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Relative Applicability of Particle Distribution Measures and Bank Slope Stability in Evaluating NPS Watershed Projects

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Introduction

Excessive amounts of fine sediments or unstable banks in streams and rivers create unsuitable habitat for aquatic organisms that thrive in hydrologic systems with balanced substrate compositions. A broad range of sediment conditions exists in streams and rivers with naturally evolving channels. In erosive settings such as mountain and foothill slopes, fine sediments are carried through the system, exposing or leaving larger and stable substrates that benefit certain biological communities and organisms. For example, trout and other gravel-spawning fish rely on substrate particles that can be manipulated for nest-building, are stable over the gestation period, and have sufficient porosity to allow interstitial flow around the eggs. In depositional settings further down the river continuum, sediment compositions naturally include greater percentages of fine sediments due to transport from upstream and less hydrologic capacity of the system to move particles. Organisms adapted to fine or unstable sediment conditions can thrive in those conditions.

As human disturbance and development increase in stream channels and catchments, the naturally balanced substrate and bank conditions can be disrupted, putting increasing stress on the resident biota (Sutherland et al. 2002). Increasing amounts of fine sediments are delivered to the stream through upland erosion or are eroded from channel banks or resuspended from existing bed sediments due to hydrologic changes (Zaimes et al. 2004; Burcher et al. 2007). Agricultural cultivation, construction associated with development, runoff from impervious surfaces, and poor drainage design on developed land can contribute to excessive delivery of sediments to streams.

Once in the channel, sediments are moved through the system depending on the sediment supply and the hydraulic capacity of the system. Excessive sediment supply can result in sediment deposition and filling of pools and interstitial spaces among gravel and larger substrates. Once sedimentation occurs and channel shape is modified, hydraulic forces can cause the channel to spread and migrate and the banks to erode as a result. Changes in hydrology caused by an increased amount of impervious surface in the drainage area can elevate peak flows and increase erosional forces on channel banks. On the other hand, a lack of sediment supply in a system with substantial capacity can result in entrenchment, head-cutting, and bank erosion as the hydraulic forces balance power with load. In many streams and rivers, bank erosion is responsible for more mobile substrate than upland sediment transport.

The mechanisms by which biota are affected by excessive fine sediments include:

- Displacement of interstitial habitat space,
- Clogging of water movement under the channel bed (hyporheic zone),
- Decreased or altered primary algal productivity,
- Increased macroinvertebrate drift,
- Abrasion or smothering of gills and other organs,
- Uptake of sediment-bound toxicants that are increasingly associated with fine particles, and
- Larger scale homogenization or disturbance of habitat types (Waters 1995; Wood and Armitage 1997; USEPA 2006).

For example, increased fine sediments displace suitable substrates or smother established fish nests and prevent or disrupt reproduction (Kemp et al. 2011). Stable channel banks retain the sediments that otherwise contribute to excessive fine sediment deposition in the wetted channel and provide important riparian and near-channel habitat conditions. In addition to impacting aquatic life conditions, unstable substrates and banks also threaten property and infrastructure around active channels.

Fine sediments and channel evolution occur naturally. Aquatic life protection is the primary impetus for differentiating natural and tolerable sediment and bank conditions from disturbed and intolerable conditions. It is critical that assessment of imbalances and impacts are made in the context of natural expectations. This technical memorandum addresses the ways in which sediment particle distribution and bank slope stability are measured and how the measurements can be used to evaluate imbalanced or unstable conditions in support of problem assessment, protection or restoration efforts, and project evaluation. It is directed towards nonpoint source (NPS) professionals with a basic understanding of habitat and biological monitoring and assessment techniques.

Measurements of Bedded Sediments and Bank Stability

Methods for measuring bedded sediments and bank stability include:

- Embeddedness and sedimentation ratings,
- Surface particle size distribution,
- Relative Bed Stability (RBS),
- Bank stability ratings,
- Sequential channel surveys,
- Bank Erosion Hazard Index (BEHI), and
- Near-Bank Stress (NBS).

