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ScienceDirect
Geomorphology 99 (2008) 150–170
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

A roughness-corrected index of relative bed stability for regional stream surveys

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Received 21 April 2007; received in revised form 19 October 2007; accepted 22 October 2007
Available online 26 October 2007

Abstract

Quantitative regional assessments of streambed sedimentation and its likely causes are hampered because field investigations typically lack the requisite sample size, measurements, or precision for sound geomorphic and statistical interpretation. We adapted an index of relative bed stability (RBS) for data calculated from a national stream survey field protocol to enable general evaluation of bed stability and anthropogenic sedimentation in synoptic ecological surveys. RBS is the ratio of bed surface geometric mean particle diameter (D_{gm}) divided by estimated critical diameter (D_{cbf}) at bankfull flow, based on a modified Shield's criterion for incipient motion. Application of RBS to adequately depict bed stability in complex natural streams, however, has been limited because typical calculations of RBS do not explicitly account for reductions in bed shear stress that result from channel form roughness. We modified the index (RBS*) to incorporate the reduction in bed shear stress available for sediment transport that results from the hydraulic resistance of large wood and longitudinal irregularities in channel dimensions ("form roughness"). Based on dimensional analysis, we derived an adjustment to bankfull shear stress by multiplying the bankfull hydraulic radius (R_{bf}) by the one-third power of the ratio of particle-derived resistance to total hydraulic resistance $(C_p/C_t)^{1/3}$, where both resistances are empirically based calculations. We computed C_p using a Keulegan equation relating resistance to relative submergence of bed particles. We then derived an empirical equation to predict reach-scale hydraulic resistance C_t from thalweg mean depth, thalweg mean residual depth, and large wood volume based on field dye transit studies, in which total hydraulic resistance C_t was measured over a wide range of natural stream channel complexity, including manipulation of large wood volumes. We tested our estimates of C_t and RBS* by applying them to data from a summer low flow probability sample of 104 wadeable stream reaches in the Coastal Ecoregion of Oregon and Washington, USA. Stream discharges calculated using these C_t estimates compared favorably with velocity–area measurements of discharge during summer low flow, and with the range of 1 to 2-year recurrence floods (scaled by drainage area) at U.S.Geological Survey gauged sites in the same region. Log [RBS*] ranged from −4.2 to +0.98 in the survey region. D_{gm} ranged from silt to boulders, while estimated bankfull critical diameter, D^*_{cbf}, ranged from very fine gravel to large boulders. The median value of D^*_{cbf} (adjusted for form roughness influences) averaged 40% (inter quartile range 28 to 59%) of the unadjusted estimate D_{cbf}. Log[RBS*] was consistently negatively related to human disturbances likely to produce excess sediment inputs or hydrologic alteration. Log [RBS*] ranged from −1.9 to +0.5 in the streams within the lower quartile of human disturbance in their basin and riparian areas and was substantially lower (−4.2 to −1.1) in streams within the upper quartile of human disturbance. The synoptic survey methods and designs we used appear adequate to evaluate *regional* patterns in bed stability and sedimentation and their general relationship to human disturbances. Although the RBS concept also shows promise for evaluating sediment and bed stability in individual streams, our approach is relatively coarse, so site-specific assessments using these rapid field methods might prudently be confined to identifying severe cases of sedimentation or channel alteration. Greater confidence to discern subtle differences in site-specific assessments could be gained by calculating RBS* using more precise field measurements of channel slope, bed particle size and bankfull dimensions, and by refining our adjustments for energy loss from channel form roughness.
Published by Elsevier B.V.

Keywords: Rivers/streams; Sediment transport; Environmental indicators; Hydraulic resistance; Bedform roughness

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0169-555X/$ - see front matter. Published by Elsevier B.V.
doi:10.1016/j.geomorph.2007.10.007

1. Introduction

Routine state and regional habitat surveys commonly measure sediment size composition and other channel attributes to assess the extent and biological effects of anthropogenic sedimentation. However, their interpretations commonly fall short of discerning probable controls on stream bed particle size because they lack key measurements and a process-based analytical framework for interpreting sediment data. Detailed studies of watershed erosion and channel sediment transport can be undertaken to assess the sources and instream impacts of sediment inputs at the scale of individual stream reaches and small basins (e.g., Trimble, 1999). These rigorous studies continue to advance and verify sediment transport theory, but are typically too intensive and costly for application in regional or routine local assessments. Synoptic surveys used by management and regulatory agencies necessarily forsake intensive study at a few locations (reaches or watersheds) in favor of obtaining measurements from many locations across larger regions; they accomplish this by using streamlined protocols to describe channel morphology, bed particle size, and other features of stream physical habitat. A need exists for field and analytical approaches that allow synoptic habitat surveys to incorporate knowledge from more intensive research, so that these surveys can be used to test hypotheses concerning the effects of human activities on streambed particle size in a regional context.

