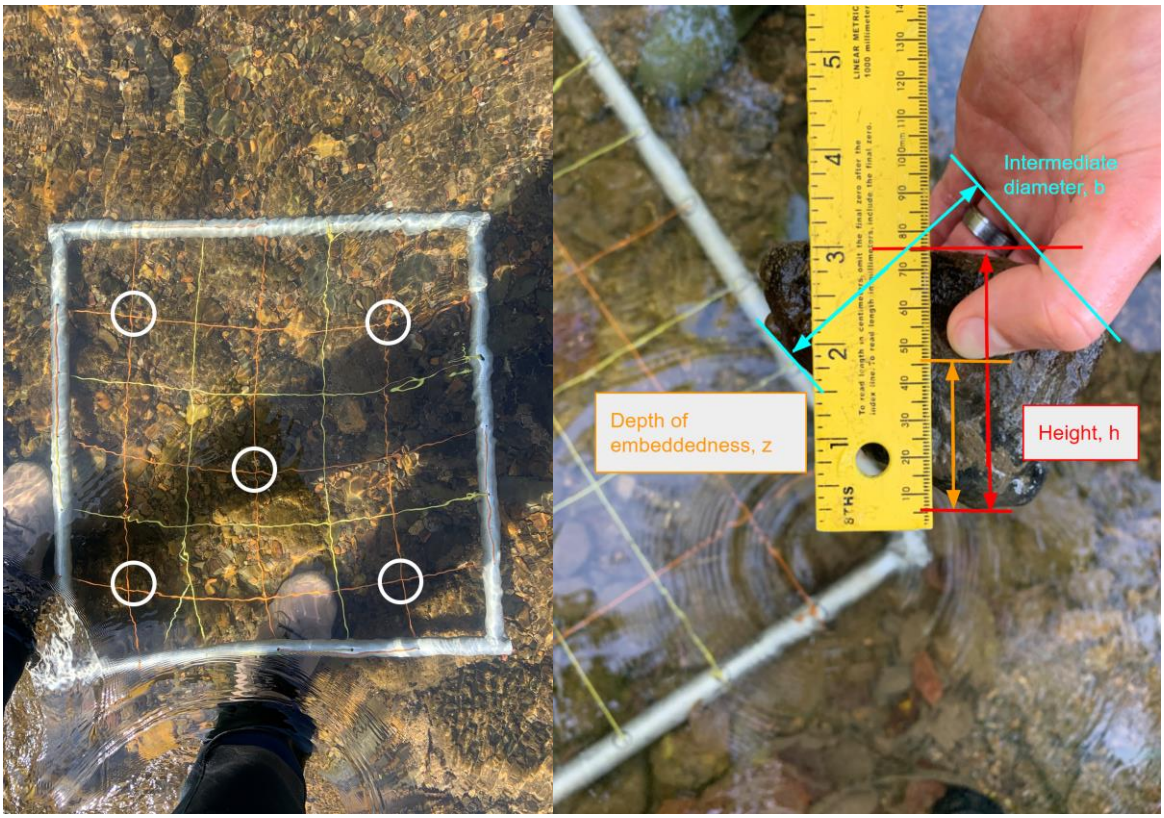

Figure 8. 0.6 m by 0.6 m aluminum pipe and string quadrant used to randomly select pebbles for embeddedness measurements with white circles indicating string intersections where pebbles will be selected (left) and measurements of a selected pebble to determine embeddedness, with thumb marking the embedded depth (right).

3.2 Stroubles Creek Field Methods

In order to consider the variation in embeddedness over time, four cross sections were marked with rebar and a 1-m by 1-m quadrat with 49 string intersections was placed adjacent to the cross section or offset 1 m downstream. Embeddedness values consist of the average of 49 pebbles measured within the $1m^2$ quadrat. Measurements were taken after significant flows, where stage at Bridge 1 exceeded 0.6 m. In order to determine consistency of measurements, for seven

visits the quadrat was offset by 1 m from the cross section such that two embeddedness points (each an average of the 49 within the quadrat) were taken (Figure 9).

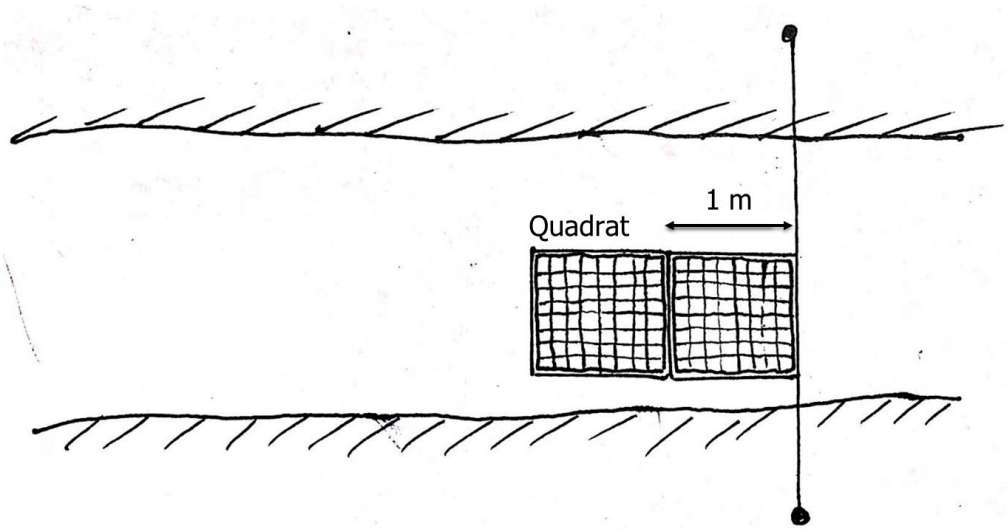

Figure 9. Diagram of two quadrat placements, one adjacent to the cross section and one offset in the downstream direction by 1 m.

3.2 Field, Upper Roanoke

3.2.1 Repeated embeddedness measurements, Upper Roanoke

In studying the Upper Roanoke River Basin, embeddedness was determined as an average of 125 particles, following the methods of Czuba et al. (2022). Over a reach of 100-200 m in length, five cross sections were selected in riffles or runs. The 0.6-m by 0.6-m quadrat pictured in Figure 8 was placed at 5 locations in the cross section, spaced at approximately equal intervals across the channel. If the cross section was less than approximately 5 m, the quadrants were spaced upstream and downstream of the cross section such that they did not overlap but were in the same riffle or run. Using the intersecting lines of the quadrant to select which rock to pick up, 5 pebbles per square were selected (Figure 8). This resulted in a total of 125 pebble measurements per site. In order to compare additional metrics of streambed fine sediment, additional measurements were taken. Within each square, a visual estimate of the percent sand cover and silt cover of each quadrant was recorded to the nearest 20%. Measurements of embeddedness at all or a subset of the sites were taken in October/November 2021, March/April 2022, June 2022, and August/September 2022.

3.2.2 NRSA method in Upper Roanoke

In order to compare results from the repeated measurements of embeddedness in the Upper Roanoke River Basin as described in section 3.2.1 with the nation-wide NRSA embeddedness measurements, the NRSA protocol for measuring embeddedness was followed at 13 sites in August and September of 2022. These measurements were taken on the same days as the repeated measurements described in 3.2.1. This method consists of dividing a reach that is approximately 40× the average wetted width into 11 cross sections and selecting pebbles that are on either edge of the water, in the thalweg, and evenly spaced between the thalweg and the edge of water, resulting in a total of 55 pebbles measured, following Fitzpatrick et al. (1998). If the pebble had a median diameter greater than 10 mm, embeddedness was calculated by eq. 6. If the pebble selected had a median diameter of less than 10 mm, embeddedness was visually estimated for the pebbles in a 10 cm diameter area around the selected pebble.

3.2.3 Surveying for channel dimensions

In the summer of 2022, 19 field sites in the Upper Roanoke River Basin were surveyed with a Topcon GTS-105 Total Station (Topcon, Livermore, California) to obtain longitudinal profiles and one representative cross section. These surveys were processed in Civil 3D and ArcGIS Pro (ESRI). Bankfull width and depth were obtained from the cross section, where the bankfull stage was identified as the lower of the two top of bank points (Figure 9). Slope was obtained from the slope between top-of-riffle points in the longitudinal profile (Figure 10). The hydraulic radius (R_h) was calculated from the wetted area (A, m^2) and perimeter (P, m) (eq. 7). Using an assumed Manning's roughness value of n = 0.035, a stage-discharge relationship was created for the cross section, using eq. 8 to calculate discharge (Q, m^3/s).

$$R_h = \frac{A}{P} \qquad (7)$$

$$Q = \frac{1}{n} A\, R_h^{\frac{2}{3}}\, S^{\frac{1}{2}} \qquad (8)$$

Bed shear velocity was calculated with both eq. 2 and 3 for varying depths to determine the bankfull shear velocity as well as the depth/discharge at which the d_{50} (determined through the pebble counts) was expected to be mobilized. Due to hiding, the majority of the bed is expected to

be mobilized at approximately the shear velocity that mobilizes the d_{50} (Garcia 2008). At most sites, surveyed cross sections did not extend significantly beyond bankfull due to vegetation in line of sight. Figure 9 and 10 show the cross section and longitudinal profile for site 1, the North Fork Roanoke River near Lusters Gate Road.

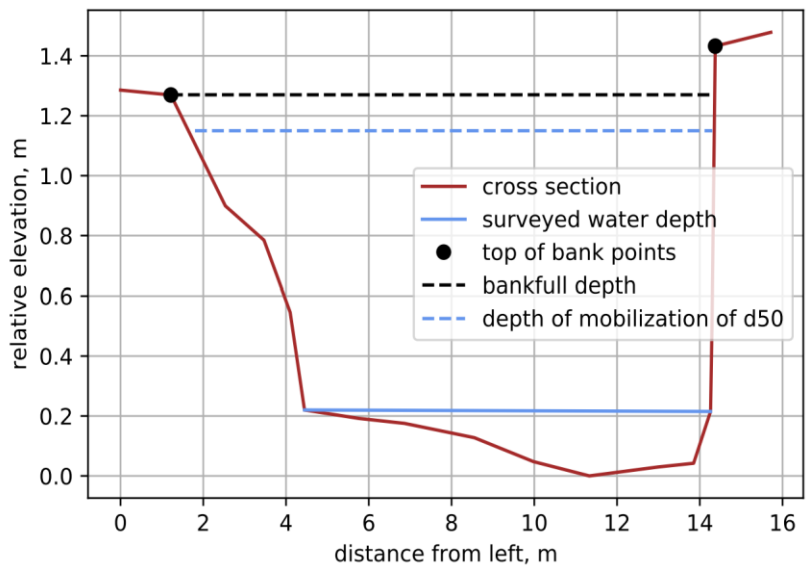

Figure 10. Representative cross section from site 1, with depth that d_{50} is mobilized (1.15 m) and bankfull depth (1.27 m). From stage-discharge and stage-shear velocity curves, bankfull discharge is 18 m^3/s and bankfull shear velocity is 0.155 m/s.

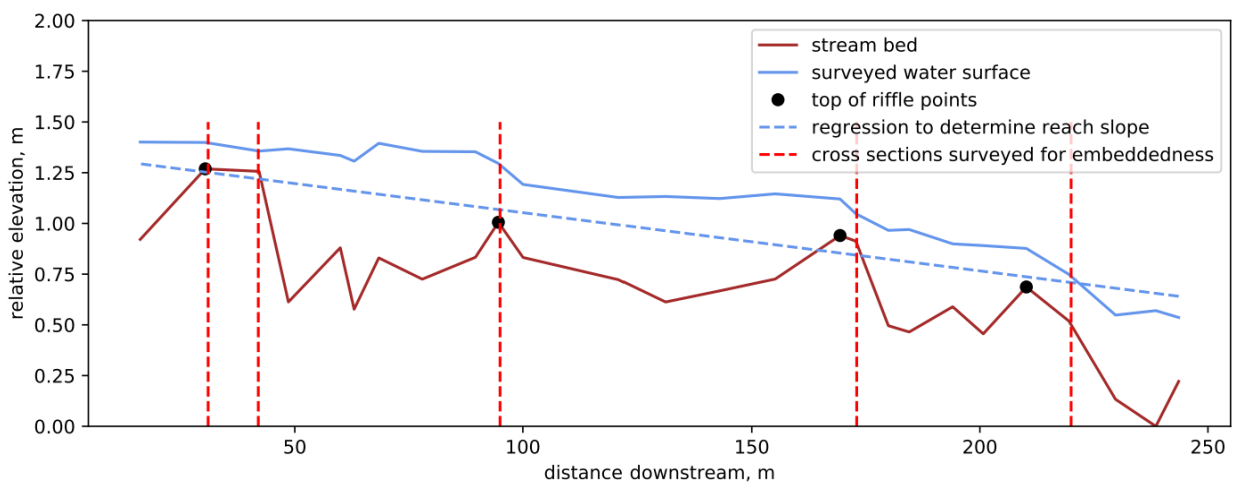

Figure 11. Longitudinal profile from site 1, surveyed summer 2022.

3.2.4 Sand collection, Upper Roanoke

Knowing the median fine grain size relative to when the bed is mobile is critical to continuing to develop the theory around the relationship between embeddedness and bankfull shear velocity. In their analysis on the gravel-sand transition, Lamb and Venditti (2016) concluded that a shift from gravel to sand would occur at a shear velocity of 0.1 m/s based on a mean sand grain size of 0.7 mm. In our model, this correlates to an embeddedness of 100%. The median sand diameter was not known at the field sites, however, which presented a source of uncertainty. In order to assess the validity of the assumption of 100% embeddedness occurring at a bankfull shear velocity of 0.1 m/s, sand samples were collected from the Upper Roanoke field sites in the spring of 2023. Grab samples of sand were collected with a measuring cup such that smaller grains would not be washed away. Grab samples for each site were composites of sand from each riffle or run sampled for embeddedness. This way, the sand collected was representative of the sand associated with embeddedness measurements. The sand samples were dried and sieved to determine the median grain size.

3.3 Remotely sensed methods, Upper Roanoke

In order to compare field measured variables (depth, slope, width, and discharge), with remotely available variables, I obtained slope and drainage area from the National Hydrography Dataset (NHD: USEPA, 2022) and slope from a 1-m DEM created from lidar points (VGIN, 2022). To determine slope from the 1-m DEM, I drew a line along the center of the surveyed reach and extracted elevations along the line. Depth, width, and bankfull discharge were calculated using regional curves from drainage area (Table 1). The Valley & Ridge physiographic province encompasses some sites and the Appalachian Highlands physiographic division includes both the Valley & Ridge and the Blue Ridge physiographic provinces. The depths were calculated with the Appalachian Highlands regional curve and were input into eq. 2 to calculate shear velocity. The width for all sites was calculated using both the Valley & Ridge and Appalachian Highland regional curves. The widths, along with the bankfull discharge from the Valley & Ridge regional curve (Keaton et al. 2005) were input into eq. 3 to calculate shear velocity. Discharges for sites in the Blue Ridge physiographic province were calculated using an equation from the adjacent province (the Valley and Ridge), leading to increased uncertainty in these calculations.

Table 1. Regional curve equations used to determine bankfull characteristics from drainage area in the Upper Roanoke River Basin.

Source	*Equation*	*Units*	*Range of Applicability*
Keaton et al. 2005	$W = 12.445(DA)^{0.4362}$	ft, mi^2	Valley & Ridge, non-urban
Keaton et al. 2005	$H = 1.001(DA)^{0.2881}$	ft, mi^2	Valley & Ridge, non-urban
Keaton et al. 2005	$Q = 43.249(DA)^{0.7938}$	ft3/s, mi^2	Valley & Ridge, non-urban
Beiger et al. 2015	$W = 3.12(DA)^{0.415}$	m, km^2	Appalachian Highlands
Beiger et al. 2015	$H = 0.26(DA)^{0.287}$	m, km^2	Appalachian Highlands

3.4 NRSA analysis

Since 2008, the EPA has been taking measurements of streams selected through a probability-based design to include a range of sizes, land uses, and ecoregions (Olsen 2007). Physical habitat, biotic, and water quality metrics are collected at these sites and these data are publicly available.

3.4.1 NRSA physical habitat

Current water depth and height from current water surface to bankfull depth were combined to determine the bankfull depth for each site. Slopes were also available for each site, as well as overall embeddedness (EMB) and channel center embeddedness (EMBC). EMBC is calculated by taking an average of the embeddedness values for the three pebbles measured in the channel over 11 cross sections, while EMB includes the two embeddedness measurements taken at the edge of the water at each cross section. Although EMBC is based on 33 rather than 55 individual measurements, it is closer to the field methods described in 3.2.1 and by Czuba et al. (2022). From this point forward, “embeddedness” reported for NRSA sites refers to the channel center embeddedness value (EMBC). Shear velocity for all wadeable sites was calculated with eq. 2, and modeled embeddedness was calculated with eq. 1. In order to determine the fit of the model (eq. 1), the median deviation from modeled baseline embeddedness was calculated for each Level II and Level III ecoregion. Ecoregions, rather than states, were used as land unit divisions because they take into physiographic province, climate, and general ecology (Omernik & Griffith 2014). There are wadeable NRSA sites in 20 Level II and 83 Level III ecoregions.

