MEASURING BEDLOAD IN COARSE-GRAINED MOUNTAIN CHANNELS: PROCEDURES, PROBLEMS, AND RECOMMENDATIONS

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ABSTRACT: Several methods for assessing bedload movement in coarse-grained channels used by USDA Forest Service research parties in the central Rocky Mountain Region are described. Volumetric sediment loads moved into weir ponds have been measured for periods exceeding 3 decades on several streams, providing a long-term index to annual sediment yield. Mean transport rates have been estimated for flows ranging from baseflow to greater-than-bankfull in 1st to 3rd order channels using bedload trapped in portable samplers. Coarse particle motion was detected by seeding channels with colored tracers or painting exposed channel surfaces prior to high flows; mobility of individual particles was determined through survey and photogrammetric methods. Study sites are in steep, cobble- and boulder-bed channels at the Fraser Experimental Forest in Colorado and on the Medicine Bow National Forest in Wyoming. We present details on techniques used, problems encountered and overcome, and limitations of the procedures in these systems. Recommendations for subsequent studies are also provided.
KEY TERMS: Bedload Transport; Mountain Streams; Measurement Procedures.

INTRODUCTION

Measuring bedload transport in coarse-grained channels can be particularly difficult because flows necessary for transporting larger particles are usually deep, turbid, and turbulent, making difficult the direct physical measurement or visual observation of particle motion. Consequently, bedload movement may be measured only indirectly, using various traps, tracers, or samplers. Difficulties in measuring bedload are compounded by erratic transport patterns, even under stable conditions (Emmett, 1980; Gomez and Church, 1989). Developing representative sampling procedures in steep mountain channels is particularly problematic due to continually fluctuating flows, the presence of large roughness elements, and uneven bed topography. Yet, the need to understand channel processes requires that some effort to measure coarse-grain movement be undertaken, recognizing the limits of our present capability to measure the processes. Several methods, used in conjunction, may be necessary to obtain a truer picture of transport patterns.

The objective of this paper is to address procedural and practical concerns encountered in measuring bedload based on our experiences with field measurements. In doing so, we focus on 3 methods for monitoring sediment movement used for varying purposes and over time frames ranging from a few years to several decades. These are: (1) measurement of total annual bedload (volumetric and particle size) from weir pond surveys and grain-size analysis, (2) estimates of bedload transport rates (mean, fractional, and at-a-vertical) from bedload collected in portable samplers, and (3) observations of coarse grain movement during seasonal runoff using colored tracer and painted channel surfaces. We also address shortcomings, problems encountered, and recommendations for future sampling projects. This is intended to be an instructive paper, to use as a guideline for developing sampling protocols. The results from these studies are published elsewhere or are in progress, as indicated in the text.

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(1) LONG-TERM RECORDS OF TOTAL ANNUAL BEDLOAD FROM WEIR PONDS

The Rocky Mountain Forest and Range Experiment Station operates several weir ponds associated with gauging stations on the Fraser Experimental Forest (FEF) and on the Medicine Bow National Forest (MBNF) (among others) (Troendle and Olsen, 1994; Troendle, et al., 1996). Long-term records of accumulation from these ponds provide a measure of total sediment moved past each site annually and are continuous over 3 decades for 4 sites on FEF and for 14 years at 2 sites in southern Wyoming; in total, there are in excess of 140 years of station record from the 6 sites.

1.1 Survey Data

All material moved as bedload and part of the material moved in suspension is effectively trapped by the stilling effect of the ponds (Leaf, 1970; Troendle, et al., 1996); only 10-15% of material transported in suspension is retained in the pond, based on inflow and outflow measurements of suspended sediment (Wilcox, et al., 1996). Each fall, after runoff from snowmelt recedes, the ponds are drained and the accumulated sediment is excavated using shovels. The bottom elevation is surveyed at established points before and after removal. Total sediment volume is calculated using differences in bottom elevations measured over the pond area. The volume (m^3) may be converted to weight (kg) by multiplying by the average density (kg/m^3) of material in the pond, when known; the relative density ranges between 1.4 and 1.7 due to differences in the organic constituent (Leaf, 1970; USDA Forest Service, unpublished data).

