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The assessment of shear stress and bed stability in stream ecology

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Summary

1. Substratum stability and shear stress exerted by flowing water can have a strong influence on the structure of benthic communities. Bed stability can be characterised in a variety of ways, e.g. flow competence, threshold of particle entrainment, measures of erosion and deposition, particle transport distance, abrasion and bedload transport rate. This paper reviews methods for the quantification of bed stability and shear stress in streams and rivers that are relevant for the examination of the relationships between stream biota and bed stability.

2. The most suitable method for a research project depends mainly on the objectives. The targeted group of biota, spatial and temporal scale of investigation, as well as hydraulic conditions and substratum characteristics at the study site(s) determine the choice of a technique for the assessment of bed stability.

3. Indirect measurement of shear stress can be more accurate than calculations based on the DuBoys equation. However, the latter is preferred for reach-wide applications within the limits imposed by hydraulic conditions. The entrainment of the substratum is most effectively assessed using a combination of shear stress and competence equations, but the latter require careful parameterisation. At the patch-scale, direct measurement of entrainment force is a valid alternative.

4. Morphometric budgeting is the most comprehensive and least invasive technique for the assessment of rates of erosion and deposition. The transport of substratum particles is efficiently monitored with *in situ* marked or active tracer particles which allow for rapid and non-invasive identification and high recovery rate. As the assessment of bedload transport rate by formulae can be inaccurate, direct measurement is preferred. However, bedload traps interfere with the substratum and continuity of measurement with samplers is limited. Thus developments in the sector of acoustic and piezoelectric devices offer a potential alternative.

5. The abrasive forces by suspended sediments on stream biota are effectively evaluated with artificial blocks that are fixed on the stream bed. Descriptive surveys that assess bed stability offer an alternative to direct measurement and calculations. They are straightforward and non-invasive but can be observer-biased. If single methods do not provide useful links with biological data this may be improved by the application of a multivariate approach.

6. Many of the methods assessed have not yet been applied in research on benthic communities, but these hydraulic and geomorphologic techniques offer considerable potential for the assessment of bed stability in stream ecology.

Introduction

Floods are an important controlling force on lotic ecosystems (Death, 2008) and influence the composition of benthic communities (Resh *et al.*, 1988; Reice, Wissmar & Naiman, 1990; Lake, 2000). Most stream ecologists agree that discharges exceeding some threshold act as a disturbance to benthic communities, although determining those values can be problematic (Poff, 1992; Death & Winterbourn, 1994).

Under low water velocity and shear stress sediment is not entrained and the impact on benthic organisms is limited to shear force (drag and lift) exerted by flowing water. This alone may cause the patchy distribution of benthic organisms and can lead to downstream displacement of macrophytes (Biggs *et al.*, 2001), periphyton (Biggs, Smith & Duncan, 1999; Suren & Duncan, 1999) and invertebrates (Lancaster & Hildrew, 1993a; Bond & Downes, 2000; Bond & Downes, 2003). As velocity and shear stress increase, phase-I bedload transport occurs when fine sediments may be winnowed (washed out) and rolled over a mostly stable coarser bed. This can lead to an additional impact on stream biota by abrasion (Downes *et al.*, 1998; Bond & Downes, 2003). At a critical flow velocity, the movement of larger particles is initiated (phase-II bedload transport). This usually involves disruption of any armour layer (see Appendix A for definitions) at the bed surface and can result in patchy areas of scour and deposition (Powell, 1998; Matthaei, Peacock & Townsend, 1999b). In more extreme events, the whole bed may be mobilised, altering the habitat structure dramatically. This can lead to displacement of plants and invertebrates (Giberson & Caissie, 1998; Matthaei, Arbuckle & Townsend, 2000; Bond & Downes, 2003) and mortality of invertebrates crushed by rolling stones. Thus floods which induce bedload transport are often associated with the most dramatic changes in the composition, density and biomass of benthic invertebrate communities (Holomuzki & Biggs, 2000; Death, 2008) and periphyton (Biggs *et al.*, 1999).

To examine the relationship between benthic biota and bed stability it is essential to quantify the latter accurately (Gordon, McMahon & Finlayson, 1992). There have been numerous attempts to do so, but most of the methods developed for stream hydraulics and fluvial geomorphology have yet to be adopted by stream ecologists. Furthermore, recent technological advances (e.g. acoustic and electronic sensors, active tracer particles and topographic survey methods) offer considerable potential for improving the measurement of bed movement for the study of stability-biota relationships.

This review presents methods that are used to assess different aspects of bed stability at different spatial and temporal scales, including: 1) shear stress, 2) entrainment, 3) erosion and deposition, 4) bedload transport and 5) abrasion. The techniques are evaluated not only for their potential to predict shear force and sediment movement *per se*, but also for their ability to explain biota-substratum stability relations.

Characteristics of bed stability

Shear stress

When stream flow lacks sufficient energy to move bedload (non competent discharges), or where the bed is armoured or substratum particles are locked together (imbricated), the shear stress exerted on benthic biota by increased flows may be sufficient to alter the composition of benthic communities (Lancaster & Hildrew, 1993a; Bond & Downes, 2000; Bond & Downes, 2003). Shear forces exerted on organisms depend on their morphometry as well as kinematic viscosity and fluid velocity. Hence, the measurement of the latter can be used to determine shear stress. However, measurement of the velocity that affects small benthic organisms is difficult due to the steep velocity gradient in the boundary layer. Consequently indirect methods, like exposure to the flow of particles of known weight and/ or size, are employed to estimate the shear stress exerted at the channel bottom.

DuBoys equation

In stream ecology it is common to use the DuBoys equation (1) to gain an estimate of the mean boundary shear stress τ_o at the reach level (e.g. Statzner, Gore & Resh, 1988; Matthaei *et al.*, 1996; Duncan, Suren & Brown, 1999; Matthaei *et al.*, 1999b).

$$\tau_o = \rho_f \, g \, R \, S_f \qquad (1)$$

The friction slope S_f (see Appendix B for symbol annotation) differs from the bed slope S_b and the water surface slope S_w, because flow resistance is responsible for energy losses (Robert, 1990). S_f can be calculated using a backwater calculation if flow data and channel geometry are available. However, the observed differences between S_f and S_w are often slight, especially under conditions of high discharge (Powell & Ashworth, 1995; Milan *et al.*, 2001). Thus, the more easily measured S_w is an acceptable first-order approximation for S_f (Baker & Ritter, 1975; Lorang & Hauer, 2003). When the width-depth ratio of the channel is high (>16.9 according to Giberson & Caissie, 1998), which is common in coarse bedload transporting streams, mean flow depth h may be substituted for the hydraulic radius R (Baker

& Ritter, 1975; Powell & Ashworth, 1995; Downes, Glaister & Lake, 1997; Giberson & Caissie, 1998). The use of local bed slope and depth instead of R and S_f in (1) might be preferable for the estimation of stream stability at the patch-scale, although actual shear stress is underestimated (Lorang & Hauer, 2003). Furthermore, it should be remembered that fluid density ρ_f is usually higher than the 1000 $kg*m^{-3}$ typically used because of suspended material, particularly during floods (Giberson & Caissie, 1998).