3.4.2 NRSA biotic metrics

Linear regressions between reported fish and benthic macroinvertebrate metrics and embeddedness were calculated within each Level II and Level III ecoregion to determine where embeddedness may be relevant to biota and to which biotic metrics embeddedness is correlated. Due to the large number of metrics (125 for macroinvertebrates and 180 for fish), two macroinvertebrate and three fish metrics were selected to highlight based on a combination of ecological relevance and relatively high correlation to embeddedness.

Macroinvertebrate metrics in the NRSA database included species richness and composition, tolerance, and habitat related metrics (Adams 2010). The total number of macroinvertebrate taxa is a common metric for regional multimetric indices (Andraso et al. 2009, Bowles et al. 1996-2012, Jessup & Neils 2011, Florida Department of Environmental Protection 2022). Specifically, the number of Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa and the percent burrowers were investigated. EPT is also a common metric in regional multimetric indices and while EPT as a group do not have a direct functional relationship with embeddedness, they are generally considered sensitive and often used as water quality indicators (Poff et al. 2006, Adams 2010, Rehn et al. 2008, Andraso et al. 2009, Bowles et al. 1996-2012). Finally, burrowers as a functional group, related to habitat, have a direct functional relationship with embeddedness as they burrow into fine sediment, protecting them from predation, and therefore were included (Suttle et al. 2004; Poff et al. 2006).

Types of fish metrics in the NRSA database included resident fish species richness, trophic composition, and fish abundance and composition (Daniels 2002). Total number of taxa, a measure of richness, and number of intolerant taxa, a metric related to habitat, are commonly used in indices of biotic integrity (Karr 1981, Daniels 2002, Andraso et al. 2009). Specifically, the number of salmonid taxa, number of intolerant taxa, and number of lithophilic taxa were investigated. The number of salmonid taxa, which relates to composition, is not relevant in all parts of the contiguous U.S. However, salmonid taxa have been shown to be responsive to embeddedness and are a culturally and economically significant group (Suttle et al. 2004). Within the NRSA dataset, intolerant fish taxa are determined by “best professional judgment” (USEPA 2020). The nature of their intolerance is not specified. However, fine sediment and high embeddedness is considered to be negatively correlated to “optimal” aquatic habitat (Barbour et al. 1999). Therefore, intolerant

fish taxa are expected to decrease with increasing embeddedness. Lithophilic spawners have a direct relationship with fine sediment and as a group include Roanoke logperch and Candy Darters, which have been shown to be responsive to embeddedness (Roberts et al. 2016, Dunn & Angermeier 2016).

4 Results

4.1 Stream lab

Substantial temporal variation in measured embeddedness was measured at each site in Stroubles Creek (Figure 12). Sampling in June and August 2022 occurred after bankfull events (stage > 1.0 m). Each site had at least one paired embeddedness measurement where two adjacent quadrats were placed adjacent to each other (Figure 8). Figure 13 demonstrates the repeatability of embeddedness measurements taken from an average of pebbles using equation 6, as the embeddedness of a single riffle or run is expected to be relatively similar within a few meters up or downstream of a given point. Measurements of embeddedness offset by 1 or 2 meters have similar values measured on the same day as those measured on the cross section, with a root mean squared error (RMSE) of 3.24% (Figure 13). The ten values of embeddedness measured at site 1 had a range of 33% (31–64%). Site 2 had an overall range of 39% (33–72 %). Site 3 had a range of 32% (24–56%). Site 4 had a range of 32% (36–68%). On average, embeddedness was higher in late spring than late summer.

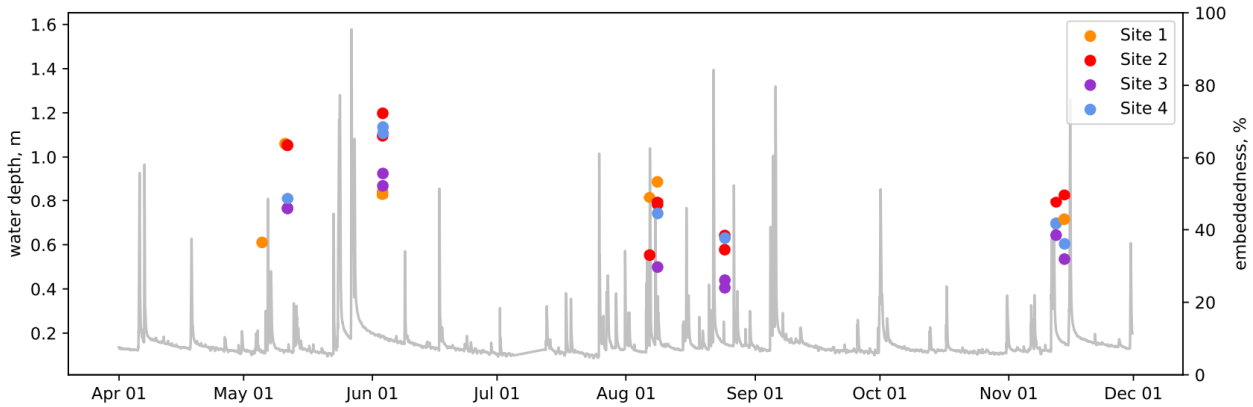

Figure 12. Embeddedness measurements at Stroubles Creek and stage measured at Bridge 1 near site 1, April to November 2022.

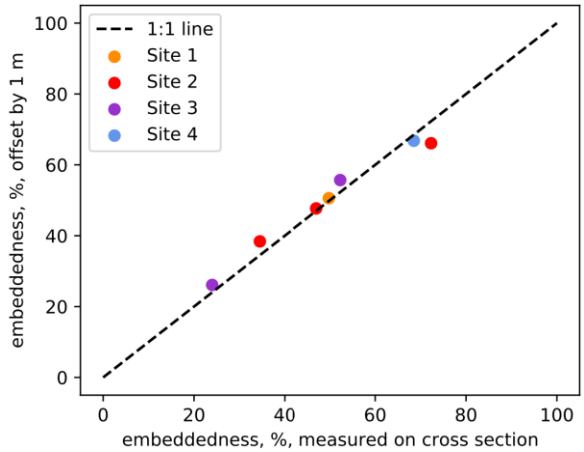

Figure 13. Paired measurements of embeddedness at Stroubles Creek, where 1:1 line represents where the upstream quadrat average embeddedness is equal to the offset quadrat average embeddedness. Review Figure 9 for setup.

4.2 Upper Roanoke

Our best estimates of shear velocity and average measured embeddedness are shown in Figure 14 as black dots. The best estimates are based on values calculated with eq. 2 with the field-measured depth, or depth calculated from the regional curve for the two sites where field depth was not measured. The slope used was an average of slopes derived from field measurements and from the 1-m DEM for the two sites not measured in the field. The uncertainty associated with the shear velocity calculation is due to several estimations of channel characteristics and two equations for calculating shear velocity (eq. 2 & 3). The slopes were from: NHD (30-m DEM), 1-m DEM, and field measurements. The NHD slope was not included for two sites where it was reported as < 0.00001 and field slopes were not included for the two sites where they were not measured. Depths and widths were from field cross section measurements and from regional curves based on drainage area (Table 1). Embeddedness varied among cross sections and with site visits. Figure 14 displays the range of embeddedness values averaged over each cross section (five per site) with dotted lines. For example, embeddedness values at site 1 at the Roanoke River ranged from 19% (average of cross section 5, measured July 2022) to 56% (average of cross section 1, measured September 2021). The range of reach-averaged values is displayed by a solid line. Of the sites visited more than once, the average range of embeddedness measurements was 10%, with a maximum of 25% and a minimum of 2%.

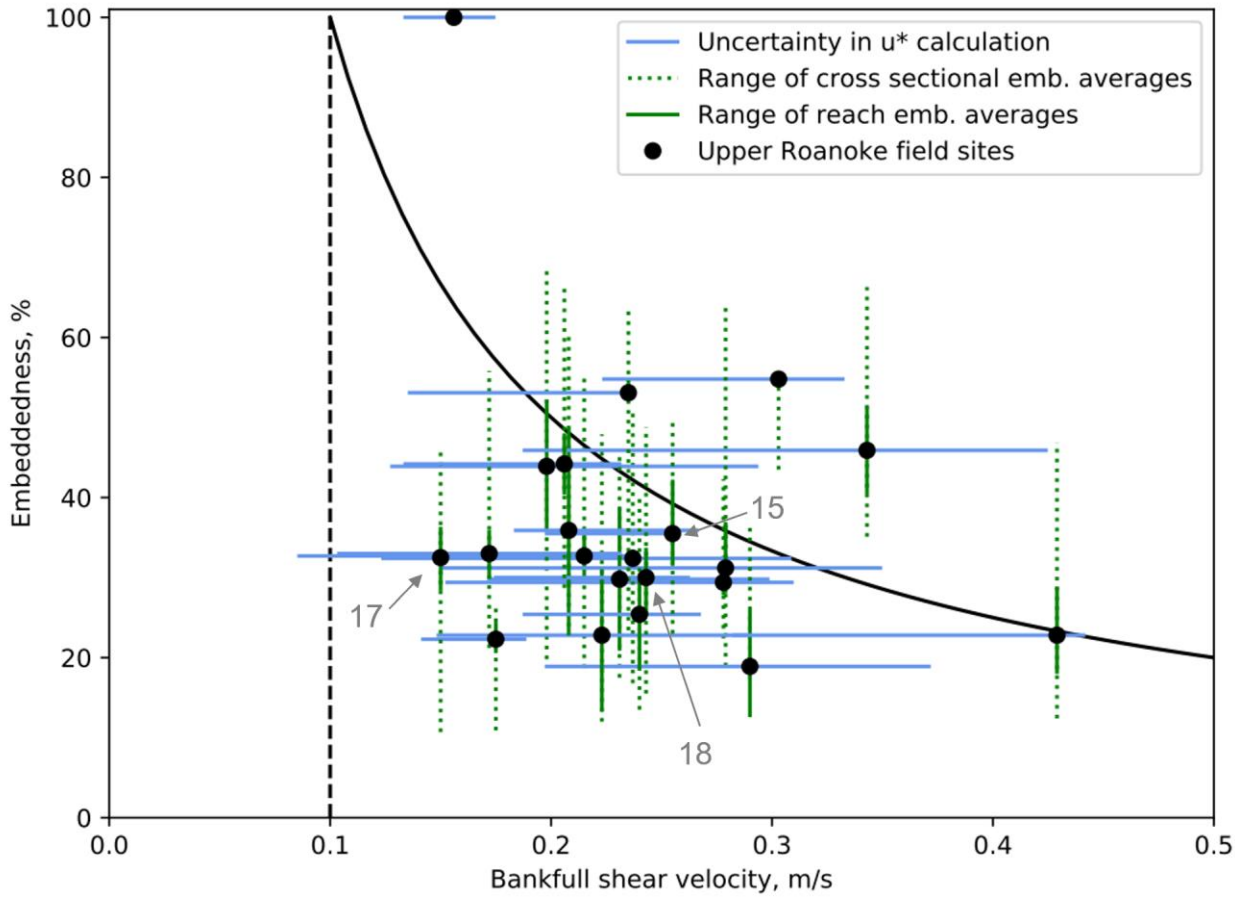

Figure 14. Measured embeddedness and reach-averaged shear velocity calculations with horizontal uncertainty for shear velocity calculations given a range of widths, depths, slopes, and calculation methods for each site, with the dot representing the best estimation. The ranges of reach-averaged embeddedness values are displayed with a solid line and the ranges of cross section averaged embeddedness values (five per reach) are displayed with a dotted line. Sites referenced in Figure 18 are indicated with gray arrows.

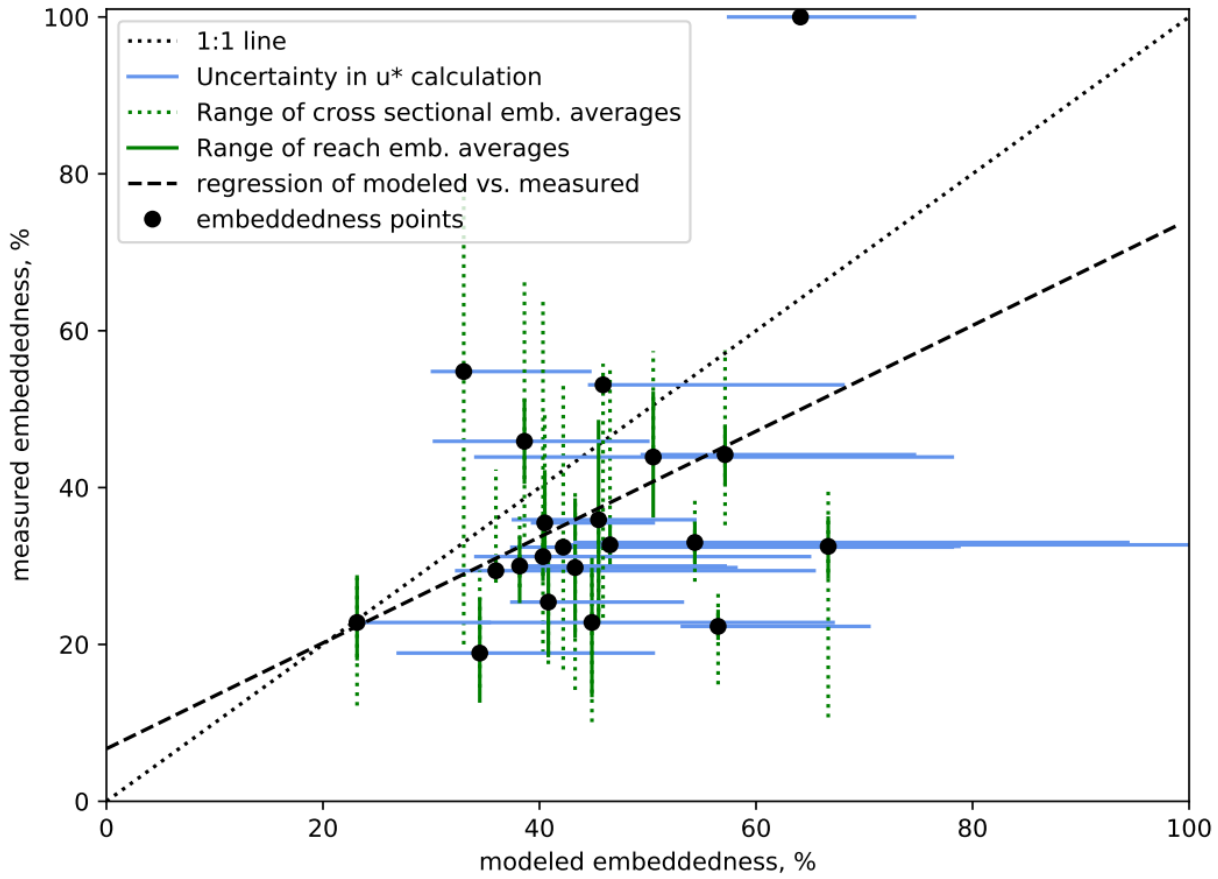

Figure 15. Modeled and measured embeddedness in the Upper Roanoke River Basin.

The measured embeddedness throughout the Upper Roanoke River Basin is on average lower than the embeddedness predicted from calculations of shear velocity. The Upper Roanoke River Basin sites have a RMSE of 18% for modeled vs. measured embeddedness, about the regression line (Figure 15). Seventy-one percent of the sites had a deviation from predicted embeddedness (1:1 line) of less than 20%. Several sites have a significant amount of bedrock. While bedrock was generally avoided where possible in the repeated measurements, it was not avoided when using the NRSA method described in section 3.2.2. Of the 12 sites measured with this method, percent bedrock ranged from 0–44%, with an average of 10%. High bedrock may limit the applicability of the proposed model of embeddedness as the theory is based on alluvial rivers with mobile beds at the bankfull stage. The variation between embeddedness measured between the Czuba et al. (2022) method and the NRSA method is displayed in Figures 16 and 17, with points with greater than 10% bedrock highlighted. Within this subset of sites, 69% were within 20% of the modeled embeddedness value, regardless of measurement method. The RMSE

for modeled vs. measured embeddedness was 17.1% for the Czuba et al. (2022) method and 16.8% for the NRSA method (Figure 17A). Ninety-two percent of these sites had less than 20% variation in embeddedness value with measurement method. The RMSE between measurement methods was 17% (Figure 17B). The average predicted embeddedness for this subset was 44%, and the average measured was 34% and 35% for the Czuba et al. (2022) and NRSA methods, respectively.