Bedded sediments can be assessed at a screening level using qualitative observations of "embeddedness," which is the degree to which larger particles on the surface are surrounded or covered by fine materials (Sylte and Fischenich 2002). In rapid assessment methods, embeddedness can be rated on a 20-point scale from "optimal" (0–25 percent covered) to "poor" (more than 75 percent covered) (Barbour et al. 1999). Other qualitative habitat ratings related to sediments include "sediment deposition," which is the amount of sediment that has accumulated in pools and the changes to the stream that have occurred, and "pool variability," which is the overall mixture of pool types found in streams, according to size and depth. With proper training, observers can calibrate their ratings to the narrative descriptions of these qualitative measures to reach high degrees of precision.

Particle size distribution is commonly measured at the streambed surface within a targeted stream reach. At the outset, a grid or transect pattern is predefined so that particles can be identified systematically, but with randomized starting points to avoid bias and to characterize the whole reach. The method was first introduced as the "Wolman Pebble Count" (Wolman 1954). At each of 100 points on a predefined sampling grid, an individual particle is selected by blindly poking at the substrate with a meter stick or finger. Each particle is classified by the size of the intermediate axis, which is neither the longest nor the shortest of the three dimensions. The size classes range from very fine silt and clay to large boulders and bedrock (Table 1). The fine sediment size category can include clay, silt, sand, and, in some cases, small pebbles. For particles less than 2 mm, sand is distinguished from clay and silt by pinching a small quantity of the substrate and determining the texture: silt and clay are smooth when rubbed between the fingers, and sand is gritty.

The particle size distribution can be summarized in several ways, such as percent silt; percent sand, silt, and clay; median particle size (D_{50}); or other size quantiles (D_{16} and D_{84}) (USEPA 2006). Percent sand, silt, and clay measures the percentage of all particles that are less than 2 mm. Percent "fines" might include particles up to 0.06 mm (silt and clay) or particles up to 6 mm, which are critical in relation to fish habitat suitability. The percentages of surficial coverage by particle size are based on the particles observed in each class and the total number of particles observed.

Table 1. Particle Size Categories (Kaufmann et al. 1999)

Size Category	Size Range (mm)
Silt, clay, muck	< 0.06
Sand	0.06–2
Fine gravel	2–16
Course gravel	16–64
Cobbles	64–250
Boulders	250–4,000
Bedrock	> 4,000

For specific studies, the pebble count method has been modified to sample different numbers of particles (50–150), use different layouts of the sampling grid (transect or zig-zag pattern), use different particle size categories, and focus on specific habitats such as potential salmonid spawning areas or wetted and dry portions of the channel (Bunte et al. 2009). The definition of the sampling reach (i.e., wetted width or bankfull width, riffles, or all habitats) can account for much of the variation in particle size distribution results. Different methods for particle selection from the bed, particle-size determination, and the use of wide, nonstandard size classes also affect results. These methods must be standardized within a study to ensure that the data are comparable.

The effort required for a quantitative pebble count is minimal for a typical habitat sampling event. With slightly increased sampling effort, the additional variables required to calculate RBS can be measured. RBS is a ratio of the median of the observed particle diameters (D_{50}) relative to the critical size of bed particles that can be mobilized during bankfull flows (D_{cbf}) (Kaufmann et al. 2008):

$$RBS = D_{50} \div D_{cbf}$$

The basis for RBS is the pebble count, from which D_{50} is calculated. D_{cbf} is calculated from channel dimensions at bankfull flows, longitudinal channel slope, and channel roughness due to woody debris and residual pools, all of which contribute to shear stress at the stream bed. The bankfull channel extent is estimated from landform shape and vegetation type. The channel width, depth, and longitudinal profile are surveyed, and woody debris is tallied. RBS is often related to percent sand and silt, however, it is scaled to specific channel expectations. For example, slow, low-gradient systems might have high percentages of fine materials and still be relatively stable, but higher gradient systems might be unstable with the same particle distribution. If more fine sediments are present than are typically mobilized (e.g., RBS<<1), the imbalance implies that a high percentage of substrates are unstable during common flow events. In coastal streams in the Pacific Northwest, RBS values in relatively undisturbed watersheds ranged from 0.15 to 1.65 (Kaufmann et al. 2009). At any given level of disturbance, smaller streams had lower RBS than streams with larger drainages.