1.2 Grain Size Analysis of Subsamples_

In recent years, samples of the accumulated material have been collected and analyzed for particle size and organic matter content (e.g., Wilcox, et al., 1996). Samples were collected at survey grid points or by grab samples from shovels during excavation; up to 40 samples, each exceeding 10 kg, were collected and analyzed at 3 of the 6 ponds. From these subsamples, we can further characterize the composition of the total load into sand, gravel, and cobble fractions. Additionally, the weight of coarse organic matter (COMC) and the suspended fraction may be estimated and subtracted from the total load to approximate the inorganic portion moved as bedload, which is the main fraction of interest for our purposes. Sediment moved primarily in suspension is separated from the total load by subtracting the fraction less than 500 microns in diameter (based on calculations and observations, 500 microns is roughly the limit of particle sizes moved by suspension in these systems). Similarly, COMC may be estimated as percent by weight of organic matter in the subsamples and subtracted from the total load.

1.3 Strengths and Weaknesses of Weir Pond Data

Data of this nature may be the best index to total transport and particle size being transported over time that we have and thus may be useful to test transport models (e.g., Troendle, et al., 1996). Mean transport rates from portable samplers, determined for several flow levels, can be integrated over the annual hydrograph to also estimate total bedload transported for a given year. We found values of total bedload determined in this manner to be comparable to those from the weir pond data (Troendle, et al., 1996). This comparability is important because, although the pond data provide a vital long-term record of sediment yield, they are of limited use for determining mean transport rates or for characterizing transport patterns within the channel itself. This is one example of where differing monitoring methods, used in conjunction, provide a more complete and reliable portrayal of transport processes.

An additional downside to using these traps is that only 1 sample (or observation) is obtained annually per site. Hence, it takes several years to build a database in this manner, which is prohibitive for many purposes. Procedurally, ponds should be excavated annually rather than measure the aggrading bed elevation year after year (as in the case of the Fool Creek pond on FEF). This is because the accumulated material is subject to settling, compaction, and decomposition of organic matter if left in place, which shifts the elevation the pond bottom and affects the volumetric measurement determined from the survey. This, in turn, influences estimates of the total load obtained from the pond data. Also, continual aggradation of material may alter the ability of the pond to retain additional sediment, thus changing the efficiency of the trap over time.

(2) BEDLOAD MEASUREMENT FROM PORTABLE SAMPLERS

There are several factors to consider in developing procedures for measuring transport rates in coarse-grained channels. Unfortunately, there is little agreement as to what constitutes a valid sediment sampling scheme in any stream system, coarse-grained or otherwise. The method used depends partially on the objectives of the monitoring, but also on timing and magnitude of high flows, personnel availability, and expense involved in collecting and analyzing samples. One must often weigh protocol and potential for increase in unexplained variability against the costs involved in obtaining samples. However, some minimum criteria must be followed to obtain representative and comparable samples. These include the selection of a suitable sampler, following appropriate sampling procedures, and other concerns, such as operator training. The following recommendations are based on the collection of samples during 1500+ visits to cobble- and boulder-bed channels at FEF and MBNF between 1992 and 1996.

2.1 Sampler Characteristics

2.1a Sampler Type

There are several types of bedload samplers, each of which have strengths and weaknesses associated with their use; however, space permits the description of only a few. As a general comment, selection of sampler type, although an important factor, is probably less crucial than the development of an appropriate sampling method (section 2.2). Assuming all other variables to be equal, one may base the selection of sampler on the characteristics or ease of use at a particular site. Generally, the sampler should lie flat on the channel bed and the nozzle opening should be two or more times larger than the grain size of interest (USGS Office of Surface Water Technical Memorandum No. 90.08, 1990). However, these recommendations may be impossible to meet in very coarse-grained channels where bed and flow conditions are less than optimal. In these systems, standard samplers, with small nozzle openings relative to bed particles, are usually used in conjunction with other methods which sample larger grains, such as painted tracers or miscellaneous basket type samplers. *Regardless of which sampler is used, it is important to be consistent and use the same type throughout the sampling duration, even with changing transport rates and patterns.* This is because we don't know how transport rates measured with different samplers compare, and there is no currently accepted means of adjusting transport rates estimated by different tools to a common base. While it is suspected that variation in sampler attributes affects the measured transport, the best sampler for obtaining "true" rates of transport is unknown.