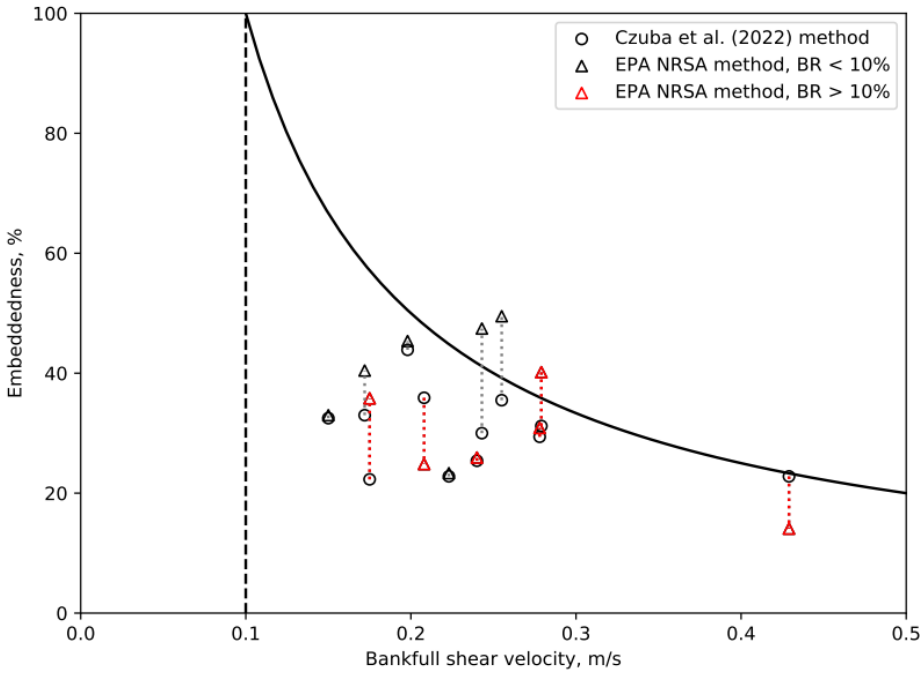

Figure 16. Comparison of average embeddedness measured with Czuba et al. (2022) and with NRSA methods. Dashed lines indicate the same site.

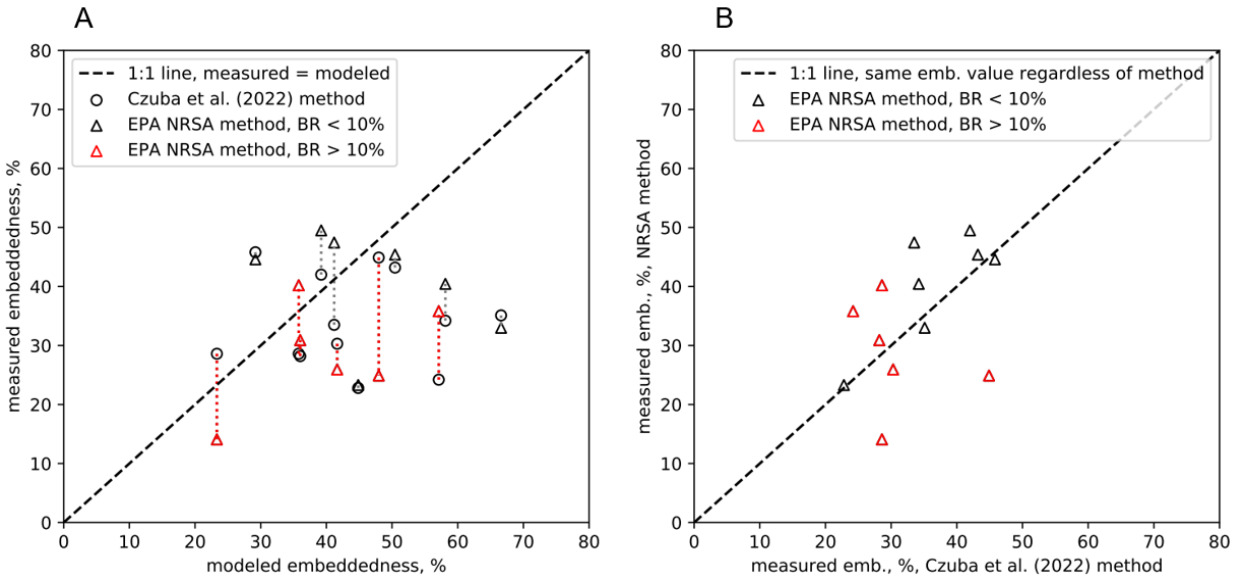

Figure 17. Comparison of embeddedness measurement methods in the Upper Roanoke River Basin.

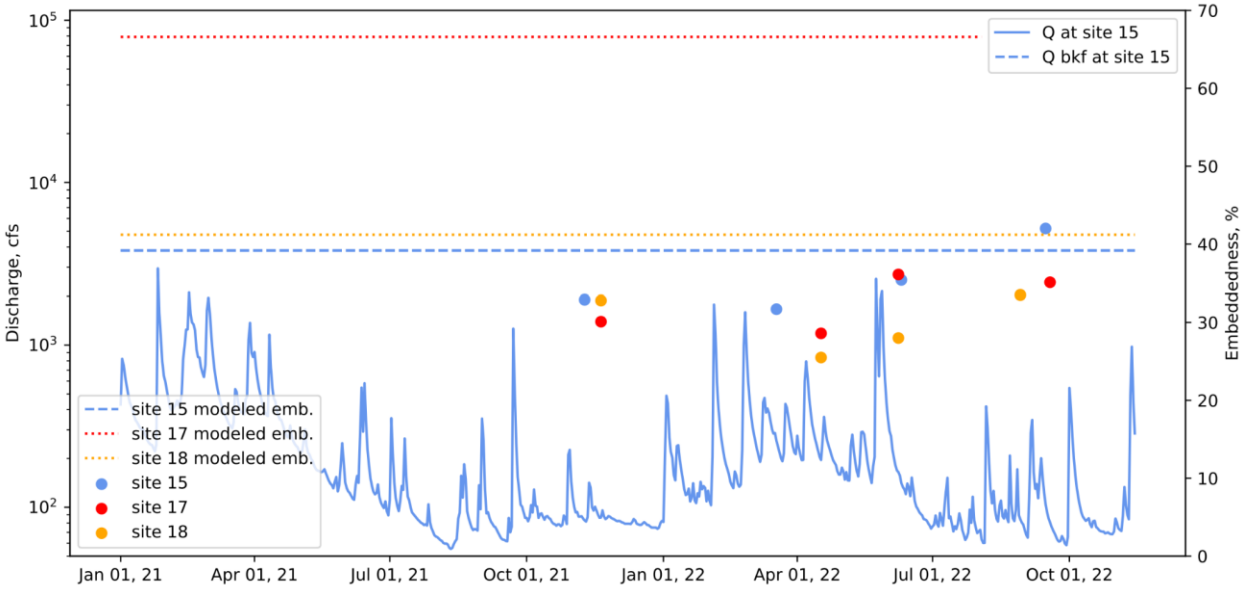

Figure 18. Embeddedness measurements and discharge measurements at sites 15, 17, and 18 on the Roanoke River in Glenvar (site 15) and Lafayette VA (sites 17 & 18). Discharge measurements from USGS gage 02054530.

Temporal variation in embeddedness measured at the Roanoke River sites was less than measured at Stroubles Creek. The three most downstream sites on the mainstem Roanoke River had ranges of 8–10% between site visits (Figure 18). The discharge measured at USGS gage 02054530 adjacent to site 15 did not exceed the bankfull discharge calculated with the Keaton et al. (2005) regional curve during the study period. Site 15, 17, and 18 on the Roanoke River had

measured embeddedness below the modeled embeddedness (Figure 18). Modeled embeddedness for the entire basin is displayed in Figure 19. The shear velocities for each reach were calculated using slopes and depths (via drainage areas and regional curves) derived from the NHD dataset. The selected sites are colored by the average measured embeddedness at that site. Network scale maps such as these may be useful in future studies of biota.

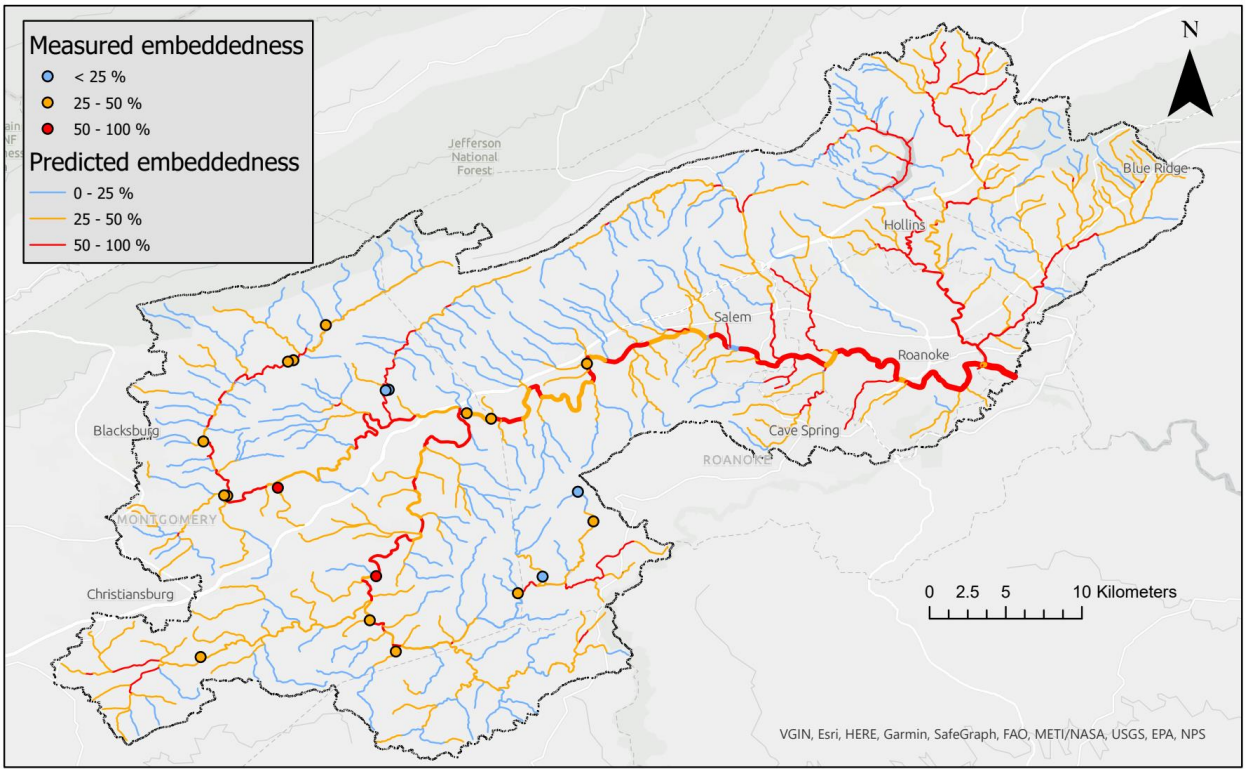

Figure 19. Predicted embeddedness and Upper Roanoke River Basin sites.

4.3 National scale

4.3.1 National scale embeddedness and shear velocity

Figure 20 and 21 show selected Level III ecoregions with relatively strong correlations between measured and predicted values of embeddedness: 6.2.11 Klamath Mountains (n = 14), 10.1.5 Central Basin and Range (n = 59), 10.2.4 Chihuahuan Desert (n = 18), 8.1.5 Driftless Area (n = 44) and 8.4.1 Ridge and Valley (n = 64). Figure 20C shows the difference between the measured embeddedness value and the modeled embeddedness value, where positive values indicate that sites were on average more embedded than modeled, and negative values indicate that sites were less embedded than modeled. The Central Basin and Range (red) was most

overestimated, and the Ridge and Valley (blue) was least overestimated. From t-tests, of these ecoregions, the Central Basin and Range (p = 0.0002, median = 18 %) and the Klamath Mountain (p = 0.011, median = 11%) sites had significantly higher embeddedness than modeled and Ridge and Valley sites had significantly lower embeddedness than modeled (p = 4.5×10^{-6}, median = –11%). The Chihuahuan Desert and Driftless Area regions did not have significantly different embeddedness between measured and modeled values. While shear velocity is correlated with embeddedness in all of these regions, the relationship does not follow the model (Figure 21).

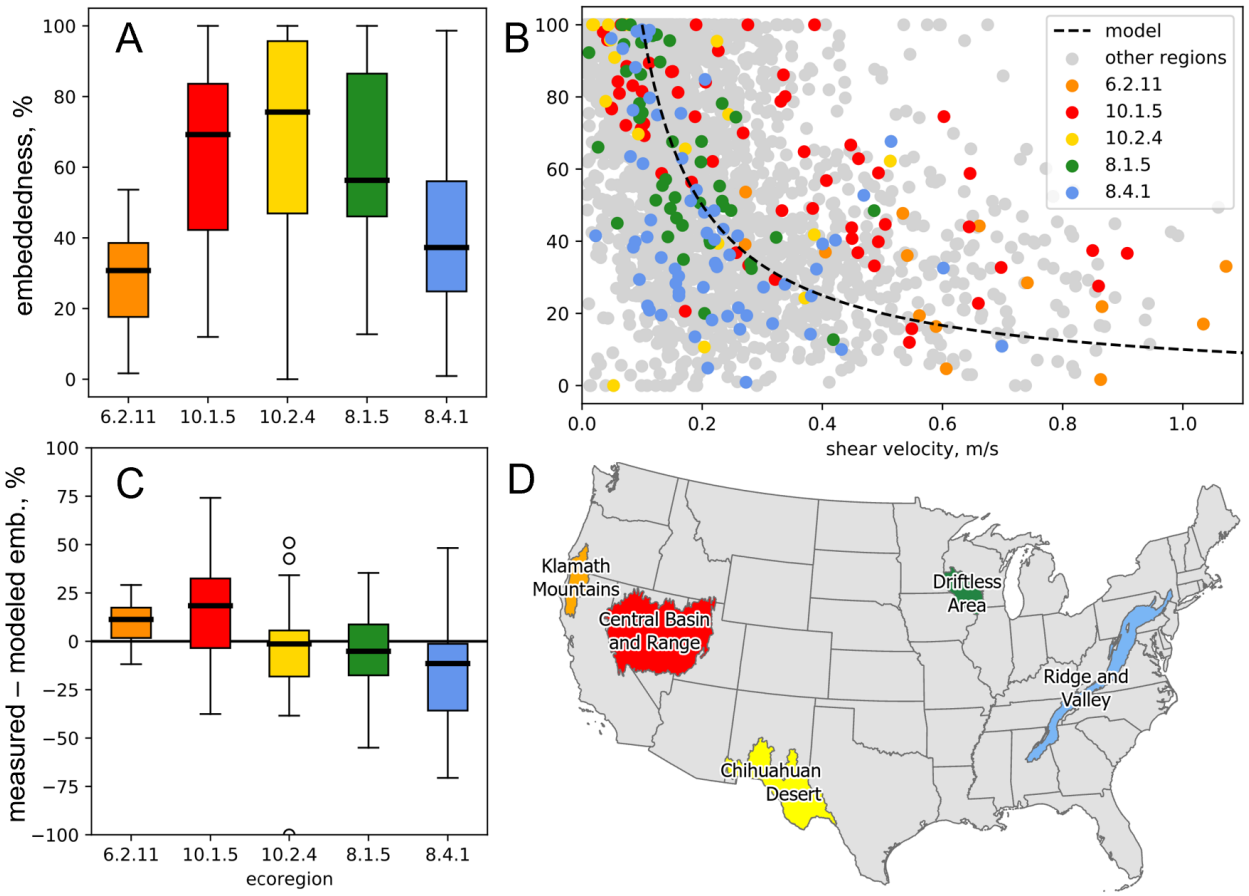

Figure 20. Selected Level III ecoregions. (A) range of values for selected ecoregions, (B) shear velocity vs. embeddedness for all NRSA sites, with selected ecoregions highlighted, (C) deviation of measured embeddedness from modeled, where positive values are more embedded than modeled and negative values are less, (D) map of selected ecoregions

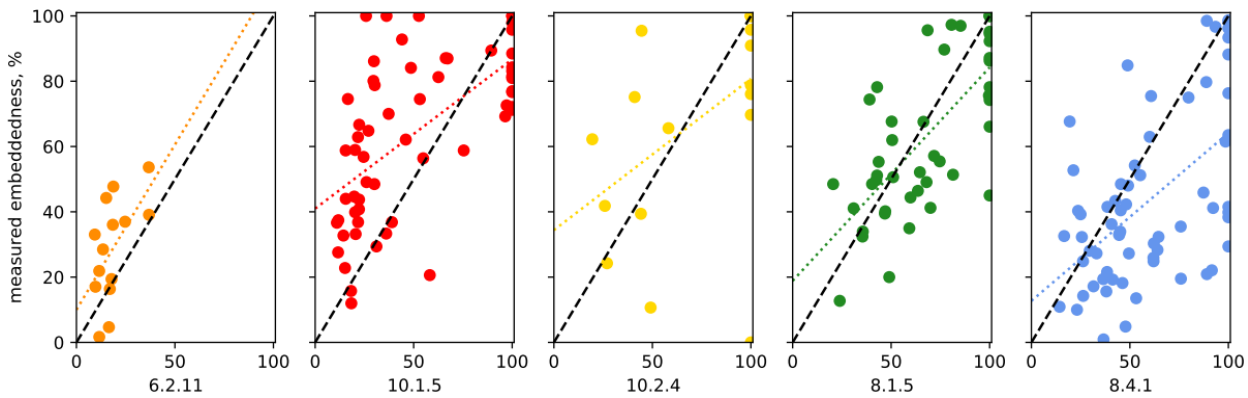

Figure 21. Modeled and measured embeddedness for selected Level III ecoregions: Klamath Mountains (6.2.11), Central Basin and Range (10.1.5), Chihuahuan Desert (10.2.4), Driftless Area (8.1.5), and the Valley and Ridge (8.4.1). Regressions for individual ecoregions are displayed with colored dotted lines and the 1:1 line where the measured embeddedness is equal to modeled embeddedness is displayed with black dashed lines.