The DuBoys equation is strictly applicable only under uniform flow conditions (implying even bed topography and regular channel geometry) in wide channels ($W/h > 20$) (Gordon *et al.*, 1992; Gore, 1996). Three-dimensional flow effects (Milan *et al.*, 2001), bedform structures (e.g. pebble clusters and imbrication) (Carson & Griffiths, 1987) and the exposure to the thalweg (main thread of maximum velocity flow) are not accounted for. The values derived are high compared with local shear stress calculated from velocity profiles (Robert, 1990), but tend to underestimate the effective shear force (Carson & Griffiths, 1987).

The theoretical assessment of mean boundary shear stress is mostly based on the DuBoys equation. The choice of the parameters determines scale and accuracy of the calculation (Table 1). As the flow in natural rivers (especially shallow high gradient boulder- and gravel-bed rivers) is usually not uniform, the explanatory power of equations assuming the latter is limited (Campbell & Sidle, 1985). This may be enhanced by the inclusion of parameters like flow resistance, channel geometry and the energy slope (Lorang & Hauer, 2003). Thus shear stress estimations based on the DuBoys formula apply best under conditions of increased relative depth ($R/D_{84} > 4$ (Hey, 1979)), e.g. during high discharges, when flow is approximately uniform (Bhowmik, 1982; Milan *et al.*, 2001). However, mean boundary shear stress from the DuBoys equation has been linked with the distribution of benthic invertebrates in several studies under various discharges (Statzner *et al.*, 1988; Matthaei *et al.*, 1996). The equation provides a useful tool for reach-wide investigations of shear stress biota relationships.

FST-hemispheres

Calibrated **F**liesswasser**St**ammtisch (FST) hemispheres of different densities offer a measure of actual near-bed shear stress at a particular point in time (Statzner & Muller, 1989; Statzner, Kohmann & Hildrew, 1991). Despite some debate about the usefulness of FST-hemispheres for assessment of near-bed shear stress (Frutiger & Schib, 1993; Statzner, 1993; Dittrich & Schmedtje, 1995) they performed consistently well as indicators of ecologically relevant near-bed shear forces in hydraulically rough stream beds (Lancaster & Hildrew, 1993b;

Scarsbrook & Townsend, 1993; Dittrich & Schmedtje, 1995; Hardison & Layzer, 2001; Merigoux & Doledec, 2004). However, Frutiger & Schib (1993) reported that only 50% of their benthic invertebrate taxa showed a relation between abundance and FST data. Statistical models based on FST measurements allow long-term characterisation of shear stress variability (Lamouroux *et al.*, 1992) that can be linked with variation in the density of invertebrate taxa in different hydraulic microhabitats (Doledec *et al.*, 2007). FST-hemispheres are a useful tool for investigating the spatial distribution of stream biota at base flow (Table 1). However, at higher discharges application is limited due to interference from bedload (impacts from saltating particles) and safety reasons (but see Gore *et al.*, 1994).

Near-bed flow velocity

Local shear stress can be estimated from measurements of flow velocity (e.g. single near-bed, vertical profile). Often a semi-logarithmic relationship between depth and velocity is assumed which is violated in reaches with high relative roughness (e.g. $h/D_{84} < 3$ (Bray, 1980)). Wiberg & Smith (1991) found that local shear stress calculated from depth averaged velocity derived from a profile was accurate for $h/D_{84} > 1$. In comparison, single point near-bed measurement allows a calculation of shear stress for the widest range of conditions, but is not as accurate as the depth averaged method. Estimations of boundary shear stress based on the relation of v and ln(1-h) in velocity profiles (e.g. Bhowmik, 1982) are the least accurate and apply in the most restricted flow conditions but require no estimate of bed roughness (Wilcock, 1996).

Effenberger *et al.* (2006) found a strong relationship between point measurements of near-bed flow velocity and the spatial distribution of invertebrates. Death & Winterbourn (1994) also found a strong positive correlation between the variability of near-bed flow velocity and the movement of marked stones.

Locally, indirect measurement of shear stress can provide more accurate results than the DuBoys approach. It may also give an indication of the impact of shear stress on stream biota (Table 1) although the small spatial and temporal extent of the measurements limits the use for larger reaches and/or long-term studies.

Substratum entrainment

Relationship between substratum grain size and tractive force

The proximal equality between mean boundary shear stress, calculated by the DuBoys equation, and the maximum diameter of entrained particles (rounded, non-cohesive, > 0.05 m) (Lane, 1955) has been widely exploited to define critical particle size for entrainment (Newbury, 1984; Death & Winterbourn, 1994; Muotka & Virtanen, 1995; Giberson & Caissie, 1998). Even for non-rounded particles comparable relationships have been developed (Newbury, 1984). Although this relationship can provide a good indication of habitat stability amongst sites within a stream (Giberson & Caissie, 1998), it can overestimate particle movement in steep or narrow rivers ($W/h < 16.5$) as well as underestimate it in wide and shallow channels ($W/h > 36.9$) (Hallisey & Belt, 1996). This approach is subject to the same constraints as the DuBoys equation and does not account for potential equal mobility due to hiding and protrusion of particles. Thus the applicability of this concept is constrained to rivers with a high relative depth ($h \gg D_{50}$) (approx. 6-7 (Newbury, 1984), >10 (Duncan *et al.*, 1999)) and bed slopes less than 0.01, conditions which are more likely to be met in lowland rivers.

Not surprisingly, therefore, several authors found no significant relationship with other measures of bed stability when they applied this approach in steep and shallow streams (Death & Winterbourn, 1994; Duncan *et al.*, 1999). In contrast Cobb, Galloway & Flannagan (1992), Scarsbrook & Townsend (1993) and Muotka & Virtanen (1995) found a link between critical tractive force and the distribution of invertebrates and bryophytes. However, the relationship between tractive force and critical particle diameter cannot predict entrainment of the substratum consistently and applies in a limited range of rivers with gentle slope and high relative depth.