The most commonly used hand-held, portable sampler is the Helley-Smith bedload sampler (Helley and Smith, 1971). The original version is constructed of 1/4" thick cast aluminum, with a 3 x 3 inch (inner dimension) intake, and an expansion ratio (exit area/entrance area) of 3.22. Since originally developed, a lighter, less expensive version has been manufactured commercially. This "GBC-type" (or sheet metal) sampler is identical to the original, except for wall thickness and the material from which it is constructed (16 gauge stainless steel instead of 1/4" cast aluminum). The GBC-type sampler was used for our efforts because they were readily available. However, there is some concern that the sampling efficiency of the modified version differs from the original; hence, bedload transport rates measured with the 2 versions of the same sampler may not be readily comparable.

The BL-84 bedload sampler (source: Federal Interagency Sedimentation Project) is newer and, although it has the same opening and wall thickness as the original Helley-Smith, it has a narrower flare and an expansion ratio of only 1.40. The altered design causes it to have a smaller hydraulic efficiency (1.35) than the Helley-Smith (1.54), so it doesn't draw in water the way the original does. A BL-84 sampler fits more easily into the channel bottom because the reduced flare is less intrusive among large grains; it is also less disruptive of the flow. In a comparison between the 2 versions of the Helley-Smith and the BL-84, the latter was preferred by operators for ease of use (Ryan, manuscript in preparation); bedload transport rates measured with the 3 samplers are compared in this forthcoming report. Of the 3 samplers, the USGS recommends that a BL-84 be used, but will accept bedload data collected with any of the 3, with documentation of sampler used (USGS Office of Surface Water Technical Memorandum No. 90.08, 1990; W.W. Emmett, personal communication, April 1996).

Another frequently used sampler for coarse-grained channels is the scaled-up version of the Helley-Smith. This sampler has the same ratio and efficiencies as the original, but has an intake opening of 6 x 6 inches (Druffel, et al., 1976). It is usually constructed of 1/4" steel plate (cable version), though the wading version may be constructed of 16 gauge stainless steel, making it lighter and easier to handle. The advantage of the scaled-up version is that it can sample larger particles. However, our operators found the larger sampler to be more difficult to place on the bed and relatively unsteady in high flows; as a result, the bed was more easily disturbed. Also, because it is heavier, larger, and more disruptive of the flow, there was a tendency for the sampler to dig down into bed. Therefore, some material trapped by the sampler may have been mined from the bed, rather than transported, leading to an overestimation of bedload movement and flow competence. In our experience, samples from the 6 x 6 inch Helley-Smith were frequently a factor of 5 or more greater than those from the 3 x 3 inch sampler, indicating differences in sampling efficacy rather than variability in the physical process (Ryan, unpublished data). This effect was more pronounced at high flows, conditions under which the 6 x 6 inch Helley-Smith is usually deployed. If the 6 x 6 inch sampler is selected for use, it is recommended that tetherlines be employed to stabilize the sampler and help keep it from mining the channel bed.

2.1b Sampler Bags

All of the portable samplers described use a similar type of nylon mesh bag to retain the sample. The characteristics of this retention bag do influence the efficiency of the sampler (Beschta, 1981), so selection of bag type is not arbitrary. For example, bags with smaller mesh restrict flow and clog faster, reducing the trapping efficiency of the sampler. Bags with larger mesh openings clog less quickly but finer material may be lost through the openings. The most commonly used mesh size is 0.25 mm. Regardless of that selected, the mesh size should be the same between samples intended for comparison, and be recorded as part of the bedload record. Clogging of the sampler bag is minimized by frequent emptying of the bag; it is recommended that sampler bags not be over 1/2 filled because of this effect (USGS Office of Surface Water Technical Memorandum No. 90.08, 1990).