The median deviation (plotted in Figure 20 C) for a given ecoregion is mapped in Figure 22 and 23. Although there is variation in the direction of deviation, whether embeddedness is overestimated or underestimated, as shown in Figure 21, there is a general trend at the Level II ecoregion scale of overestimation in the eastern U.S. and around the Great Lakes and underestimation in the semi-arid and mountainous west.

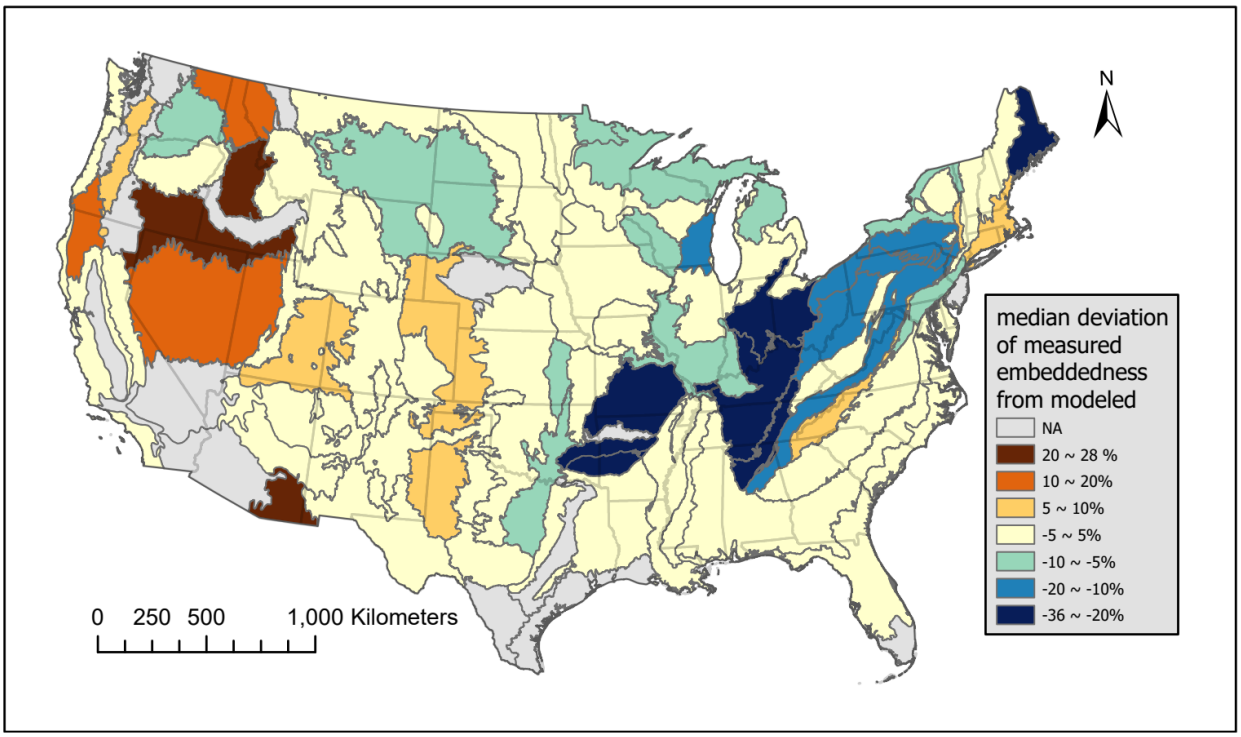

Figure 22. Median deviations by Level III ecoregion from modeled embeddedness.

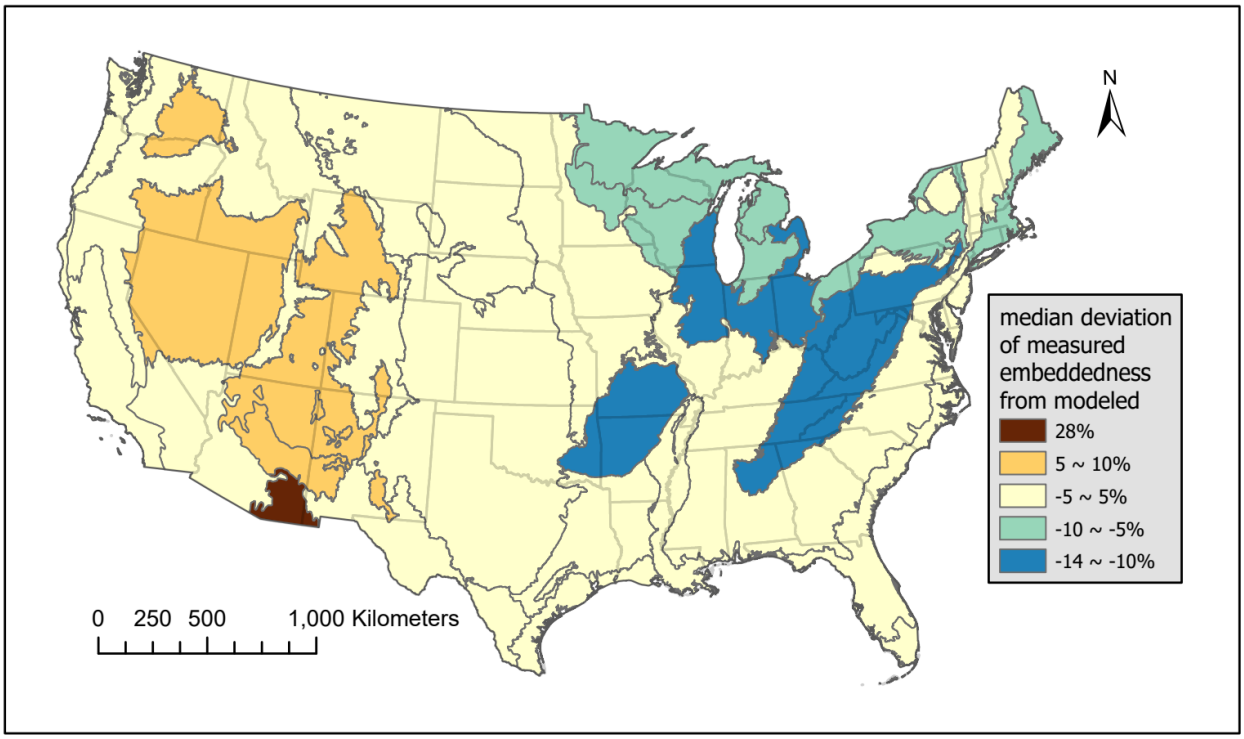

Figure 23. Median deviations by Level II ecoregion from modeled embeddedness.

Variations from the proposed baseline embeddedness, calculated with shear velocity, may be caused by variable sediment inputs, represented in Figure 2. We expect that higher fine sediment inputs lead to higher measurements than modeled. Other reasons for variation may be sand cover and presence of bedrock. Percent sand was reported in the NRSA dataset, and percent sand cover is more commonly described in the engineering literature than embeddedness (Wilcock and Crowe, 2003). Sand cover is strongly correlated with embeddedness, but distinct from it. Figure 24 shows sand cover and embeddedness, with a 1:1 line showing where they are equal. There are 96.3% of the NRSA sites with a higher measure of embeddedness than sand cover (Figure 24). When streams are not fully alluvial, a majority of the bed material may not be mobilized at bankfull (or otherwise formative) discharge. Additionally, bedrock is counted as 0% embedded. Figure 25 highlights sites with > 10% bedrock, showing that there is a high concentration of sites with low shear velocities overestimating embeddedness at these sites.

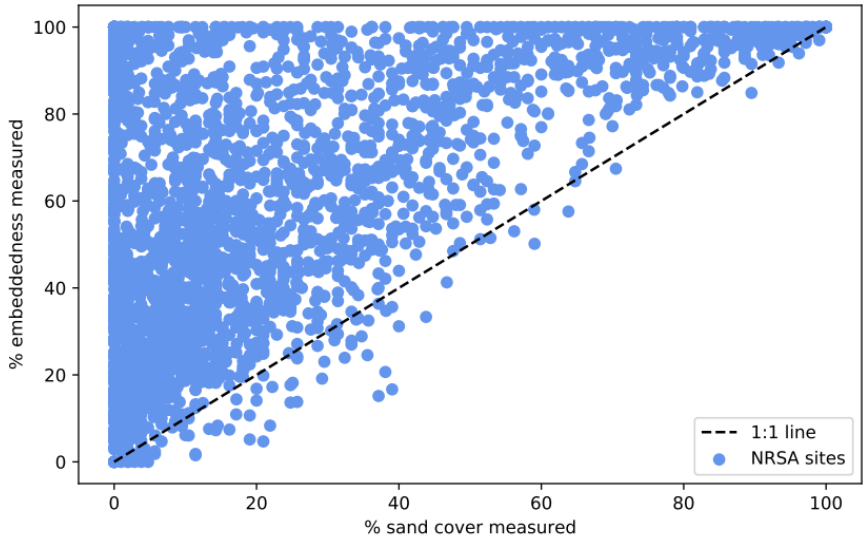

Figure 24. Relationship between two fine sediment metrics included in the NRSA dataset.

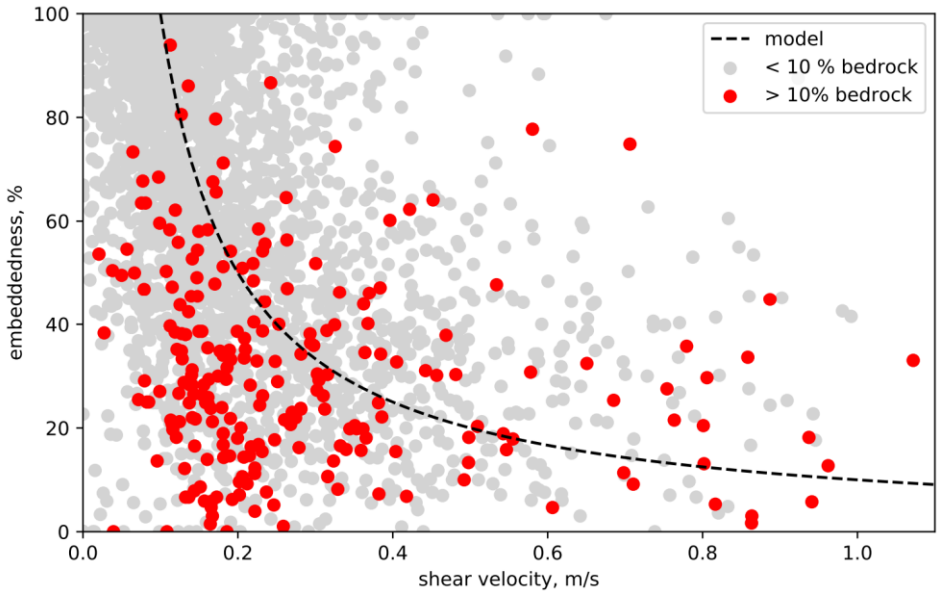

Figure 25. Impact of bedrock on embeddedness model with NRSA dataset.

4.3.2 National scale embeddedness and biotic metrics

Of the 125 benthic macroinvertebrate metrics and the 180 available fish metrics, five were selected to highlight the relationships of embeddedness and biota. The relationships analyzed in this section are results of measured embeddedness values and measured biotic metics directly from the NRSA dataset, without the associated uncertainty of the shear velocity–embeddedness relationship described above. For benthic macroinvertebrates these are the percent burrower taxa and number of Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa. For fish, these are the

number of lithophilic taxa, number of intolerant taxa, and number of salmonid taxa. We also investigated the total number of taxa for both benthic macroinvertebrates and fish, which were weakly correlated ($R^2 < 0.1$) with embeddedness in all ecoregions on both the Level II or III scale. For the other five metrics, the correlation coefficients (R^2 values) for linear regressions of the metric and measured embeddedness are mapped by Level III and Level II ecoregion. Regions with $n < 10$ are mapped as gray regions in these figures.

Percent burrower taxa

To include an adequate sample size, discussion of regression relationships is limited to regions with $n > 30$. At the Level II scale, of the regions with $n > 30$, the Central USA Plains (8.2), the Atlantic Highlands (5.3), the Western Cordillera (6.2), and the Mixed Wood Plains (8.1) had R^2 values greater than 0.1, with $p < 0.01$. All regions with statistically significant correlations ($p < 0.05$) positively correlated percent burrower taxa and measured embeddedness. This relationship is plotted in Figure 28. This relationship is strongest (limiting to $n > 30$) in the Ridge and Valley ($R^2 = 0.27$), Northern Appalachian and Atlantic Maritime Highlands ($R^2 = 0.26$), Central Basin and Range ($R^2 = 0.26$), Wyoming Basin ($R^2 = 0.24$), and High Plains ($R^2 = 0.23$). There is a significant relationship ($p < 0.05$ and $n > 30$) in 12 Level III ecoregions (of 26 with $n > 30$) and 9 Level II ecoregions (of 12 with $n > 30$).

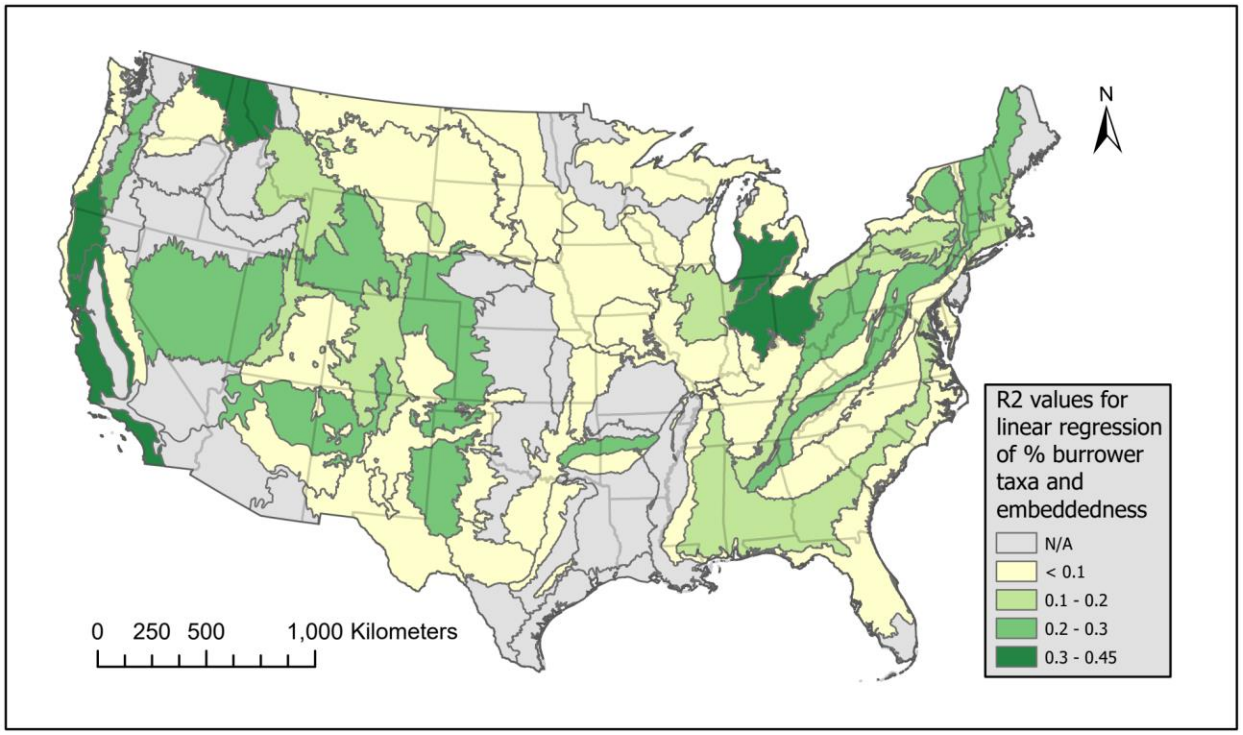

Figure 26. Positive correlation between embeddedness and % burrower taxa mapped by Level III ecoregion.