Shields equation

The Shields equation (2) (Shields, 1936) relates boundary shear stress to particle entrainment. It estimates the critical shear stress for a substratum grain size D_i at the point of incipient motion.

$$\tau_{crit} = \theta_{crit} (\gamma_s - \gamma_f) D_i \qquad (2)$$

The Shields coefficient θ_{crit} is a non-dimensional variable dependent on particle shape, substratum particle size distribution, exposure and other packing factors (Lorang & Hauer, 2003). It reaches a constant value for non-cohesive materials larger than 6 mm (Lorang & Hauer, 2003) for hydraulically rough beds (boundary $Re > 100$). θ_{crit} varies coarsely between 0.02 and 0.08, but more extreme values have been reported (Ashworth & Ferguson, 1989; Buffington & Montgomery, 1997; Shvidchenko, Pender & Hoey, 2001). Increasing channel slope (related to relative flow depth (h/D_{50})), decreasing relative size (D_i/D_{50}) and substratum heterogeneity (size distribution) increases the Shields coefficient systematically (Bathurst, Graf & Cao, 1987; Buffington & Montgomery, 1997; Shvidchenko *et al.*, 2001). Furthermore, the definition of incipient motion (e.g. reference- or visual observation-based), grain shape, orientation, hiding effects (e.g. sheltering of smaller particles by larger), as well as discharge and bank vegetation influence θ_{crit} (Andrews, 1984). Values for θ_{crit} derived from visual-based studies (typically around 0.045) are recommended for analyses of incipient motion in discrete bed surface patches. In contrast, the usually higher reference-based θ_{crit} may give a better estimate of entrainment on a reach-average level because of its derivation from bedload transport measures and thus the integration of differential bed patch mobility (Buffington & Montgomery, 1997). Compared with the original Shields coefficient of 0.06, in gravel bed streams with a heterogeneous substratum, a lower θ_{crit} is expected, for instance down to 0.02 in high gradient rivers ($S_w > 0.002$), where $D_{Max}/D_{50} > 22$ (Lorang & Hauer, 2003) and the effects of form roughness and form drag resistance are considerable. A value of 0.045 for θ_{crit} has been used in many studies and is widely accepted for beds with coarse particles and high boundary Reynolds numbers (Miller, McCave & Komar, 1977; Yalin & Karahan, 1979; Komar, 1989; Duncan *et al.*, 1999).

There have been several attempts to improve the Shields equation and to widen its range of use (e.g. Komar, 1987; Thompson & Croke, 2008). Formulae such as Equation (3) incorporate the effects of hiding and heterogeneous beds in the Shields equation (Komar, 1989):

$$\tau_{crit} = 0.0045\ (\gamma_s - \gamma_f)\ D_{50}^{0.65}\ D_i^{0.35} \qquad (3).$$

Duncan *et al.* (1999) also applied corrections to allow for small relative depths (h/D < 2.5) and high water surface slopes. Thompson & Croke (2008) incorporated the effects of bed form, microtopography and bed packing into the Shields equation. Lorang & Hauer (2003) found that critical shear stress calculated with a modified Shields equation overestimated the actual value for large cobble- and boulder-bed rivers by as much as an order of magnitude.

Andrews (1983) (cf. Parker, Klingeman & McLean, 1982) proposed the following relationship to calculate θ_{crit} for $0.3 < D_{isurface}/D_{50subsurface} < 4.2$:

$$\theta_{crit} = 0.0834\ (D_{isurface}/D_{50subsurface})^{-0.872} \qquad (4).$$

This highlights the fact that critical shear stress is influenced more by relative grain size than absolute grain size (Ferguson, 1994; Shvidchenko *et al.*, 2001). With the typical ratio of $D_{50surface}/D_{50subsurface} = 2.5$ for gravel bed rivers (Parker *et al.*, 1982) θ_{crit} can be estimated. However, in other studies the value for the first factor in (4) lies between 0.019 and 0.087, whilst the exponent ranges from -0.32 to -1.25 (Buffington & Montgomery, 1997) and the values differ between riffles and pools (Sear, 1996).

A comparison between mean boundary shear stress (1) and critical shear stress for a particular grain size has been used to indicate zones of entrainment (Milan *et al.*, 2001), calculate the critical size of substratum particles moved (Duncan *et al.*, 1999) and define critical depth (Fuller *et al.*, 2002). Predictions of entrainment were well correlated with measurements of morphological change in most areas of a gravel bed stream (Milan *et al.*, 2001) and entrainment of *in situ* tagged particles (Biggs *et al.*, 2001). Bed stability measurements derived from a combination of (1) and (3) showed a strong relationship with the composition of bryophyte communities (Duncan *et al.*, 1999) and periphyton biomass (Biggs *et al.*, 2001) (Table 2).

Given the difficulties of selecting the most suitable parameters for empirical equations or the Shields coefficient, the calculation of the critical shear stress for entrainment is not straightforward, especially when a wide range of streams is being examined. However, for reach-scale investigations of the relationship between biota and bed stability a combination of the DuBoys formula and an advanced Shields equation (e.g. Duncan *et al.* 1999) may be useful.

Empirical equations of critical shear stress

Several studies have produced empirical entrainment equations of the type $\tau_{crit} = a D^b$ (Thompson & Croke, 2008), where a and b range from 26.6 to 110 and 0.38 to 1.21 respectively. The large range in parameter values is due to the difference in substratum assemblage between sites and differing methods used to define parameters (Lorang & Hauer, 2003). These empirical entrainment equations are thus too stream-specific to allow a general application of this approach.

Spring balance

Downes *et al.* (1997) used spring balances to measure the force necessary to initiate motion of particles in streams. This cannot be related directly to the critical shear stress but high forces will generally equate with high shear stresses as long as selective entrainment occurs (Downes *et al.*, 1997). This is a labour intensive methodology for reach-scale studies and the choice of particles can be subjective, but it will reflect actual shear stress to entrain particles better than indirect measurements.

Erosion and deposition

Scour chains and other buried devices

In both ecology and hydrology the deployment of metal scour chains is a common method for measuring scour and deposition of bed materials (Laronne & Duncan, 1992; Laronne *et al.*, 1992; Palmer, Bely & Berg, 1992; Matthaei *et al.*, 1999b; Matthaei, Guggelberger & Huber, 2003; Effenberger *et al.*, 2006). It allows quantification of the height of fill and the depth of scour with an accuracy ranging from $<D_{25}$ to D_{84} (Laronne *et al.*, 1994; Matthaei *et al.*, 2003) on a patch-scale systematic grid. Installation is relatively rapid (33 chains per person per day (Matthaei *et al.*, 1999b)) and causes little damage to sediment structure. Effenberger *et al.* (2006) observed no long-term effects on the invertebrate community. The chains proved to be resistant to dislocation and can be relocated after floods with the help of coloured ropes or magnetic tracers. However, the assessment of temporal variation of scour and fill during bed moving events is limited and relocation is required after each event that is likely to result in substratum movement (Laronne *et al.*, 1994). As (phase-I) bedload transport occurs in patches in gravel bed rivers the suggested resolution of measurement is higher than one observation per square metre (Matthaei *et al.*, 1999b; Laronne, Garcia & Reid, 2001).