Interpreting the extent of human influences on sediment in streams from regionally extensive surveys is difficult because, even in landscapes with uniform lithology and land use, bed particle size varies naturally in streams of different sizes and slopes. Therefore, it is essential to have some efficiently obtained measure of how much the bed surface particle size (e.g., D_{50} or percent fines) in a stream deviates from that expected based on natural controls in the absence of human activities. Among streams flowing within a region at the same slope, large, deep streams naturally tend to have coarser beds than small, shallow streams because the greater shear stresses of their deeper flows tend to quickly transport fine particles downstream (Lane, 1955; Leopold et al., 1964; Morisawa, 1968). The size composition of a streambed depends on the balance between the rates of supply of various sediment sizes to the stream and the rate at which the flow moves them downstream — i.e., the stream's sediment transport capacity relative to its sediment supply (Mackin, 1948; Schumm, 1971; Dietrich et al., 1989). The sediment supply rate and the type and size of particles delivered to a stream by upslope erosion and mass transport are influenced by basin characteristics, including lithology, topography, climate, vegetative cover, runoff characteristics, and land disturbances. On the other hand, the potential sediment transport competence and capacity of a stream are largely dependent on its slope, watershed area, and runoff regime, characteristics that determine the velocity and depth of water flow. Transport competence, the maximum size limit for particles that a stream can mobilize through bed shear stresses, can be lessened by bedforms, bank irregularities, large wood, and other channel features that increase hydraulic resistance and dissipate energy in turbulence (Buffington and Montgomery, 1999a). Transport capacity depends upon the amount of the bed surface exposed to competent shear stresses and the duration of competent flows.

By comparing the size range of streambed sediments with a stream's erosive competence (i.e., bed shear stress) during typical flood conditions, researchers have evaluated bed stability over a wide range of stream slopes, drainage areas, and bed particle sizes (e.g., Dingman, 1984; Dietrich et al., 1989; Gordon et al., 1992; Buffington, 1995; Montgomery et al., 1999). If the average size of particles making up a streambed surface is finer than the average size the stream is capable of moving, those sediments move frequently, rendering the bed relatively unstable. Such comparisons of observed bed particle size with critical diameter calculated from shear stress have been used to evaluate the effects of sediment supply (e.g., Buffington and Montgomery, 1999b; Montgomery et al., 1999), large-scale roughness elements such as large wood and bed forms (Buffington, 1995, 1998; Buffington and Montgomery, 1999a, 2001), or frequency of competent flows (e.g., Bledsoe et al., 2007). We calculate relative bed stability (RBS) here as the ratio of observed stream bed surface particle diameter divided by the critical, or mobile particle diameter (Dingman, 1984; Gordon et al., 1992). RBS is equivalent to the bed textural fining measure calculated by Buffington and Montgomery (1999a,b), and is also analogous to relative bed stability measures defined by Jowett (1989) as the ratio of critical bed particle entrainment velocity to actual near-bed velocity or by Olsen et al. (1997) as the ratio of critical shear stress to bankfull shear stress. In the sense that it is a comparison of bed particle size to the inferred maximum size that bankfull flows are competent to move, the RBS ratio is also conceptually similar to the bed stability ratio defined and discussed by Dietrich et al. (1989) as the median diameter of the stream bed armor layer divided by that of the substrate beneath that layer, which is taken to be the bedload. RBS is also analogous to the riffle stability index of Kappesser (2002), which estimates the mobile fraction of bed particles on a stream riffle by comparing the relative abundance of various particle sizes present on the riffle with the dominant large particles on an adjacent bar.

Although the potential reduction of sediment transport competence resulting from large scale bed form roughness and large wood is well known, detailed research approaches to quantify it are time-consuming, so have not been applied in broad regional surveys. We are not aware of any bed shear stress, critical diameter, or RBS formulations other than that of Kaufmann et al. (1999) that explicitly account for large-scale bedform roughness and large wood in a way that might be calculated from synoptic stream survey data. Their approach was developed to enable general evaluation of bed stability and anthropogenic sedimentation in regional ecological surveys. In this study, we modify the approach of Kaufmann et al. (1999) by using empirically derived relationships to compute an effective hydraulic radius (in effect partitioning shear stress), and by allowing the dimensionless critical shear stress (Shields parameter) in the critical diameter calculation to vary as a function of particle Reynolds number. The adjusted hydraulic