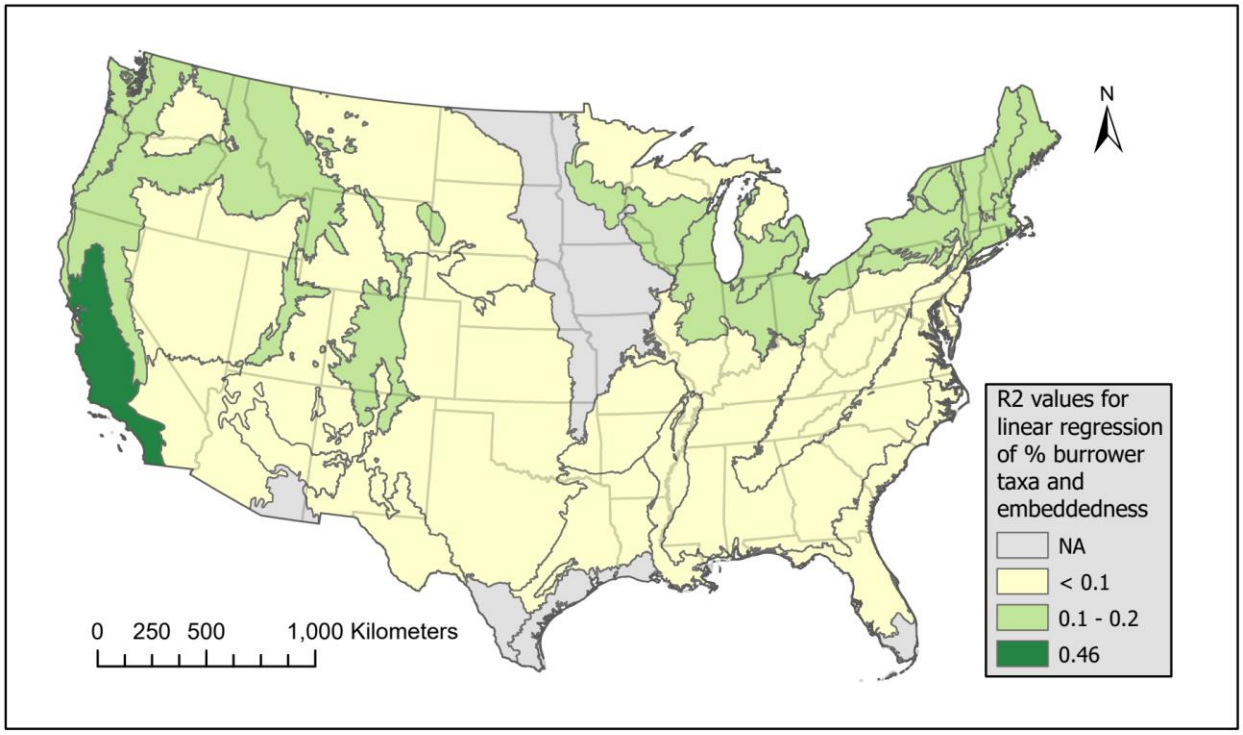

Figure 27. Positive correlation between embeddedness and % burrower taxa mapped by Level II ecoregion.

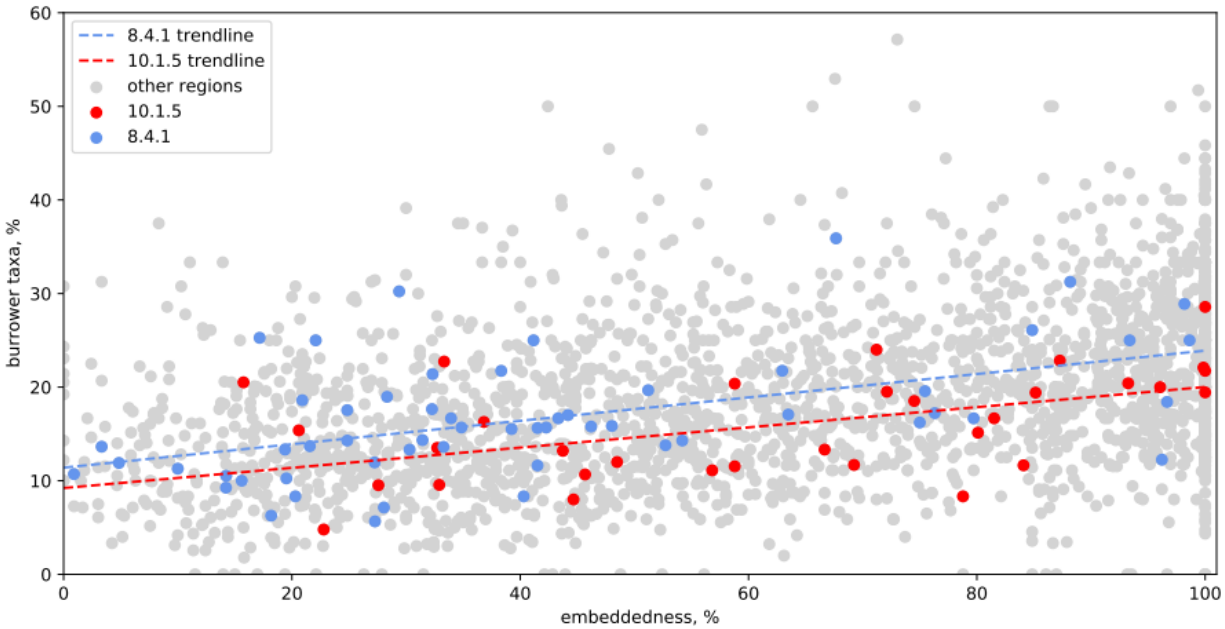

Figure 28. Embeddedness and percentage of taxa that are burrowers with points from the Central Basin and Range (10.1.5) and the Ridge and Valley (8.4.1) regions highlighted.

Number of EPT taxa

Though this varies by individual Level III ecoregion (Figure 28), the embeddedness generally explains more variation in the number of EPT taxa in the western United States (Figure 29). Nationally, the number of EPT taxa decreases with increasing embeddedness. This relationship is strongest (limiting to $n > 30$) in the Central Basin and Range, Ridge and Valley, Southern Rockies, and North Central Appalachians Level III ecoregions. There is a significant relationship ($p < 0.05$ and $n > 30$) in 13 Level III ecoregions (of 30 with $n > 30$) and 9 Level II ecoregions (of 13 with $n > 30$). An example of this relationship is presented in Figure 31.

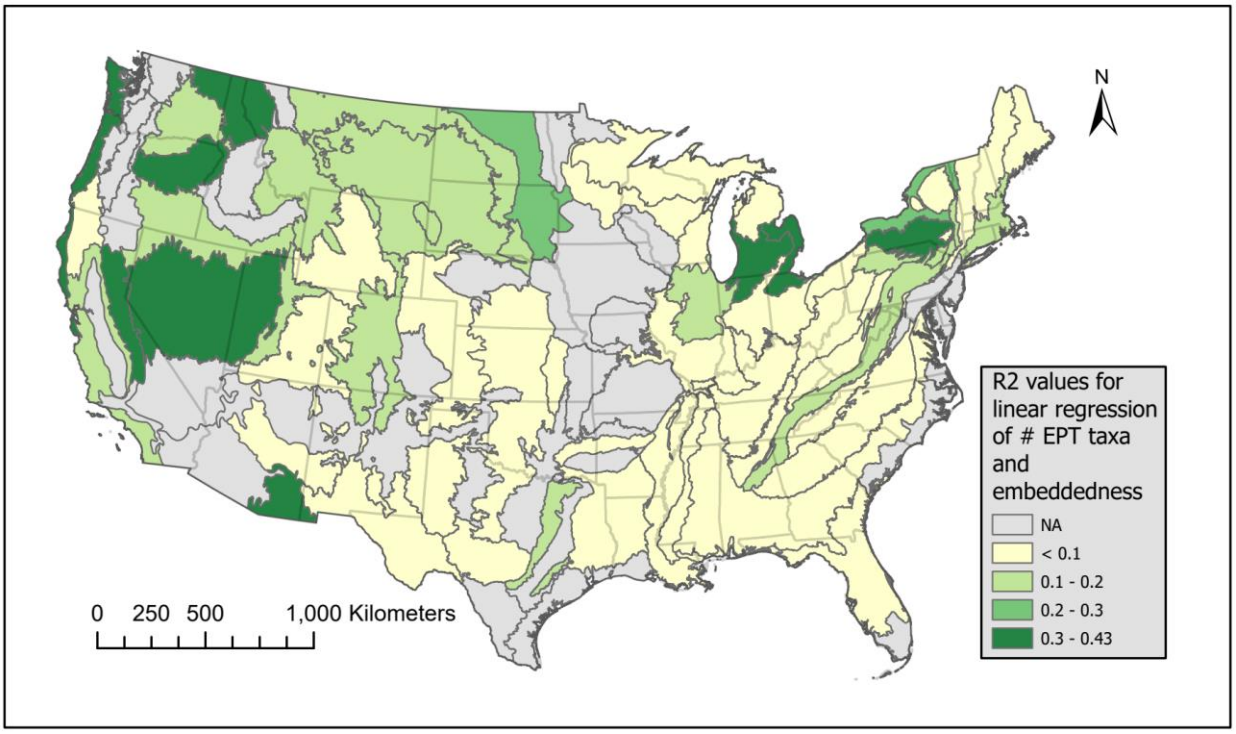

Figure 29. Negative correlation between embeddedness and number of EPT taxa mapped by Level III ecoregion.

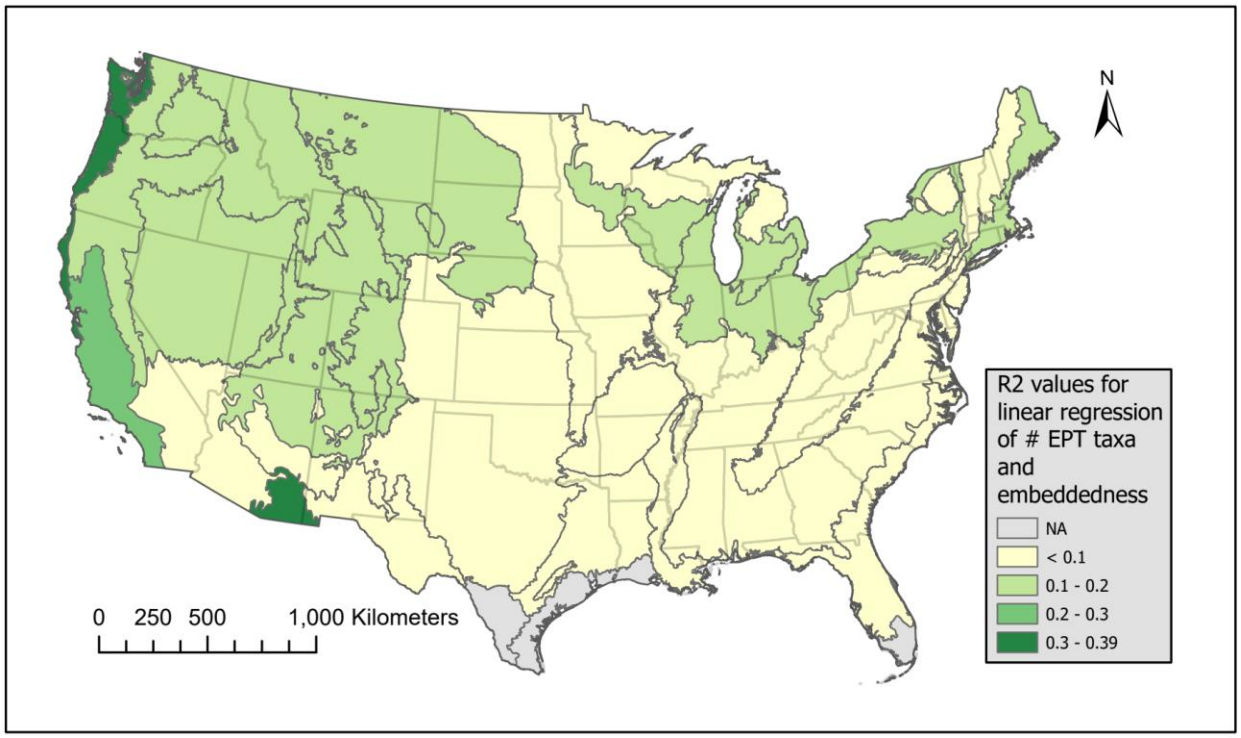

Figure 30. Negative correlation between embeddedness and number of EPT taxa mapped by Level II ecoregion.

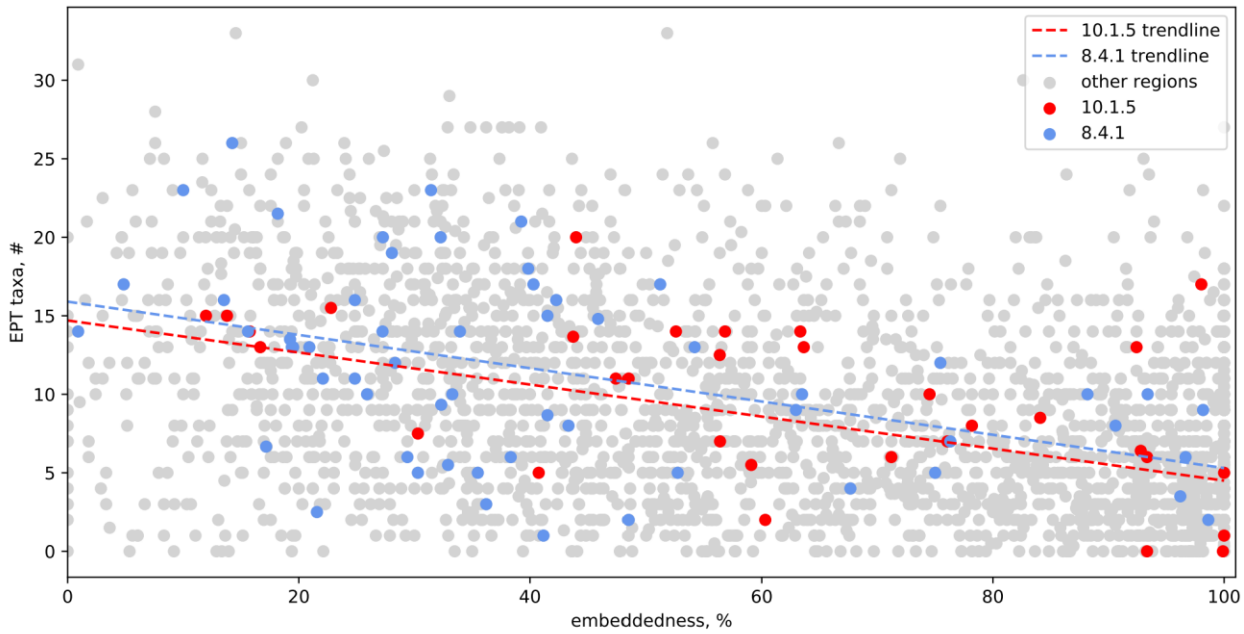

Figure 31. Embeddedness and number of EPT taxa with points from the Central Basin and Range (10.1.5) and Ridge and Valley (8.4.1) regions highlighted.

Number of lithophilic taxa

Nationally, the number of lithophilic taxa decreases with increasing embeddedness (Figure 33). This relationship is strongest (limiting to n > 30) in the North Central Hardwood Forests (r^2 = 0.37), the Northern Great Lakes and Forests (r^2 = 0.19) and the Northern Allegheny Plateau (r^2 = 0.16). There is a significant relationship ($p < 0.05$ and n > 30) in 9 Level III ecoregions (of 37 with n > 30) and 8 Level II ecoregions (of 12 with n > 30).

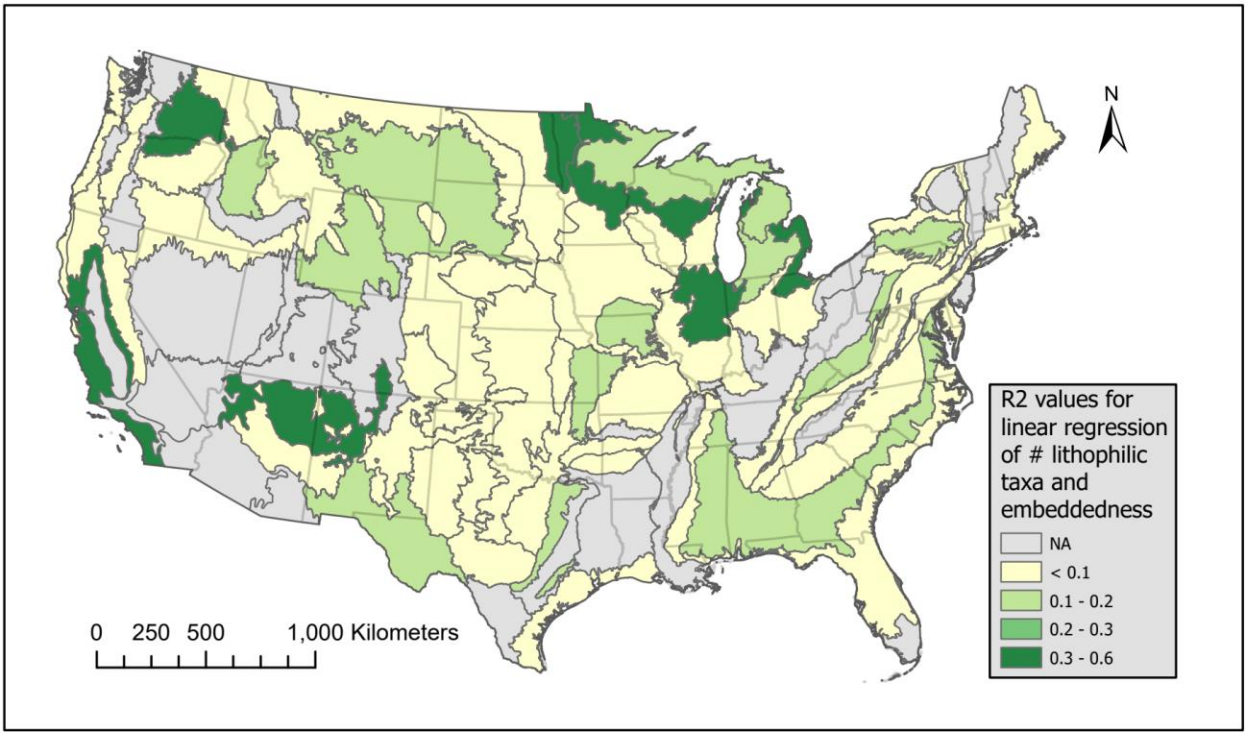

Figure 32. Negative correlation between embeddedness and number of lithophilic taxa mapped by Level III ecoregion.