Scour chains were employed for the identification of stable bed patches which can serve as local refugia for benthic organisms during floods (Matthaei *et al.*, 1999b). Measures of scour and fill using scour chains have been related to density and vertical distribution of invertebrates (Palmer *et al.*, 1992; Effenberger *et al.*, 2006) as well as to the spatial distribution of benthic algae (Matthaei *et al.*, 2003) (Table 3).

Alternatively, metal scour plates, buried at fixed depths can serve as measurement of scour depth and in sandy streams columns of dyed sand inserted in the top layer of the bed can replace scour chains (Palmer *et al.*, 1992). Wilcock (1997) measured the depth of entrainment with buried painted gravels. But both installation and retrieval require a disturbance of the substratum. Hence these methods are not appropriate for studies targeting benthic biota or for armoured and imbricated streambeds. Pressure pillows inserted into the surface of an artificial stream bed were used by Kurashige (2002) to measure sedimentation rates continuously but the construction was susceptible to damage during high bedload discharges.

Morphometric sediment budget models

Movement of the substratum is reflected in changes of the morphology of the channel (Leopold, 1992). These changes can be assessed with repeated airborne surveys using digital photogrammetry or laser altimetry (e.g. Lane, 2001; Westaway, Lane & Hicks, 2001) or ground surveys employing tacheometry or photogrammetry (e.g. Ferguson & Ashworth, 1992; Lane, Chandler & Richards, 1994; Fuller *et al.*, 2002; Heritage & Milan, 2004).

Ground surveys have been conducted with a theodolite-EDM system (Chappell *et al.*, 2003; Fuller, Large & Milan, 2003b; Fuller *et al.*, 2005) but more recently also with Real Time Kinematic differential-GPS (RTK-dGPS) (Brasington, Rumsby & McVey, 2000; Fuller & Hutchinson, 2007). The difference in altitude of cross-sections or digital elevation models (DEM) between surveys is used to determine areas of quantified deposition or erosion (Brasington *et al.*, 2000; Brewer & Passmore, 2002). The calculation with DEMs is preferable because sediment budgets derived from planform and cross-section measurement underestimate the magnitude of volumetric change compared with DEM subtraction, nor do they permit identification of the spatial pattern of volumetric change (Fuller *et al.*, 2003a). Altitude measurements with RTK-dGPS or a theodolite-EDM system are, within the limits imposed by surface roughness (e.g. D_{50}) highly accurate and more than 2000 points with high spatial resolution can be obtained per day (Brasington *et al.*, 2000). The use of a GPS system is, however, limited at closed canopy sites and in deep valleys where satellite reception is critical.

Brasington, Langham & Rumsby (2003) indicate that ground surveys are much more precise than remote survey methods (especially at submerged zones; cf. Westaway, Lane & Hicks, 2000) and thus preferable for morphometric budgeting. However, for very wide river beds or reaches of more than a few hundred metres in length, the use of photogrammetry should be considered (Lane, Westaway & Hicks, 2003).

Morphometric budgeting has the advantage over scour chains to be less invasive and the ability to monitor an entire reach. However, scour chains may integrate effects of scour-fill compensation during single events. Both techniques give a lower bound estimate of the sediment flux because they do not account for substratum that is transported completely through the reach (Fuller *et al.*, 2003a). According to Martin & Church (1995) the morphometric approach provides information of a quality comparable or superior to that of direct measurements of transport, yet requires less field effort. Its application is restricted to gravel- and cobble-bed rivers. To the best of our knowledge these measures have not been used in connection with biological data.

Bed load transport

Bedload is the sediment component that moves downstream by rolling or saltation. In rivers and streams where hydraulic conditions are generally unsteady (Lisle *et al.*, 2000) and spatial substratum grain size variability is high (Dollar, 2002), transport rate is highly variable in space and time (Gomez, 1991; Batalla, 1997; Ferguson, 2003; Vericat & Batalla, 2007). Bedload discharge also depends on the supply of sediments within the catchment and lateral and longitudinal connectivity of the river (Dietrich *et al.*, 1989; Hooke, 2003; Fryirs *et al.*, 2007). The transport of substratum can be expressed as volumetric change in sediment budgets, transport rate at a point, cross-sectional discharge or distance travelled by individual particles. Techniques for measuring bedload transport are ideally non-intrusive, flexible and representative for different types of transport (Ergenzinger & de Jong, 2003). To date most stream ecologists have only been interested in qualitative measures of bed stability. At the single particle-scale, qualitative assessment might be sufficient, but for whole reaches bedload transport occurs on a continuous graduation. For stream ecologists, quantitative measures of bedload transport can act as a superior indicator for the level of bed stability, particularly if only partial mobilisation of the bed occurs.

Tracer particles

Tracers are well suited for the stochastic and spatially variable nature of bedload transport because they reflect the movement of individual particles of known characteristics (Wilcock, 1997). Marked or tagged natural particles and artificial tracers are used to assess step length of movement (e.g. Habersack, 2001), proportion of the bed surface entrained (e.g. Laronne & Duncan, 1992), transport behaviour (e.g. Gottesfeld & Tunnicliffe, 2003) and transport rate (e.g. Ergenzinger & Conrady, 1982), or as an indicator of bed stability (e.g. Death & Winterbourn, 1994). Further they could facilitate the measurement of recolonisation periods of individual particles.

Stones coated with ordinary paint or fluorescent dye placed on the riverbed are often employed by ecologists and hydrologists (Death & Winterbourn, 1994; Townsend, Scarsbrook & Doledec, 1997; Ferguson & Wathen, 1998; Death, 2002; Ergenzinger & de Jong, 2003; Death & Zimmermann, 2005), but they have the disadvantage of a low recovery rate due to burial (Table 4). To overcome this, metal bars (Laronne *et al.*, 1992; Schmidt & Ergenzinger, 1992) or magnets (Hassan, Church & Schick, 1991; Laronne & Duncan, 1992; Bunte, 1996; Ferguson & Wathen, 1998) can be inserted into the particles and they are detected using a metal detector or a magnetometer respectively. Magnetic tracers usually have a larger detection range (McEwan, Habersack & Heald, 2001) than metal tracers. An easier but less durable alternative to the insertion of metal is the wrapping of stones with aluminium foil (Sear *et al.*, 2003). The transport rate and transport behaviour of particles marked with magnets or stones containing magnetic minerals can be monitored with a bar equipped with electromagnetic coils across the stream (Ergenzinger, 1985; Carling *et al.*, 1998; Froehlich, 2003) or with a longitudinal line of "Bed Movement Detectors" (Gottesfeld & Tunnicliffe, 2003). The overpassing of a magnetic particle induces an electric signal which is stored with high temporal resolution. The calculation of bedload discharge is possible using dispersion models (Sear *et al.*, 2000b).