Bank stability can be assessed at a screening level using qualitative observations in a rapid assessment framework (Barbour et al. 1999). In this widely used monitoring technique, left and right banks are rated on a 10-point scale from “optimal” (>95 percent stable banks) to “poor” (60–100 percent of bank has erosional scars). Signs of erosion are outlined in narrative descriptions of the rating scale, including crumbling, unvegetated banks, exposed tree roots, and exposed soil (Barbour et al. 1999). Even though such descriptions are qualitative, assessors can achieve a high degree of precision using this method if they become well-calibrated through training and replicate observations.

Quantitative bank erosion is typically monitored over 5–30-year time periods using sequential photography, planimetric resurvey and repeated cross-profiling, and measurements of channel dimension using bank pins or tree roots as stable benchmarks (Lawler 1993; De Rose and Basher 2011; Dick et al. 2014).

- Sequential aerial photography is used to measure lateral channel migration over large areas or multiple channels. Remote sensing is becoming more accurate with the use of LIght Detecting And Ranging (LIDAR) methods, with stated accuracies of <0.15 m vertically and <0.4 m horizontally compared to typical accuracies of 5 m for aerial photography (De Rose and Basher 2011).
- Surveys of channel dimensions over time are highly accurate but time-intensive and are usually limited to a few locations. Survey markers are established during the first visit as a reference for all planimetric and profile measurements. Repeated mapping of channel cross-sections over time reveals changes in the channel profile resulting from bank erosion or channel deposition.

- Bank pins are metal rods driven into the bank to establish benchmarks for erosion measurement. As the bank erodes, the pins are exposed and the length of the exposed pin is remeasured. Methods using tree root exposure can detect erosion rates over time from a single visit because changes in the anatomy (e.g., tree rings) and scarring of roots indicate time of exposure for existing roots (Dick et al. 2014). The tree-ring method requires interpretation of tree-ring anatomy and is most accurate for recently exposed roots (i.e., 7 years or less).

Streambank erosion processes are driven by two major components: stream bank characteristics (erodibility) and hydraulic/gravitational forces. These components can be estimated using the BEHI and NBS methods, which are both rapid field monitoring methods that indicate bank susceptibility to the erosive forces acting on the stream bank (Rosgen 2001). The quantitative BEHI variables include the bank height-to-bankfull height ratio, the root depth-to-bank height ratio, weighted root density, bank angle, and bank protection afforded by debris and vegetation (Figure 1). Scores of 1 (very low bank erosion potential) to 10 (extreme potential) are associated with each of the five measures. The scores are added as a site erodibility risk score (BEHI) on a scale of 1–50 and further modified using two qualitative observations: stream bank material composition and stratification. NBS methods further quantify the erosive forces at each site by rating velocity gradient and near-bank stress/shear stress (Table 2).

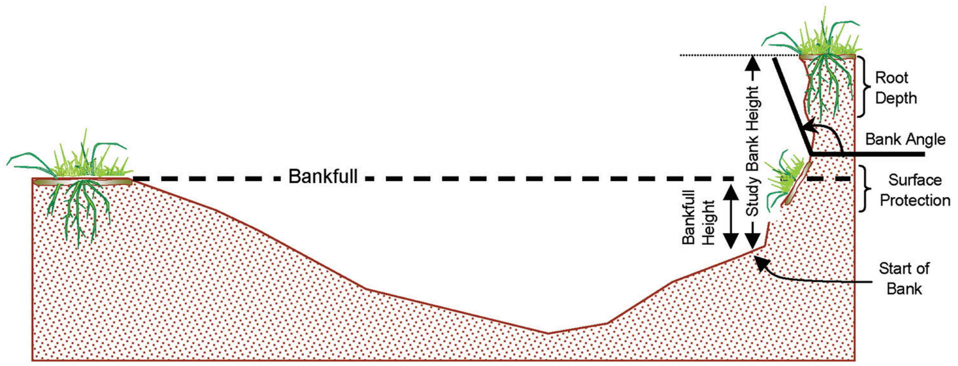

Figure 1. Channel Cross Section Showing Features Measured for BEHI (Rosgen 2001).