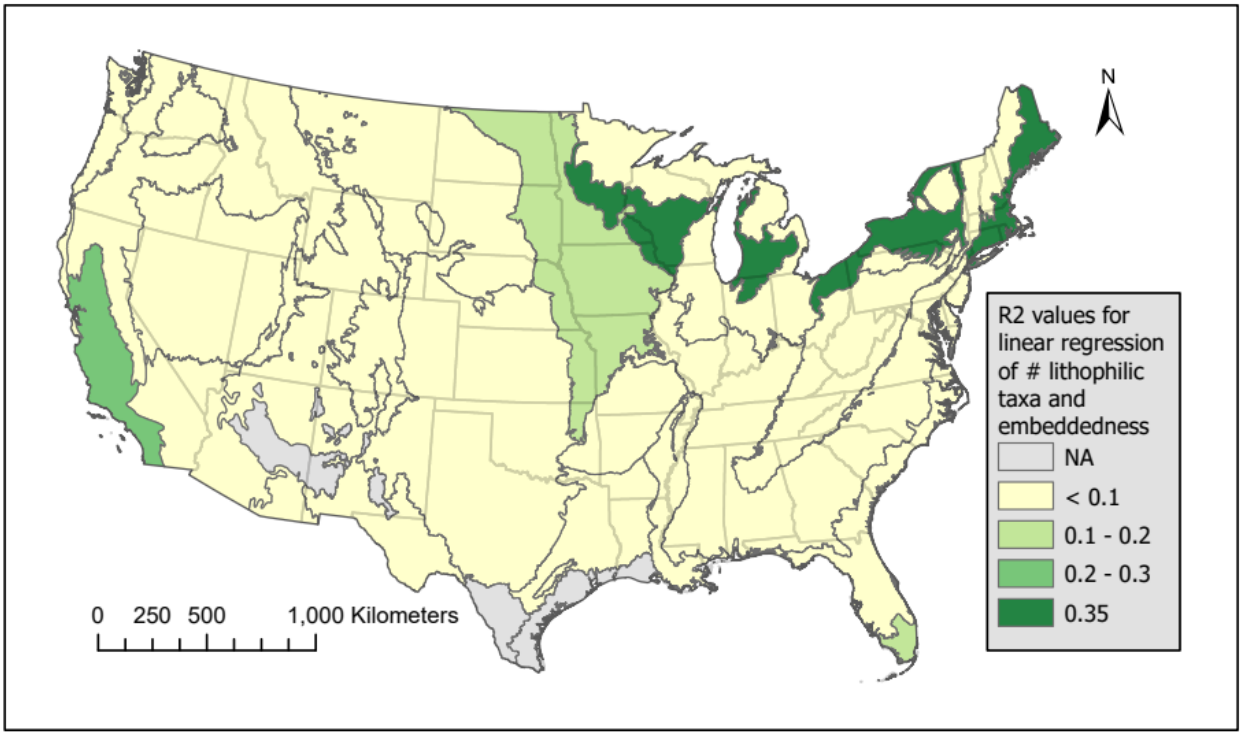

Figure 33. Negative correlation between embeddedness and number of lithophilic taxa mapped by Level II ecoregion.

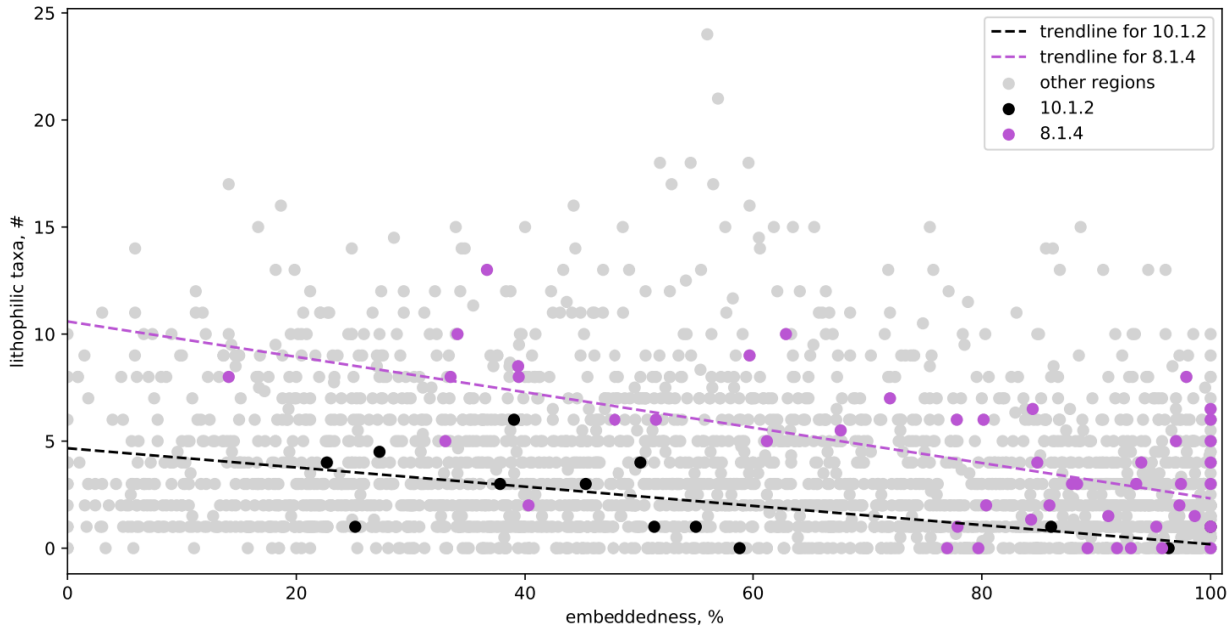

Figure 34. Embeddedness and number of lithophilic taxa with points from the Columbia Plateau (10.1.2) and the North Central Hardwood Forests (8.1.4) regions highlighted.

Number of intolerant taxa

Number of intolerant fish species as determined by "best professional judgment" (USEPA 2020), decreases with increasing embeddedness (Figure 36). This relationship is strongest (limiting to n > 30) in the Central Basin and Range ($r^2 = 0.25$), the Central Irregular Plains ($r^2 = 0.20$) and the Wasatch and Uinta Mountains ($r^2 = 0.18$). There is a significant relationship ($p < 0.05$ and $n > 30$) in 13 Level III ecoregions (of 37 with n > 30) and 10 Level II ecoregions (of 12 with n > 30).

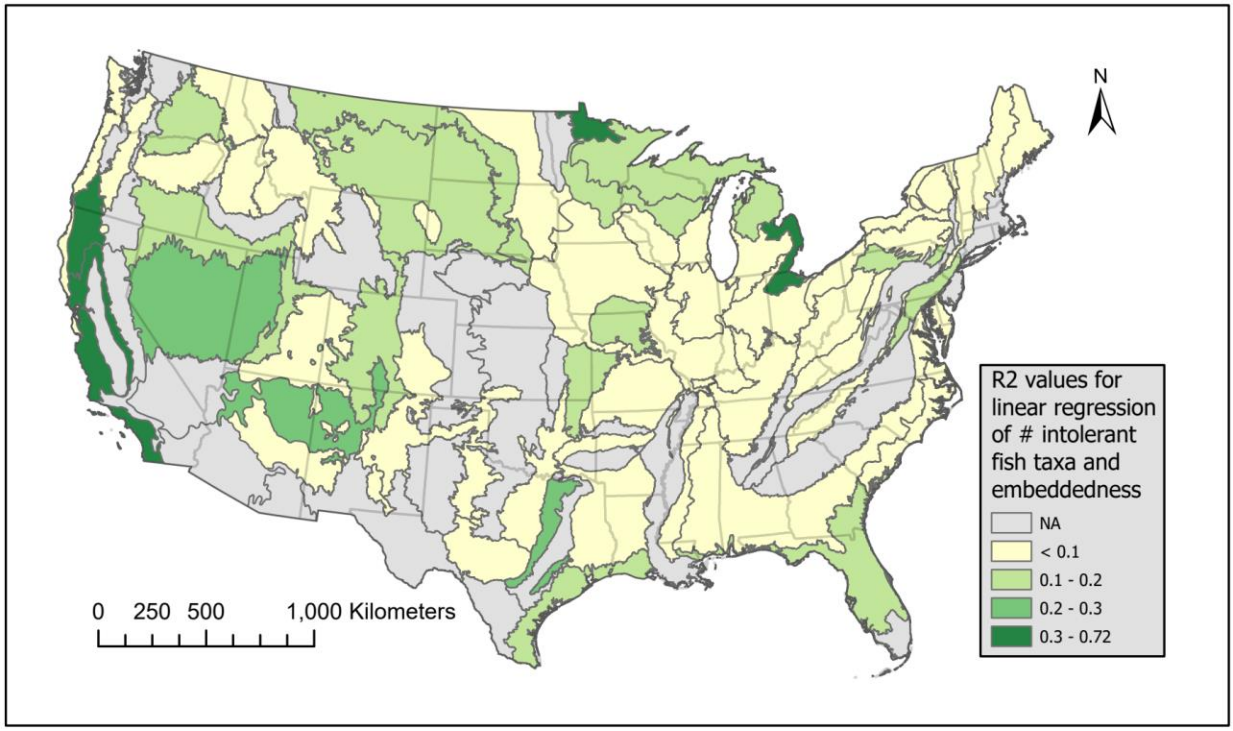

Figure 35. Negative correlation between embeddedness and number of intolerant fish taxa mapped by Level III ecoregion.

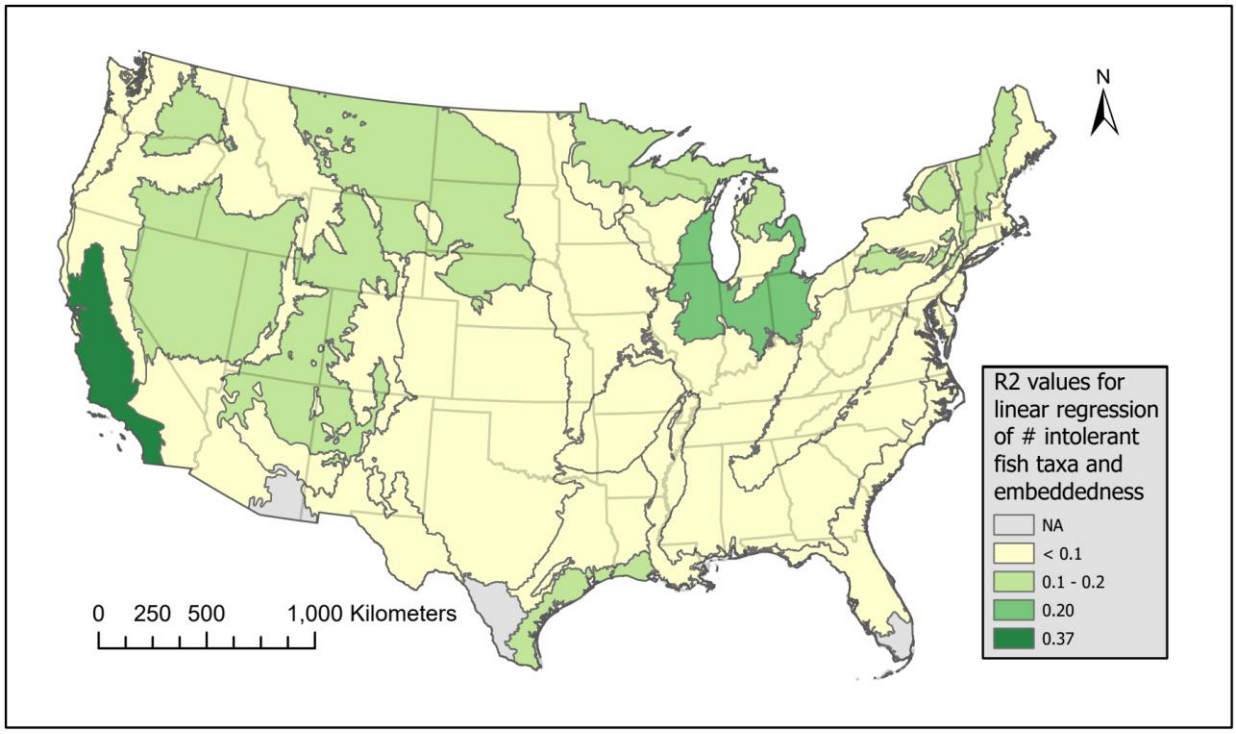

Figure 36. Negative correlation between embeddedness and number of intolerant fish taxa mapped by Level II ecoregion.

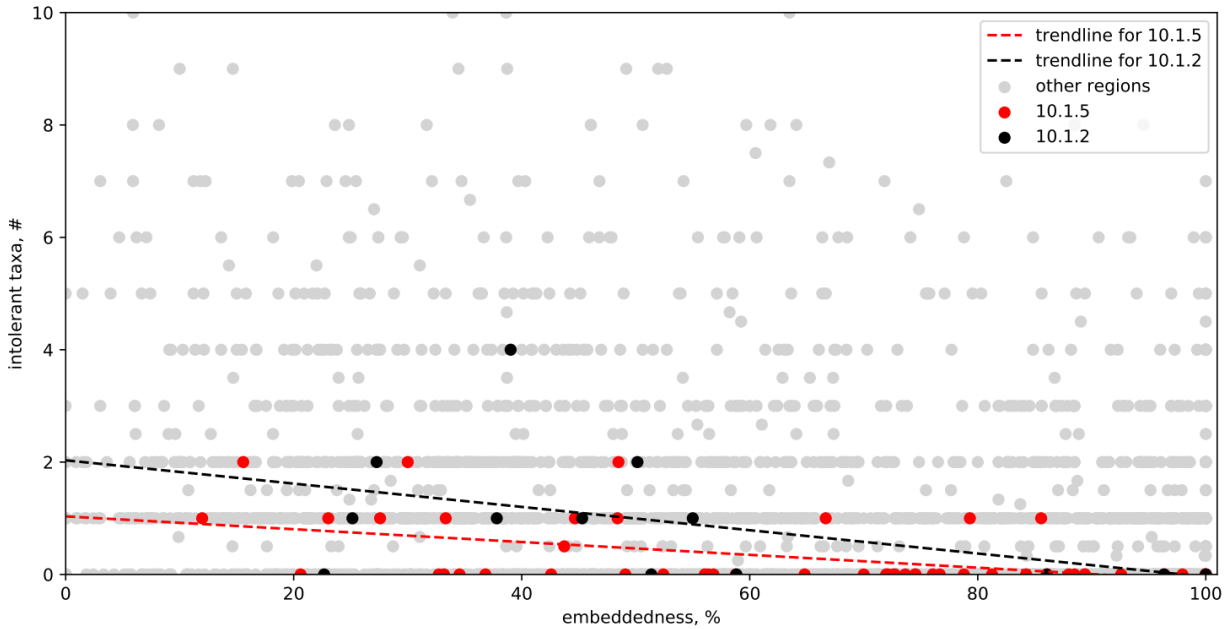

Figure 37. Embeddedness and number of intolerant fish taxa with points from the Central Basin and Range and Columbia Plateau regions highlighted.

<u>Number of salmonid taxa</u>

Salmonids were found to be negatively correlated with embeddedness. This relationship is strongest (limiting to n > 30) in the Central Basin and Range ($r^2 = 0.26$), the Southern Rockies ($r^2 = 0.21$), and the Northwestern Great Plains ($r^2 = 0.20$). There is a significant relationship ($p < 0.05$ and n > 30) in 8 Level III ecoregions (of 37 with n > 30) and 6 Level II ecoregions (of 12 with n > 30).