Marking of tracer particles has been further advanced via insertion of radio transmitters into a particle. A signal is transmitted either continuously, at a programmed interval or when the particle is turned 180° (Ergenzinger, Schmidt & Busskamp, 1989; Schmidt & Ergenzinger, 1992; Busskamp & Hasholt, 1996; Habersack, 2001). The tagged stones can be tracked from the banks with a set of antennae but application is restricted to shallow water and low conductivity (Ergenzinger & de Jong, 2003). Battery capacity (size) is a trade-off between life span and lower size boundary of particles (Habersack, 2003). These tags enable the monitoring of step length and transport behaviour as well as initiation of motion.

Radioactive tracers (e.g. ^{137}Cs) are an alternative to tags because they do not change density or centre of gravity (e.g. Bartnik, Madeyski & Michalik, 1992). However, they are no longer widely applied due to environmental issues (Ergenzinger & de Jong, 2003). The employment of tracers of differing lithology from the natural substratum (Mosley, 1978; Kondolf & Matthews, 1986) provides an effective and easy measure for event-based distribution of transport length, although recovery rate is low.

For the *in situ* marking of substratum particles Downes *et al.* (1998) and Matthaei, Peacock & Townsend (1999a) used chisels and drills with long drill bit extensions, but relocation is difficult and embeddedness may be disturbed during the marking process. Thus this method is more suitable for the qualitative measurement of entrainment. Barquin & Death (2006) used dyed quick curing concrete mix to mark embedded stones.

Artificial stones provide an alternative to natural particles and also give the opportunity to examine the influence of shape on transport length (Schmidt & Ergenzinger, 1992). The use of cast aluminium forms avoids the insertion of metal bars in pebbles (Sear *et al.*, 2003). The collection of complex information about particle transport is also possible with artificial boulders like the DUMPLING (Ergenzinger & de Jong, 2003), although its size and weight restricts its application to bouldery streams.

The measurement of bedload transport with tracers provides comparable results to direct measures but requires less effort and avoids large-scale intervention in the stream bed. For low transport rates, tracers are likely to be more accurate (Wilcock, 1997). However, the dominating influence of bed structure and channel morphology on the distribution of tracer stones and the weak relationship with stream power (Kondolf & Matthews, 1986; Hassan, Church & Ashworth, 1992) suggests that short-term studies with tracers are not sufficient to compute rates of bedload transport. In contrast, shorter-term studies are more suitable for investigating the movement of surface particles because the transport rate of tracer particles decreases due to vertical mixing (burial) and storage in less active zones of the system (e.g. floodplain, bars) (Ferguson *et al.*, 2002). If particles have to be removed from the stream for marking, bed structures and imbrication are destroyed and tracer particles placed on the bed surface may not represent the size characteristics of the substratum (Downes *et al.*, 1998; Biggs *et al.*, 1999). Longer-term studies can account for this, but they do not provide information about the frequency and magnitude of single disturbance events. The subjective choice and the shape of particles, as well as their number, may bias the results of tracer experiments (Schmidt & Gintz, 1995; Duncan *et al.*, 1999; Warburton & Demir, 2000; Ferguson & Hoey, 2002).

Nevertheless, a stability index derived from tracer experiments showed a strong negative relationship with invertebrate diversity and periphyton biomass (Death & Winterbourn, 1995; Death, 2002; Death & Zimmermann, 2005) (Table 4). *In situ* marked stones were also used to identify stable stones that can serve as refugia during floods (Matthaei *et al.*, 2000). They relate the shear forces to the local substratum and consequently give a better estimate of bed stability than unembedded tracers (Downes *et al.*, 1998; Matthaei *et al.*, 1999a). In combination with a non-invasive detection technique, *in situ* marked particles may be highly appropriate for ecological studies. Along with the objectives of a study, selection of an optimal tracer technique should consider representation of the substratum, tracer recoverability, longevity, durability, possibility of explicit identification of particles as well as labour and cost efficiency (Sear *et al.*, 2000b).

Bedload transport sampler and traps

The rate of bedload transport can be assessed with samplers and traps at various scales (Table 5). The most common handheld bedload transport samplers are of the pressure-difference type (Helley-Smith-, VUV- and Arnhem sampler) with orifices up to 0.05 m^2 (Leopold, 1992; Hoey, Cudden & Shvidchenko, 2001; Hardardottir & Snorrason, 2003). Their sampling efficiency usually varies between 30% and 70%, but can be up to 100% (Helley-Smith sampler) (Gomez, 1991). A common constraint of these samplers is that the opening area needs calibration for hydraulic and substratum conditions (Gomez, 1991) but, much more critically, the sampling scheme should be sufficient to account for the cross-sectional substratum variability of the reach and the temporal variability in bedload transport (Ergenzinger & de Jong, 2003). This requires adjustment of the sampling period and may result in large sampling efforts in wide rivers. Therefore, predictions of bedload transport based on sampler measurements are often not very accurate (uncertainty of ±50%) (Wilcock, 2001). In conditions encountered in mountain streams (e.g. local high flow velocities and high surface roughness) bedload transport samplers are less applicable (Mizuyama, Fujita & Nonaka, 2003). Here portable net traps fixed to platforms on the stream bed may be used, delivering similar results to pit traps (Wilcock, 2001; Bunte & Abt, 2003; Bunte *et al.*, 2004). Bedload samplers are not frequently employed by stream ecologists perhaps because of the mentioned constraints and inaccuracy. However, for small-scale, event-based studies they constitute a potentially valid option for direct measurement of bedload transport rate.