Table 2. NBS Variable and Rating Categories (Rosgen 2001)

Bank Erosion Risk Rating	Velocity Gradient	Near-Bank Stress/Shear Stress
Very Low	< 0.5	< 0.8
Low	0.5 – 1.0	0.8 – 1.05
Moderate	1.1 – 1.6	1.06 – 1.14
High	1.61 – 2.0	1.15 – 1.19
Very High	2.1 – 2.4	1.2 – 1.6
Extreme	> 2.4	> 1.60

Application of Bank and Sediment Measurements

Measures of sediment and bank stability can be applied to monitoring existing channel conditions, trends over time, and responses to disturbances or restoration efforts. Potential applications include:

- Assessment of habitat conditions for aquatic life uses,
- Setting priorities for protection and restoration, and
- Monitoring of restoration effectiveness.

Condition Assessment

Rapid monitoring methods provide screening-level data that can lead to more detailed assessments in targeted areas. Many states use rapid bioassessment protocols (RBPs) for assessing biological and habitat conditions in statewide ambient monitoring frameworks (Barbour et al. 1999). While those methods are qualitative, they also are rapid and can be applied in many sites with relatively low effort. By integrating the rapid habitat assessments with biological sampling locations, the bedded sediment and bank stability measures—embeddedness, sediment deposition, pool variability, bank stability, and bank vegetative cover—can be related to biological conditions to infer possible causes of impaired aquatic life uses.

Indicators of substrate instability have been used in statewide assessments (e.g., in Oregon and New Mexico) for the purpose of establishing regionally specific bedded sediment thresholds (Jessup 2009; Jessup et al. 2014). Following analytical methods proposed in the *Framework for Developing Suspended and Bedded Sediment (SABS) Water Quality Criteria* (USEPA 2006), least-disturbed reference conditions and stressor-response analyses were used to identify percent sand and fines and RBS index values that were protective of aquatic life uses.

In developing meaningful indicators of habitat integrity, Jessup (2011) compared habitat measurements and observations in upland, riparian, and instream landscapes along a disturbance gradient. The statewide analysis of Idaho streams concluded that bank stability was one habitat measure that was related to areas degraded by landscape disturbance and to biological conditions, indicating its utility for both assessment and effectiveness monitoring.

Setting Priorities

Information gained from monitoring bedded sediment conditions in either an ambient or targeted approach can inform management decisions to protect or restore habitats and biological assemblages such as algae, macrophytes, invertebrates, and fish. For example, if bedded sediment conditions show excessive fines or low RBS values, then the sources of the sediment requiring best management practices (BMPs) are likely to be upland disturbance, bank erosion, or both. Excessive channel armoring (lack of fines) would also indicate vulnerability of stream banks as the immediate source of sediment load required by high flows.

The BEHI and NBS risk ratings can be calibrated to actual erosion rates using quantitative bank erosion measures in a limited number of sites. The resulting calibration curves can be used with BEHI and NBS to predict bank erosion rates for new sites. Managers can use those predictions to identify key areas for implementing restoration efforts and management controls.

In a study of sediment thresholds in New Mexico (Jessup et al. 2014), percent sand, silt, and clay substrates was used as a preliminary indication of excess sediments, while the RBS was used to help interpret the assessments (Figure 2). In this figure, suggested benchmarks are solid lines and alternative benchmarks for screening are dashed. Sites in the upper-right quadrant have high percentages of sand and fines, but the relatively high RBS indicates that fewer fine sediments are present than are typically mobilized. This result could mean that the higher percentages of sand, silt, and clay are appropriate in certain streams because they are not expected to be unstable during typical storm flows.