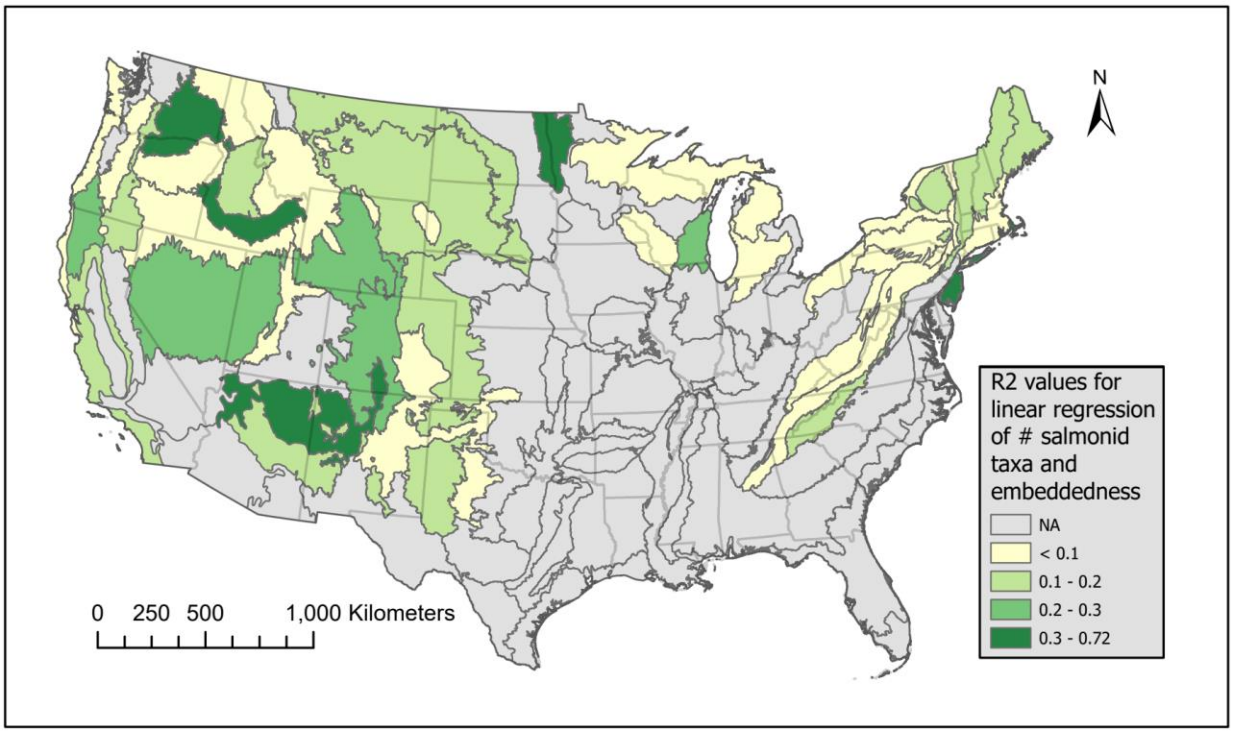

Figure 38. Negative correlation between embeddedness and number of salmonid taxa mapped by Level III ecoregion.

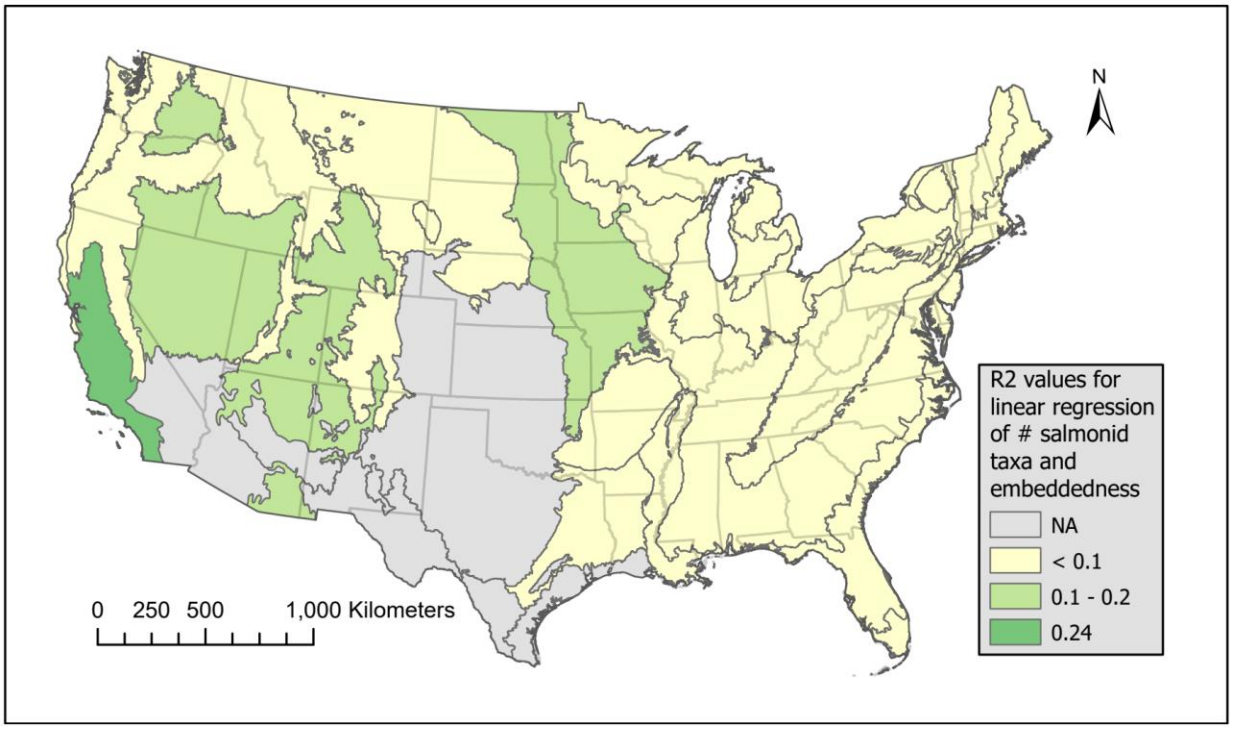

Figure 39. Negative correlation between embeddedness and number salmonid taxa mapped by Level II ecoregion.

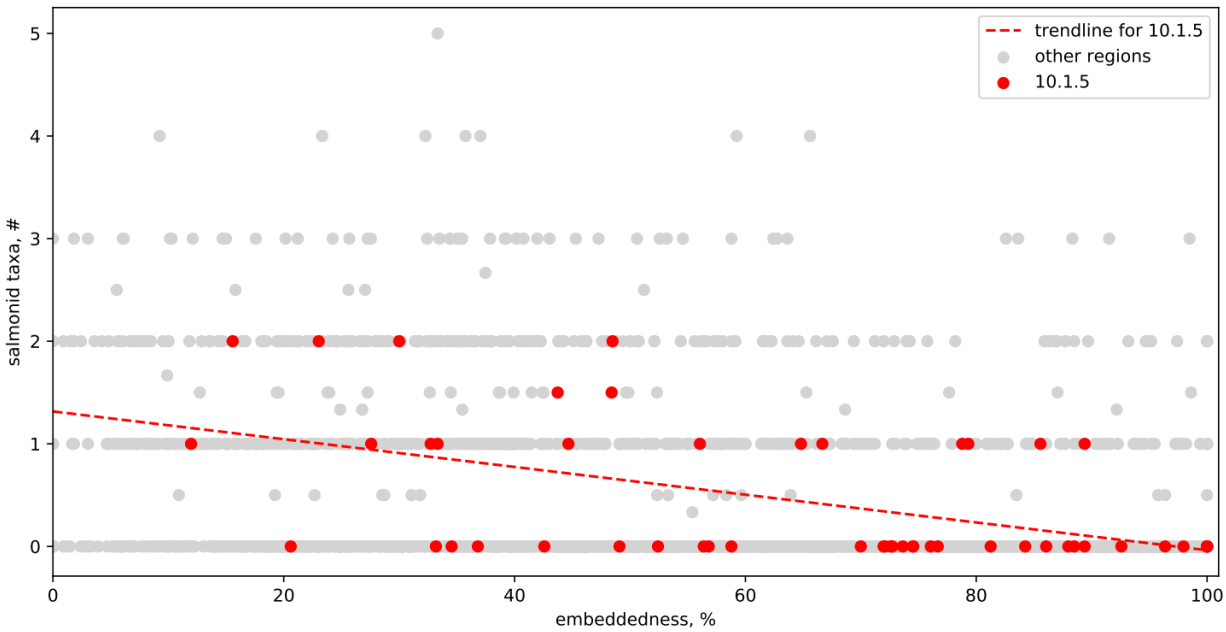

Figure 40. Embeddedness and number of salmonid taxa with points from the Central Basin and Range (10.1.5) region highlighted.

5. Discussion

5.1 Temporal variability in embeddedness

Embeddedness was expected to vary over time, with measured embeddedness closest to predicted embeddedness immediately following bankfull events, because bankfull conditions occur every 1~2 years and stream capacity to mobilize sediment varies between bankfull events. Specifically, bankfull events are expected to fully mobilize the bed, resulting in a resetting of the bed to the predicted level of embeddedness. The relatively low uncertainty of the method of measuring embeddedness by averaging values of individual pebbles was supported by the small range in values (RMSE = 3.24 %) of quadrats measured side by side in Stroubles Creek. The range in embeddedness values over time is an order of magnitude larger than the range between paired quadrat measurements, indicating that the temporal variation measured in this stream was significant.

The hypothesis that embeddedness would vary over time was supported by measurements at Stroubles Creek, though the relationship with percent of the bed mobilized by the last significant flow, time since the last bed mobilization, and seasonality have not been fully analyzed. Wynn et al. (2008) investigated bank erosion in Stroubles Creek over the course of a year and found

significantly higher rates of soil erosion in the winter, mostly due to freeze-thaw cycling. This indicates that more fine sediment is available in the winter and spring, which could account for the higher measures of embeddedness at those times. Repeated measurements in the Upper Roanoke River Basin also support the hypothesis that embeddedness in a given reach will vary over time with a minimum range of 2% difference between site visits and a maximum range of 25%. The relationship between temporal variation in embeddedness and seasonality or time since the most recent significant flow event has not been fully analyzed.

5.2 Regional variability in model fit

The model fits for ecoregions were expected to vary because sediment supply, geology, and frequency of bankfull events, etc. varies regionally. Sediment yield is highest in semi-arid regions (Leopold et al. 1964). In relatively low sediment-supply regions (e.g., Appalachian Mountains) the embeddedness-shear velocity relationship was expected to be similar to that shown in our preliminary results (Czuba et al. 2022); whereas, in relatively high sediment-supply regions (e.g., Pacific Northwest) we expect embeddedness to be generally higher for a given value of bankfull shear velocity. While the Level II correlations show general trends and can account for some areas that did not have a large sample size, some of the regional variation may be lost at the Level II scale. Conversely, there may be a significant relationship between embeddedness and shear velocity at the Level II scale that is not representative of a Level III ecoregion within that area where the model performs poorly. This hypothesis is supported, particularly on the Level II ecoregion scale, by the median deviations by region, as mapped in Figure 22. The spatial variation on the Level III spatial scale is mapped in Figure 21.

Sediment supply is not considered in this model, but over or underestimation of embeddedness by region informs how sediment supply may fit into the model. On the scale of Level III ecoregions with greater than 30 points, embeddedness was most overestimated in the Ozark Highlands (92%), the Interior Plateau (84%), and the Ridge and Valley (77%) regions. This is expected to indicate that these are supply limited systems, where winnowing results in lower embeddedness than modeled by shear velocity. The most underestimated were the Northern Basin and Range (89%), and the High Plains (69%). This underestimation implies that the system is transport limited, where the stream does not have the capacity to carry all of the fine sediment supplies.

All ecoregions were compared with a single model in order to determine variation among regions. However, this model (eq. 1) could be adapted for each ecoregion. Some of these regions (Fig. 20c) are substantially above or below the modeled baseline embeddedness. There are sources of variability (sediment supply and sand grain size) that are affecting the overall estimation. The way the measured embeddedness and shear velocity or modeled embeddedness has been plotted provides a consistent way based on the same curve to compare all the regions. Figure 20-22 are not an overall measure of the predictability of embeddedness for a given region. Instead, best-fit lines of the same form of the curve can be applied to each region to assess the overall predictability of that region, although at a loss of ease of intercomparing. For instance the Ridge and Valley (-11% median) the data still fit the general trajectory of the curve (Figure 20c), such that shifting the baseline curve downward with different coefficients would produce a strong regional predictive relationship.

5.3 Functional relationships between macroinvertebrates and embeddedness

Percent burrower taxa were expected to increase with increasing embeddedness as increased embeddedness is related to increased fine sediment generally, and burrowing macroinvertebrate taxa are protected from predation (Suttle et al. 2004) by fine sediment. This hypothesis was supported, with percent burrower taxa having a significant relationship with embeddedness in 43% of Level III ecoregions and 69% of Level II ecoregions. Although EPT do not have a direct functional relationship with fine sediment, they are often considered in relation to general habitat quality. This association of poor aquatic habitat with higher embeddedness (Barbour et al. 1999) is supported by the negative correlation between number of EPT taxa and embeddedness. This association is not, however, supported by the relationship between total number of macroinvertebrate taxa and embeddedness, as there were no significant relationships found.

5.4 Fish metrics and embeddedness

Because juvenile salmonid growth has been shown to decrease with increasing embeddedness, the number of salmonid taxa were expected to decrease with increasing embeddedness. This hypothesis was supported as significant relationships were found in some, but not all, ecoregions. Lithophilic spawners and intolerant taxa also decreased with increasing

embeddedness. Lithophilic spawner taxa decreasing is consistent with specific lithophilic species (Candy Darters and Roanoke logperch) demonstrating a negative correlation with embeddedness (Dunn & Angermeier 2016, Roberts et al. 2016). “Intolerant” is used within the NRSA dataset without context other than that it is based on “best professional judgment” (USEPA 2020). Biological experts may determine whether the designation of “intolerant” includes taxa intolerant to fine sediment. Similar to the total number of benthic macroinvertebrate taxa, there was no significant relationship found between the total number of fish taxa and embeddedness. This supports the hypothesis that because biota have varying positive and negative responses to fine sediment, the total number of taxa for fish and for macroinvertebrates was not expected to be significantly correlated with embeddedness.

5.5 Regional variability in relationship between embeddedness and biotic metrics

Biota respond to a suite of environmental variables of which embeddedness is only one. Therefore, the strength of correlations between embeddedness and biotic metrics were expected to vary by ecoregion. This hypothesis was supported by the spatial variability in the correlation between embeddedness and biotic metrics, particularly at the coarseness of Level III ecoregions. Level II may show general trends but also may be too coarse for some applications.

5.6 General limitations of model

The method of predicting embeddedness on a network scale through remotely sensed variables that can be used to calculate shear velocity requires continued development. As remote sensing technology advances, the error in remotely sensed slopes are expected to decrease. For example, the slopes derived from the NHD are based on a 30-m DEM (USEPA, 2021). The National Hydrography Dataset is in the process of being updated to be based on a 10-m DEM instead (Buto and Anderson 2020). While slopes derived from lidar data (around 1 m) would be preferable, and reasonably close to the values from the field data, processing lidar data over large scales is computationally and data storage intensive. Regional curves for bankfull geometry are also expected to improve with time, although constructing these equations is a time intensive process and may progress slower than remote sensing for slope and drainage area. Even in the field, identifying bankfull stages is a subjective process and bankfull width and depth vary longitudinally (Lindroth et al. 2020). Bankfull (the state where water fills the channel) is not

always the flow condition at which the bed of the stream is mobilized, adding additional uncertainty (Pfeiffer et al. 2017).

Implementing this model requires several assumptions which increase uncertainty. Rivers are assumed to be fully alluvial and the bed is assumed to be mobilized at bankfull flow. Not all rivers included in this study are alluvial, which is noted by the presence of bedrock. Additionally, bankfull flow does not mobilize the majority of the bed in all rivers. In order to calculate shear velocity from bankfull geometry, a wide rectangular channel is generally assumed.

The true value for embeddedness is unknown. To get more precise in calculating shear velocity, for sites with measured cross sections, it would be important to measure several cross sections to obtain averages within a reach and to specify the roughness. Fluid flow and sediment motion are not linearly related therefore the averaging of fluid discharge or velocity across a reach, fed through transport equations, does not result in an accurate average sediment flux (Yager et al. 2018). This may be true of sediment mobilization in the bed and into suspension. While these limitations must be noted, there are remotely available parameters that can be used to easily calculate an average reach shear velocity, which is useful in creating reach-averaged, network-scale estimates or predictions of embeddedness. Sand grain size may also factor into the shear velocity required to mobilize the bed (Pfeiffer et al. 2017).

5.7 Biotic applicability

We anticipate that mapping basin-wide embeddedness will be useful, along with other metrics, in determining current and potential habitat for various stream biota. This type of map is demonstrated in Figure 19. The predicted embeddedness values could be shifted by the median deviation for the region of interest, mapped in Figure 21 and 22 or individual best fits of the curve can be fit to the region first to locally calibrate the curve, and then applied to the network prediction. Geographical variation in response of fish and benthic macroinvertebrate taxa to sediment indicate that embeddedness will be most useful for prediction of biota on a regional scale. There are significant correlations between several other biotic metrics, not specifically mentioned in this thesis, and embeddedness that warrant further investigation.