Slot traps of various dimensions, inserted into the river bed, are used in many parts of the world (Salehi, Lagace & Pesant, 1997; Martin-Vide *et al.*, 1999; Hassan & Church, 2001; Sear *et al.*, 2003; Bond, 2004). They range from small sized pit traps, without continuous measurement, to Birkbeck samplers and large, stream-wide constructions for continuous monitoring. The latter is achieved with the employment of a weighing device (pressure cushion, load cell) below the sampling box or outside the channel (vortex tube, pump, conveyor belt) (Gomez, 1991; Sear *et al.*, 2000a; Ergenzinger & de Jong, 2003; Sear, 2003). Load cell systems are more reliable than pressure cushion devices because they are less susceptible to damage (e.g. puncture of pressure pillows) (Lewis, 1991). Smaller pit traps may fill rapidly during large events but are generally more accurate than handheld bedload transport samplers (Wilcock, 2001). Sampling efficiency for pit traps is up to 100%, decreasing with increasing fill (Laronne *et al.*, 2003). In particular at base flow, bedload transport traps may also sample suspended sediments (Batalla, 1997). The installation and maintenance of a bedload trap is expensive and involves a serious disturbance of the stream bed and biota. For this reason, bedload traps have not been used for investigations of benthic biota but for long-term projects they offer a useful tool for the assessment of ecologically relevant bedload discharge. As an alternative, monitoring of sediment volume accumulated in natural traps (basins), reservoirs or retention and diversion devices provides an opportunity to assess bedload transport rate, but calibration to exclude suspended sediments is difficult (Gomez, 1991).

Acoustic sensors

Acoustic sensors can be used to assess bedload transport intensity and the onset and cessation of movement (Ergenzinger & de Jong, 2003). In addition, estimates of transport rate using acoustic energy and estimates of transported particle size using the emitted frequency can be obtained (Bogen & Moen, 2003; Downing *et al.*, 2003; Froehlich, 2003; Mizuyama *et al.*, 2003). Hydrophones must be calibrated against actual bedload samples at each site. The sensor consists of a plate fixed horizontally on the bed (Bogen & Moen, 2003), a vertical pressure plate (Downing *et al.*, 2003) or horizontal steel pipes across the stream bed (Froehlich, 2003; Mizuyama *et al.*, 2003). Calibration limits the application at numerous sites, but the accuracy can be similar to a bedload trap. Acoustic Doppler Current Profiling (ADCP) allows the combined measurement of multi dimensional flow and velocity of bedload and suspended load (Rennie & Millar, 2004). Limitations of this technique include problems with the differentiation between near-bed suspension, bedload and fine grained bottom sediments as well as varying sensitivity to different particle sizes (Kostaschuk *et al.*, 2005).

Other sensors

Richardson, Benson & Carling (2003) presented an electronic sensor that allows detection of the momentum of impacting particles in bedrock channels. It gives a relative measure of bedload transport but needs to be calibrated. The latter can create some difficulties because the sensor measures a combination of grain mass and speed.

The piezoelectric bedload impact sensor employed by Rickenmann & McArdell (2007) can measure impacts of transported grains larger than 10 – 30 mm. These sensors are placed in an array over the whole stream width in a concrete bar. The measure is a reliable and continuous indicator of total bedload transport, but it needs to be calibrated and has limited accuracy for single events or small bedload volumes. Further it gives no information about the grain size distribution of the overpassing sediments (Rickenmann & McArdell, 2007).

Bedload transport formulae

Bedload transport formulae (e.g. Schoklitsch-type equation (5)) are generally based on four principal approaches: shear stress, stream discharge, stream power and a stochastic function for sediment transport (Gomez & Church, 1989).

$$q_b = X' S_f (q - q_{cr}) \qquad (5)$$

In this example, bedload discharge q_b depends on excess water discharge and a sediment coefficient X'. Most bedload transport formulae originate from physical principles but their precision has been improved by the use of empirical datasets from flumes and streams. The formulae are consistent in that they employ in most instances the same hydraulic parameters (energy gradient, flow velocity, depth and discharge) which are in part intercorrelated (Gomez & Church, 1989; Martin & Church, 2000). Most formulae are well suited and parameterised for the dataset of their development, but fail when applied to other conditions (Knighton, 2008). They are based on limited basic assumptions which vary between streams and even within streams (e.g. selective entrainment). Characteristics like armouring, exposure to flow, equal mobility, variable sediment supply and pulsing cannot be fully accounted for, although some approaches try to incorporate these points (Parker, 1990; Duan & Scott, 2007; Thompson & Croke, 2008). Furthermore, the spatial variability within a stream is ignored because of the one-dimensional nature of the formulae (Hoey *et al.*, 2001; Ferguson, 2003; Martin & Ham, 2005). The result of comparative studies with bedload samplers/ traps (Gomez & Church, 1989; Batalla, 1997; Martin-Vide *et al.*, 1999; Habersack & Laronne, 2002; Barry, 2004) and morphologic budgeting (Martin & Ham, 2005) show clearly that bedload transport formulae perform inconsistently (but see Bartnik *et al.*, 1992). Thus, bedload transport formulae need to be carefully selected according to the conditions for which they were developed, for instance turbulent and shallow mountain streams require other types of models than gravel-bed rivers (Biggs *et al.*, 2001; Mizuyama *et al.*, 2003; Ancey *et al.*, 2008). Additionally, empirical parameters and the entrainment threshold have to be determined to suit a new dataset, which is a difficult task (Wilcock, 2001; Habersack & Laronne, 2002). Thus the application of direct measurements of bedload transport is preferable to the use of bedload transport formulae (Gomez, 1991; Laronne *et al.*, 1992).

Abrasion by suspended sediments

Abrasion is an often neglected form of disturbance which can affect benthic flora and fauna. At normal flows the stream biota may be subjected to constant *in situ* abrasion by small suspended particles, which may represent a significant disturbance at higher discharges (Biggs, 1996; Peterson, 1996). It is unclear if sandblasting affects invertebrates (Rosenberg & Wiens, 1978; Culp, Wrona & Davies, 1986; Bond & Downes, 2003) but the effect on benthic algae is clearly recognised (Biggs *et al.*, 1999; Webb *et al.*, 2006).

The exposure of natural or artificial tracers to abrasion is an obvious opportunity for quantification (Table 6). The use of natural rocks that are cut in cubes or artificial blocks improves the visual monitoring of abrasion because the loss of edges and corners is simply detected. Furthermore, impact marks on the cube faces are subject to easy distinction and aide the interpretation of bedload moving events (Brewer, Leeks & Lewin, 1992). Blocks that are of the same lithology as the river sediments have the advantage that they provide a better estimation of the actual abrasion in the channel. However, for the quantification of the impact on biota a measure of relative abrasion is sufficient. Thus ecologists prefer to use artificial tracers, like autoclaved lightweight aerated concrete blocks (Webb *et al.*, 2006). The latter have standardised material properties and abrade consistently proportional to the physical work performed on their surface. Moreover the abrasion rate is high enough to allow short deployment times (e.g. 2 months) which minimises mass loss by dissolution. Abrasion blocks need to be protected from the impact of bedload transport to gain a pure measure of abrasion by suspended particles. There is also the choice between blocks fixed on the stream bed or on bedrock, semi-mobile tethered blocks as well as loose tracer particles of known weight and size (Stott & Sawyer, 2000). For measurements relevant to stream invertebrates or periphyton it is preferable to place the blocks on the stream bed. Although fixed or tethered blocks may split and get lost or buried by sediments, the recovery rate can be high (Brewer *et al.*, 1992). These methods do not allow distinction between effects of sandblasting, overpassing bed materials and the physical impingement of fast flowing water. However, the practical consequences for ecologists are small because, in the field, biota are usually exposed to a combination of these effects (Webb *et al.*, 2006).