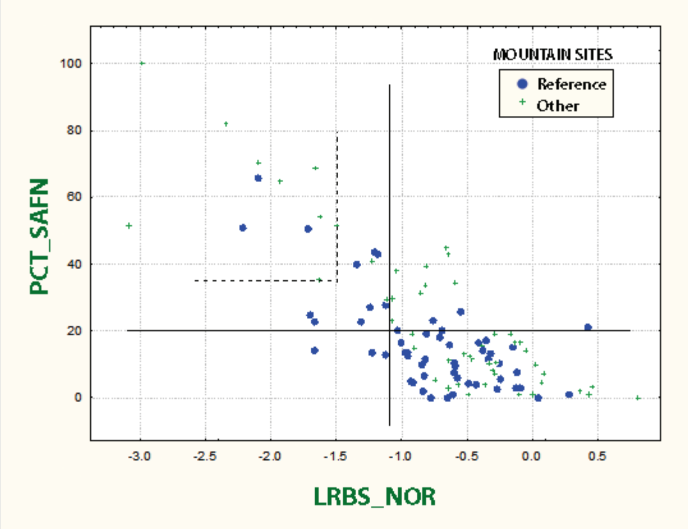

Figure 2. Sediment Benchmarks for Percent Sand, Silt, and Clay (PCT_SAFN) and RBS (log transformed and excluding bedrock, LRBS_NOR) for the Mountain Site Class in New Mexico (Jessup et al. 2014).

The Watershed Assessment of River Stability and Sediment Supply (WARSSS) is an example of an assessment framework to guide sediment management actions for streams (Rosgen 2006). WARSSS includes three phases in increasing levels of detail from reconnaissance to screening to prediction. WARSSS is based on modeled associations between sediment sources and channel conditions. Field observations are used for model calibration. A monitoring methodology related to the prediction process allows validation of the assessment approach and tracks the effectiveness of recommended mitigation to reduce existing excess sediment loading and improve channel stability.

Project Effectiveness

Pebble count data can be used to detect changes in sediment particle distributions over time, thus indicating habitat degradation or successful restoration. Variability can be estimated from repeated samples within sites (Stribling et al. 2008). Repeated samples over short time intervals can give an estimate of precision associated with sampling error. Repeated samples over longer time periods (e.g., seasons or years) can indicate temporal effects. A measured change greater than the detectable difference attributable to sampling error or random temporal change would indicate true improvement or degradation of sediment conditions.

Project monitoring in the Upper Grande Ronde Basin, Oregon, Section 319 National Nonpoint Source Monitoring Program project established linkages between stream restoration BMPs and stream and biological characteristics (Drake 1999). For example, correlation analysis of 50 variables indicated that channel and riparian characteristics and water quality variables indicative of disturbances are correlated to fish assemblage composition. While stream temperature was shown to be the essential limiting variable describing the variance in fish data for the Upper Grande Ronde Basin, percent sand and fines substrate also was shown to be a significant contributor to the statistical model used in canonical correspondence analysis.

The effects of rotational animal stocking on sediment composition were evaluated in Minnesota streams (Magner et al. 2008). The analyses indicated that particle size distributions measured from pebble counts shifted towards larger particles on sites where grazing was excluded or limited than on sites with continuous grazing in the riparian zone. The BMP appeared to be effective in reducing fine sediment in streams. In another study, pebble count statistics showed little or no change resulting after stream bank and channel restoration in an urban setting. A slight decrease was indicated in the percent sand, silt, and clay, but the authors assumed that the sediment BMPs were ineffective and that overwhelming flow factors should be addressed with additional BMPs (Selvakumar et al. 2009).

Summary

Substrate particle size distributions and bank stability can be measured using rapid qualitative methods for screening-level assessments and coarse evaluation of conditions in relation to potential stressors. More complex sediment measurements yield precise results that can be used to detect relatively small changes in channel conditions. Those measures generally are used in a monitoring context to detect conditions and changes over time in relation to disturbances or restorations. The bank stability measures and erodibility indices can be used not only to characterize current conditions, but also to predict potential future problems for proactive management.

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