The R^2 values representing the relationships between embeddedness and various biotic metrics are based on linear regression, which does not encapsulate the complexity of the

relationship. This analysis is primarily for the purpose of identifying what biotic metrics may be related to embeddedness in various spaces. However, for the investigated metrics (Figures 27, 30, 33, 36, & 39) these relationships were best-fit with linear regressions with no threshold responses present. This may not be the case for all metrics. Further investigation of the particular relationships is recommended. For example, Dunn and Angermeier (2016) found a linear decline in juvenile Candy Darters from 0 - 50 % embeddedness, with few juveniles present in areas with > 50% embeddedness. This illustrates the utility of even rough estimations of embeddedness, e.g. estimating areas where embeddedness is expected to be greater than 50 %, and thus juvenile Candy Darters are expected to be absent. Embeddedness is only one metric of fine sediment deposition, and the physical structure of fine sediment deposition and stream bed structure in general is only one factor in any biotic metric. Water chemistry can be equally if not more important (Bertrab et al. 2013). Mapping predicted embeddedness could be overlaid with known species distributions as well as other threats and habitat variables or models. Many biotic metrics are correlated with embeddedness, though there is significant spatial variation in significance of these correlations.

6. Future Work

The methods of modeling and measuring embeddedness discussed in this thesis will benefit from further investigation into spatial and temporal variability. In order to increase functional application of eq. 1, future work includes determining best-fit coefficients by ecoregion. These values, as well as the median deviations mapped in Figures 21 & 22, will allow for prediction of embeddedness from shear velocity at a network scale in areas outside of southwest Virginia. In the nationwide relationship between formative shear velocity (via averaged channel dimensions and slope) and embeddedness, we have not investigated the particular role of anthropogenic influence on the measurements of embeddedness. Sediment supply may be investigated with the NRSA dataset by determining sources of impairment or sediment inputs via the Revised Universal Soil Loss Equation (RUSLE), bank erosion estimates, or known anthropogenic influences such as major construction or presence of dams. Significant questions remain about the roles of temporal variability and the impact of sediment supply and grain size in predicting embeddedness. Ongoing steps include measuring variation in embeddedness with time and sediment inputs in a flume, where variation is controlled and with field measurements, particularly in Stroubles Creek, where stage and velocity are measured.

7. Conclusions

Embeddedness is negatively correlated with shear velocity. While there remains significant uncertainty in regards to application of the relationship proposed by Czuba et al. (2022), it has potential for usefulness nationwide. Nationally, measurements of embeddedness were higher than modeled in areas that may have higher sediment supply, and lower than modeled in regions with low fine sediment supply. Further research will involve calculating best-fit values for coefficients *a* and *b* by ecoregion to decrease uncertainty for national scale application. By calculating shear velocity through remotely sensed channel geometry metrics, embeddedness may be predicted throughout a stream network. Embeddedness is generally higher in areas with higher sediment loading and varies with time, though the function and scale of this variation has not been fully investigated.

Lotic biota respond to embeddedness, with regional variation. As biota respond to both water quality and habitat, embeddedness will only ever be one metric in the consideration of habitat suitability. Burrowing macroinvertebrate taxa, which may use increased sand to escape predation, increased with increasing embeddedness while the number of Ephemeroptera, Plecoptera, Trichoptera (EPT) taxa, the number of lithophilic spawning fish, and the number of salmonid taxa decreased. Highly embedded substrate is generally considered poor habitat, which was supported by a trend of decreasing intolerant fish taxa with increasing embeddedness. While intolerant taxa did have a significant relationship in several ecoregions, the classification for "intolerant" was not published. Biologists may identify specific taxa or groups of taxa that fall in this group with a functional relationship to embeddedness which would be a better candidate for comparison. Richness (total number of taxa) for both macroinvertebrates and fish did not show a significant correlation, indicating that embeddedness, and fine sediment in general, is not necessarily an impairment to all stream habitat, but is impactful for particular taxa.

References

Adams, K. (2010). Guidance for Stressor Identification of Biologically Impaired Aquatic Resources in Washington State. Washington State Department of Ecology. Publication no. 10-03-036. 114 pp

Andraso, G.M., Grazio, J.L., & Phillips, E. (2009). Assessment of fish and macroinvertebrate assemblages in Fourmile Creek (Erie Co., PA) prior to stream improvement efforts. Journal of the Pennsylvania Academy of Science, 83 (2/3), 67-76.

Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling. (1999). Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish, Second Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Bowles, D.E., Bolli, J.M., & Clark, M.K. (2013). Aquatic invertebrate community trends and water quality at Homestead National Monument of America, Nebraska, 1996-2012. Kansas Academy of Science, 116(3-4), 97-112.

Bunte, K. & Abt, S.R. (2001). Sampling frame for improving pebble count accuracy in coarse gravel-bed streams. JAWRA Journal of the American Water Resources Association, 37: 1001-1014. https://doi.org/10.1111/j.1752-1688.2001.tb05528.x

Marta Gerta Von Bertrab, Andreas Krein, Sonja Stendera, Frankie Thielen, Daniel Hering. (2013). Is fine sediment deposition a main driver for the composition of benthic macroinvertebrate assemblages?, Ecological Indicators, Volume 24, 2013, Pages 589-598, ISSN 1470-160X, https://doi.org/10.1016/j.ecolind.2012.08.001

Bieger, K., Rathjens, H., Allen, P.M., & Arnold, J.G. (2015). Development and evaluation of bankfull hydraulic geometry relationships for the physiographic regions of the United States. Journal of the American Water Resources Association (JAWRA) 51(3): 842-858. DOI: 10.1111/jawr.12282

Brunke, M. (1999). Colmation and depth filtration within streambeds: retention of particles in hyporheic interstices. *International Review of Hydrobiology*, 84(2), 99-117. https://doi.org/10.1002/iroh.199900014

Buto, S.G., & Anderson, R.D. (2020). NHDPlus High Resolution (NHDPlus HR)---A hydrography framework for the Nation: U.S. Geological Survey Fact Sheet 2020-3033, 2 p., https://doi.org/10.3133/fs20203033.

Czuba, J. A., Hirschler, M., Pratt, E. A., Villamagna, A., & Angermeier, P. L. (2022). Bankfull shear velocity predicts embeddedness and silt cover in gravel streambeds. *River Research and Applications*, 38(1), 59–68.

Daniels, R. A., Riva-Murray, K., Halliwell, D. B., Vana-Miller, D. L., & Bilger, M. D. (2002). An index of biological integrity for northern mid-atlantic slope drainages. Transactions-American Fisheries Society, 131(6), 1044–1060.

Dauwalter, D. C., Pert, E. J., & Keith, W. E. (2003). An index of biotic integrity for fish assemblages in Ozark highland streams of Arkansas. Southeastern Naturalist, 2(3), 447–468.

Dunn, C. G. & Angermeier, P. L. (2016) Development of habitat suitability indices for the Candy Darter, with cross-scale validation across representative populations. *Transactions of the American Fisheries Society*, 145(6) 1266-1281, DOI: 10.1080/00028487.2016.1217929 To link to this article: https://doi.org/10.1080/00028487.2016.1217929

Ferguson, R. I., & M. Church (2004). A simple universal equation for grain settling velocity, J. Sediment. Res., 74(6), 933–937, doi:10.1306/051204740933.

Fitzpatrick, F. A., Waite, I. R., D'Arconte, P. J., Meador, M. R., Maupin, M. A., & Gurtz, M. E. (1998). Revised Methods for Characterizing Stream Habitat in the National Water-Quality Assessment Program. USGS WRI Report 98-4052. Available at https://pubs.usgs.gov/wri/wri984052/pdf/wri98-4052.pdf

Florida Dept of Environmental Protection. (2022). Development and application of DEP bioassessment methods.

Garcia, M. H. (2008). Sedimentation Engineering: Processes, Measurements, Modeling, and Practice. ASCE Manuals and Reports on Engineering Practice No. 110. ASCE.

Govenor, H., Krometis, L.A.H., Willis, L., Angermeier, P.L., & Hession W.C. (2019). Macroinvertebrate sensitivity thresholds for sediment in Virginia streams. Integrated Environmental Assessment and Management, 15(1) 77-92.

Hill, R. A., Fox, E. W., Leibowitz, S. G., Olsen, A. R., Thornbrugh, D. J., & Weber, M. H. (2017). Predictive mapping of the biotic condition of conterminous U.S. rivers and streams. Ecological applications : a publication of the Ecological Society of America, 27(8), 2397–2415. https://doi.org/10.1002/eap.1617

Jones, J. I., Murphy, J. F., Collins, A. L., Sear, D. A., Naden, P. S., & Armitage, P. D. (2011). The impact of fine sediment on macroinvertebrates. River Research and Applications, 28(8), 1055–1071. https://doi.org/10.1002/rra.1516

Karr, J. R. (1981). Assessment of biotic integrity using fish communities. Fisheries, 6(6), 21–27. https://doi.org/10.1577/1548-8446(1981)006<0021:AOBIUF>2.0.CO;2

Karr, J.R., K.D. Fausch, P.L. Angermeier, P.R. Yant, & I.J. Schlosse. (1986). Assessment of biological integrity in running waters: A method and its rationale. Illinois Natural History Survey Special Publication 5, Champaign, Illinois.

Keaton, J.N., Messinger, T., & Doheny, E.J. (2005). Development and analysis of regional curves for streams in the non-urban Valley and Ridge Physiographic Province, Maryland, Virginia, and West Virginia. U.S. Geological Survey Scientific Investigations Report 2005-5076. 116 pp.

Lamb, M. P., & Venditti, J. G. (2016). The grain size gap and abrupt gravel-sand transitions in rivers due to suspension fallout. *Geophys. Res. Lett.*, 43, 3777-3785. https://doi.org/10.1002/2016GL068713

Leopold, L.B., Wolman, M.G., & Miller, J.P. (1964). Fluvial Processes in Geomorphology. W.H. Freeman and Company. San Francisco, U.S.

Lindroth, E. M., Rhoads, B. L., Castillo, C. R., Czuba, J. A., Güneralp, I., & Edmonds, D. (2020). Spatial variability in bankfull stage and bank elevations of lowland meandering rivers: Relation to rating curves and channel planform characteristics. Water Resources Research, 56(8), e2020WR027477. https://doi.org/10.1029/2020WR027477

Mebane, C. A., Maret, T. R., & Hughes, R. M. (2003). An index of biological integrity (IBI) for pacific northwest rivers. Transactions of the American Fisheries Society, 132(2), 239–261. https://doi.org/10.1577/1548-8659(2003)132<0239:AIOBII>2.0.CO;2

McHugh, P., & Budy, P. (2005). A comparison of visual and measurement-based techniques for quantifying cobble embeddedness and fine-sediment levels in salmonid-bearing streams. North American Journal of Fisheries Management, 25(4), 1208–1214. https://doi.org/10.1577/M04-209.1

Montgomery, D. R. & Buffington, J. M. (1993). Channel classification, prediction of channel response, and assessment of channel condition: Olympia,Washington State Department of Natural Resources Report TFW-SH10-93-002, 84 p.

Jessup, B. & Neils, D. (2011). Site classification for the New Hampshire Benthic Index of Biotic Integrity (B-IBI) using a non-linear predictive model. New Hampshire Department of Biological Services. 55 pp.

Olsen, T. (2007). National flowing waters assessment survey design: 2008-2009. U. S. Environmental Protection Agency Report. 12 pp.

Omernik, J.M., Griffith, G.E. (2014). Ecoregions of the Conterminous United States: Evolution of a Hierarchical Spatial Framework. Environmental Management 54, 1249–1266. https://doi.org/10.1007/s00267-014-0364-1

Pfeiffer, A. M., Finnegan, N.J., & Willenbring, J.K. (2017). Sediment supply controls equilibrium channel geometry in gravel rivers. Proceedings of the National Academy of Sciences. 114(13), 3346-3351. https://doi.org/10.1073/pnas.1612907114

Pizzuto, J.E., Hession, W.C., & McBride, M. (2000). Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. Geology, 28(1), 79-82

Poff, N.L., Olden, J.D., Vieira, N.K.M., Finn, D.S., Simmons, M.P. & Kondratieff, B.C. (2006) Functional trait niches of North American lotic insects: traits-based ecological applications in light of phylogenetic relationships. Journal of the North American Benthological Society 25(4), 730-755.

Rehn, A.C., May, J.T., & Ode, P.R. (2008). An index of biotic integrity (IBI) for perennial streams in California's Central Valley. California Department of Fish and Game, Aquatic Bioassessment Lab. 33 pp.

Resh, V. H., Norris, R. H., & Barbour, M. T. (1995). Design and implementation of rapid assessment approaches for water resource monitoring using benthic macroinvertebrates. *Australian Journal of Ecology*, 20, 108-121.

Roberts, J. H., Anderson, G. B., & Angermeier, P. L. (2016). A Long-term study of ecological impacts of river channelization on the population of an endangered fish: Lessons learned for assessment and restoration. *Water*, 8(240).

Rosenberger, A. & Angermeier, P. L. (2003). Ontogenetic shifts in habitat use by the endangered Roanoke logperch (*Percina rex*). *Freshwater Biology*, 48, 1563-1577. https://www.fs.fed.us/rm/pubs_other/rmrs_2003_rosenberger_a001.pdf

Sennatt, K. M., Salant, N. L., Renshaw, C. E., & Magilligan, F. J. (2006). Assessment of methods for measuring embeddedness: application to sedimentation in flow regulated streams, *J. Am. Water Resour. Assoc.*, 42(6), 1671-1682. https://doi.org/10.1111/j.1752-1688.2006.tb06028.x

Sutherland, A. B., Culp, J. M., & Benoy, G. A. (2010). Characterizing deposited sediment for stream habitat assessment. *Limnol. Oceanogr. Methods*, 8(1), 30-44. https://doi.org/10.4319/lom.2010.8.30

Suttle, K. B. Power, M. E., Levine, J. M., & Camille McNeely. (2004). How Fine Sediment in Riverbeds Impairs Growth and Survival of Juvenile Salmonids. Ecological Applications, 14(4), 969–974. http://www.jstor.org/stable/4493596

USEPA (U.S. Environmental Protection Agency). (2020). National Rivers and Streams Assessment 2013-2014 Technical Support Document. EPA 843-R-19-001. Office of Water

and Office of Research and Development. Washington, D.C. https://www.epa.gov/national-aquatic-resource-surveys/nrsa

USEPA (U.S. Environmental Protection Agency). National Aquatic Resource Surveys. National Rivers and Streams Assessment 2018-2019 (data and metadata files). Available from U.S. EPA web page: https://www.epa.gov/national-aquatic-resource-surveys/data-national-aquatic-resource-surveys. Date accessed: 2022-10-01.

USEPA, U.S. Environmental Protection Agency. (2021). National Hydrography Dataset (NHDPlusV2). Retrieved September 15, 2021 from https://www.epa.gov/ waterdata/get-nhdplus-national-hydrography-dataset-plus-data

USEPA, U.S. Environmental Protection Agency (2022). ATTAINS Program Data: 303(d) Listed Impaired Waters NHDPlus Indexed Dataset with Program Attributes. Last accessed 1 July 2022 at https://www.epa.gov/waterdata/waters-geospatial-data-downloads#303dListedImpairedWaters

VGIN, Virginia Geographic Information Network (2022), Virginia LiDAR downloads: 2018 Virginia FEMA NRCS South Central LiDAR B1. Accessed October 2022 at https://vgin.vdem.virginia.gov/apps/VGIN::virginia-lidar-downloads/explore

Wharton, G., Mohajeri, S. H., & Righetti, M. (2017). The pernicious problem of streambed colmation: a multi-disciplinary reflection on the mechanisms, causes, impacts, and management challenges. *WIREs Water*, 4, e1231. https://doi.org/10.1002/wat2.1231

Wilcock PR., Barta AF, Shea CC, Kondolf GM, Matthews WVG, Pitlick J. (1996). Observations of flow and sediment entrainment on a large gravel-bed river. Water Resour Res. 32(9):2897–2909. doi:10.1029/96WR01628.

Wilcock, P. R., and J. C. Crowe (2003), Surface-based transport model for mixed-size sediment, J. Hydraul. Eng., 129, 120 – 128, doi:10.1061/(ASCE)0733-9429(2003)129:2(120)

Wood, P. J., & Armitage, P. D. (1997). Biological effects of fine sediment in the Lotic Environment. Environmental Management, 21(2), 203–217. https://doi.org/10.1007/s002679900019

Wynn, T.M., Henderson, M.B. & Vaughan, D.H. (2008). Changes in streambank erodibility and critical shear stress due to subaerial processes along a headwater stream, southwestern Virginia, USA

Yager, E. M., Jeremy G. Venditti, Heidi J. Smith, Mark W. Schmeeckle. (2018). The trouble with shear stress. *Geomorphology*, 323, 41-50. https://doi.org/10.1016/j.geomorph.2018.09.008