Abrasion coefficients derived from laboratory experiments are an easy alternative to field measurements but they generally underestimate the actual abrasion in rivers (Lewin & Brewer, 2002). Sklar & Dietrich (2004) presented a model to predict bedrock abrasion by saltating particles but it has not yet been applied in context with stream biota.

Descriptive surveys of substratum stability and multivariate approaches

Pfankuch Stability Index

The Pfankuch Stability Index is a qualitative measure that describes the probability of occurrence of substratum-moving discharges (Pfankuch, 1975). It consists of 15 variables representing properties of the upper and lower banks and the stream bed. Despite its subjectivity it shows a strong positive relation with the entrainment of painted stones

(Townsend *et al.*, 1997), but not when the painted stones are used as an indicator of tractive force over time (Death & Winterbourn, 1994). If just the stream bottom component of the Pfankuch Index is employed, the relationship with other stability measures is considerably higher (Death & Winterbourn, 1994; McIntosh, 2000) and the assessment of stability at finer spatial scales might be possible (Winterbourn & Collier, 1987).

Descriptive approaches for the assessment of stream bed stability provide an easily applicable tool which has been widely exploited for investigations of biota in streams. Their major problem is the propensity to be observer-biased (Duncan *et al.*, 1999). Additionally, large temporal variation in scores can occur between surveys of the same reach by the same observer (A. C. Schwendel, unpublished data). Nevertheless, relations between bed stability assessed with the stream bed component of the Pfankuch Index and biological data have been established (Table 7).

Multivariate approaches

Approaches that combine more than one measure of bed stability can have a stronger relationship with biological data because they can incorporate different aspects of substratum stability. Death & Winterbourn (1994) showed that a multivariate instability score consisting of hydraulic parameters (patch-scale), the movement of painted stones, water temperature and the bottom component of the Pfankuch index (reach-scale) had a stronger positive linear relationship with invertebrate species richness than with any of the constituent single variables.

Conclusions

The composition of benthic communities is a function of habitat and biotic interactions. Habitat stability in rivers is primarily determined by the forces of flowing water exerted on biota and substratum. Hence measurement of shear stress and substratum stability can indicate the distribution of benthic stream organisms, but they differ in precision and the aspect of bed stability they describe. Clearly there is no single technique suitable for all applications. Thus the selection of an appropriate method is subject to: (1) targeted fauna (mobility and range of activity), (2) spatial and (3) temporal scale of investigation (flood event-based or long-term), (4) hydraulic and (5) substratum conditions, and (6) research question of the study (e.g. range of flow, aspect of bed stability).

Most of the methods presented have been developed for research into stream hydraulics and fluvial geomorphology. Despite recent technological advances and development of new techniques only a few of them have been applied in ecological studies. Given the importance of bed stability for the biota of many streams and rivers and the multitude of ways to characterise that stability, we would like to encourage stream ecologists to consider also the potential of alternative techniques highlighted in this review for examining the links between stream stability and biota.

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Table 1: Methods for the assessment of shear stress (for annotations see Appendix B)

Method	Scale	Constraints	Interference with substratum	Accuracy/ Relation to biological data
Du Boys equation	reach	uniform flow, W/h > 20	low (measurement of parameters)	overestimation of local shear stress (Robert, 1990) but underestimation of mean shear stress (Carson & Griffiths, 1987), recommended to assess the spatial distribution of invertebrates (Statzner *et al.*, 1988)
DuBoys equation (using h and S_b)	patch	uniform flow	low (measurement of parameters)	underestimation of local shear stress (Lorang & Hauer, 2003)
FST-hemispheres	patch to reach, short-term	usually normal flow conditions	low	related to invertebrate distribution (Dittrich & Schmedtje, 1995; Merigoux & Doledec, 2004), negative linear relationship with invertebrate taxon richness (Merigoux & Doledec, 2004) and with mussel density (Hardison & Layzer, 2001)
Point near-bed flow velocity	patch	$h/D_{84}>3$	low	related to invertebrate distribution (Effenberger *et al.*, 2006)
Depth averaged near-bed flow velocity	patch	simple flow geometry, logarithmic velocity profile	low	3 times more accurate than point measurement (Wilcock, 1996)
Velocity profile	patch	simple flow geometry, logarithmic velocity profile	low	profiles least accurate compared to point and depth-averaged velocity, but no knowledge of bed roughness necessary (Wilcock, 1996)

Table 2: Methods for the assessment of critical shear stress and flow competence (for annotations see Appendix B)

Method	Scale	Constraints	Interference with substratum	Accuracy/ Relation to biological data
Critical shear stress				
$\tau_{crit} \approx D$ (Lane, 1955)	reach	$h >> D_{50}$, $S_w < 0.01$, uniform flow, unarmoured bed	low (measurement of D)	weak relationship with other measurers of bed stability or bryophyte cover (Death & Winterbourn, 1994; Duncan *et al.*, 1999), linked to bryophyte (Muotka & Virtanen, 1995) and invertebrate distribution (Cobb *et al.*, 1992), negative linear to number of invertebrates (Death & Winterbourn, 1995)
$\tau_{crit} = \theta_{crit} * (\gamma_s - \gamma_f) * D_i$	patch	uniform flow, uniform bed, low h/D_i, low S	low (measurement of parameters)	depending on choice of θ_{crit}
$\tau_{crit} = \theta_{crit} * (\gamma_s - \gamma_f) * D_{50}^c * D_i^d$	patch	uniform flow, low h/D_i, low S	low (measurement of parameters)	depending on choice of c, d, θ_{crit}
Combination of Shields equation and DuBoys equation (+ corrections (Duncan *et al.*, 1999))	reach	uniform flow, unarmoured bed	D, R, S	related to actual entrainment (Milan *et al.*, 2001), negative linear relationship with bryophyte cover (Duncan *et al.*, 1999), related to periphyton biomass (Biggs *et al.*, 1999)
$\tau_{crit} = a * D^b$	patch	site specific	low (measurement of D)	depending on parameters a, b
Spring balance	patch	subjectivity of particle choice	high	(Downes *et al.*, 1997)

Table 3: Methods for the assessment of erosion and deposition

Method	Scale	Constraints	Interference with substratum	Accuracy/ Relation to biological data
Scour chains	patch/ reach, event-based	substratum < boulders	intermediate during installation	related to distribution of algae (Matthaei *et al.*, 2003) and invertebrate taxa (Palmer *et al.*, 1992; Effenberger *et al.*, 2006)
Scour plates	patch, event-based	substratum < boulders	high	related to vertical invertebrate distribution (Palmer *et al.*, 1992)
Dyed sand columns/ painted gravel	patch, event-based	substratum size	high	related to vertical invertebrate distribution (Palmer *et al.*, 1992)
Pressure pillows	patch, continuous	substratum < boulders	high during installation	(Kurashige, 2002)
Morphometric budgeting	reach, event-based	gravel/ cobble substratum	low	accuracy depends on surface roughness (Brasington *et al.*, 2000)

Table 4: Methods for reach-scale tracking of tracer particles

Method	Constraints	detection depth	recovery rate	Relation to biological data and comments
Tracking of initially unembedded particles				
painted tracer (visual)	armour layer, burial	surface	15-60%	negative with periphyton biomass (Death & Zimmermann, 2005), negative linear with invertebrate species number and species richness (Death & Winterbourn, 1995; Death, 2002; Death & Zimmermann, 2005), quadratic with invertebrate taxon number (Townsend *et al.*, 1997)
metal tracer (passive)	armour layer, particle size	0.5-1 m	50-90%	
stones wrapped in aluminium foil (passive)	armour layer	0.25 m		
magnetic tracer (passive)	armour layer, particle size	0.5-1 m, usually higher than with metal tracer	50-90%	
transmitters (active)	armour layer, particle size, battery*, low conductivity	shallow water	up to 100%	* life span: a few weeks to 10 months (size 0.01 m to 0.08 m respectively)
radioactive tracer (passive)	armour layer, environmental issues		ca. 5%	
different lithology (visual)	armour, burial	surface	5-30%	
artificial tracer (visual/ passive)	armour layer, representativeness of substratum	variable	ca. 35%	
DUMPLING (active)	size (0.3 m), weight (37 kg)		100%	
Tracking of initially embedded particles				
chiselled stones (visual)	particle choice	low	low	
dyed quick concrete mix (visual)	particle choice	surface		distribution of invertebrates (Barquin & Death, 2006)

Table 5: Methods for the assessment of bedload transport

Method	Scale	Constraints	Interference with substratum	Accuracy/ Relation to biological data
pressure-difference sampler	patch, short-term	orifice area (up to 0.05 m^2), upscaling to stream width	low	sampling efficiency usually 30 – 70%, can reach up to 100%, small volume
Birkbeck slot sampler	patch/ reach	slot width, upscaling to stream width	high for installation	continuous during smaller floods
sediment trap	cross-section, continuous		high for installation	sampling efficiency up to 100%
acoustic sensors	patch/ reach	calibration	low – high for installation	comparable accuracy as bedload traps (Downing *et al.*, 2003)
ADCP	patch/ reach	sandy substratum, high suspended load	non	
electronic momentum sensor	patch	calibration	low	measures a combination of particle size and speed (Richardson *et al.*, 2003)
piezoelectric sensors	reach, long-term	calibration	low (installation)	limited accuracy for single events (Rickenmann & McArdell, 2007)
bedload transport formulae	reach	calibration site specific	low (measurement of parameters)	inaccurate for general application

Table 6: Methods for the assessment of abrasion by suspended sediments

Method	Scale	Constraints	Interference with substratum	Accuracy/ Relation to biological data
Stone blocks	patch	absolute	low	actual abrasion of sediment
Artificial blocks	patch/ months	dissolution, high bedload transport	low	only relative measurement
Abrasion coefficients	reach/ patch	calibration	none	underestimation of actual abrasion (Lewin & Brewer, 2002)

Table 7: Descriptive surveys for the estimation of bed stability on a reach-scale

Method	Constraints	Interference with substratum	Accuracy/ Relation to biological data
Pfankuch Index	subjectivity of perception	none	related to other measures of bed stability, negative linear relationship with invertebrate taxon number (Townsend *et al.*, 1997)
Pfankuch Index bottom component	subjectivity of perception	none	positively related to other measures of bed stability (Death & Winterbourn, 1994), negative linear relationship with bryophyte cover (Suren, 1996; Duncan *et al.*, 1999), negative linear relation to invertebrate species richness, number and density (Death & Winterbourn, 1995; Death, 2002)

Appendix A: Definitions

Armour layer	Coarse surface layer in streams that inhibits the entrainment of underlying finer material
Bed roughness	Relief of roughness elements on the channel boundary, normally a function of grain size and flow depth
Energy gradient	Difference in potential and kinetic energy per horizontal distance between two points in a stream
Flow competence	Ability of a stream velocity to move particles of a particular size as bedload
Imbrication	Overlapping and interlocking of particles
Incipient motion	Beginning of (grain) movement
Laser altimetry	Approach to obtain measurements of surface elevation with laser scanning techniques
Pebble cluster	Feature developed by stream flow over alluvial beds consisting of a group of particles
Photogrammetry	Approach to obtain measurements by means of photography
Reynolds number	Nondimensional parameter of fluid motion which determines the extent to which viscosity modifies flow
Stream power	Index for the erosive capacity of stream, defined as energy dissipation per unit area, stream length or mass of water.
Tacheometry	Survey technique that produces rapid measurements of direction, elevation and distance using a kind of theodolite
Thalweg	Deepest continuous longitudinal line along a river

Appendix B: Symbol annotation

τ_o	mean boundary shear stress (N m^{-2})
τ_{crit}	critical shear stress at incipient motion (N m^{-2})
ρ_f	density of the fluid (for pure water approx. 1000 kg m^{-3})
g	gravity acceleration (9.81 m s^{-2})
R	Hydraulic radius (= A P^{-1}) (m)
A	cross-sectional area (m^2)
P	Wetted Perimeter at a cross-section (m)
S_f	Friction slope (dimensionless)
S_w	Slope of water surface (m m^{-1})
S_b	Slope of stream bed surface (m m^{-1})
h	water depth (m)
D_{50}	substratum grain size for which 50% are finer (mm)
D_{84}	substratum grain size for which 84% are finer (mm)
D_i	substratum grain size for which i% are finer (mm)
D	substratum grain size (mm)
γ	specific weight (= ρ g) (kg m^{-2} s^{-2})
s	sediment
f	fluid
θ_{crit}	Shields coefficient or dimensionless critical shear stress
v	flow velocity (m s^{-1})
W	stream width (m)
Re	Reynolds number
a, b, c, d	empirical factors in entrainment formulae
q_b	bedload discharge
q	water discharge (m^3 s^{-1})
q_{cr}	critical discharge (m^3 s^{-1})
X’	sediment coefficient