Sampler bags wear out over time, especially when bumped against coarse bed material. We found stiffer bags with double stitching to be more sturdy and longer lasting than those with more flexible mesh and only single stitching. If collecting samples on a daily basis at 5 or 6 sites, one can expect bags to last about a month. Under similar circumstances, bags with flexible mesh and single stitching lasted about a week. It is recommended that several backup bags be available in the event that some are ripped or lost to the flow.

2.1c Sampler Handles

Another frequently overlooked detail of a wading sampler is the construction of the handle. The length and stability of the handle are important factors influencing an operators ability to place the sampler without disturbing the bed. The handle needs to be long enough so that it easily reaches the channel bottom, whether sampling from a boat, bridge, or while wading. Additionally, there should be a solid connection between the handle and the sampler head so that the sampler doesn't "pivot." Likewise, the handle needs to be sturdy and unbending in high flows. Conversely, the handle should not be too heavy because of the greater potential for weightier samplers to "mine" the bed.

In our experience, light-weight, telescoping handles were not sturdy enough for high flows, often snapping at the tubing connection. We replaced such handles with solid pieces of galvanized steel or aluminum tubing (3/4"). Handles up to 8' in length easily reached the channel bottom from our 1-2' high sampling platforms, while providing the necessary strength and stability.

2.2 Sampling Methods

Bedload movement can be highly variable in coarse-grained systems, both spatially and temporally. Spatially, transport often occurs in zones, the position of which is unpredictable and does not always correspond with the highest velocity or shear stress (Emmett, 1980). Additionally, zones of high transport may shift position with flow level (Bathurst, et al., 1986; USDA, unpublished data). Temporally, transport has been associated with the movement of bedforms, clusters, sheets, or pulses, which are often independent of variations in discharge (e.g., Gomez, et al., 1989).

Quantification of mean transport rates requires procedures that account for the erratic nature of bedload movement. Sufficient samples from different positions in the channel (or *verticals*) are needed for a representative spatial measure. Additionally, the total sampling period must be long enough to measure a suitable temporal average. There are, however, no hard and fast rules as to the procedures which will accomplish this, only some rough guidelines, described here and by others (e.g., Emmett, 1980; USGS Office of Surface Water Technical Memorandum No. 90.08, 1990; Gomez, et al., 1991). Furthermore, methods may vary with the objectives of the study and on the extent to which cross-sectional data are needed.

2.2a Composite vs. Separated Samples

Bedload samples may either be separated by vertical or composited into a single sample. *Separated* samples are emptied after measuring each vertical and are useful for assessing the contribution of bedload from various points within the cross-section. The same verticals must be measured at each visit if an analysis of transport at-a-vertical is desired. *Composite* samples consist of sediment collected from all verticals combined into one. In collecting composite samples, the sampler bag doesn't need to be emptied after each vertical if there is sufficient room to prevent overfilling (and the sampling time is equal for each vertical). Typically a "bedload sample" is a composite sample collected at one visit, unless indicated otherwise. Separated samples may be compared to composite samples by calculating the mean of the transport estimates from all verticals. As may be expected, separated samples are more expensive and time consuming to collect and analyze.

2.2b Number and Spacing of Verticals

Because bedload is transported unevenly within the channel, it is necessary to sample the entire cross-section over a variety of flows to identify the position and stability of transport zones. The more verticals used, the better the estimate of the mean rate and the more detailed cross-sectional patterns become; there is, however, a tradeoff between adding verticals and minimizing the time required to sample a cross-section.

One method frequently used in gravel-bed channels is to sample a minimum of 20 equally-spaced points per traverse, with 2 traverses made per bedload sample (Emmett, 1980); with this method, about 40 vertical measurements comprise one sample. However, this number of verticals is probably excessive in small mountain streams; because channels are typically narrower, the sampler occupies a larger proportion of the streambed, so fewer verticals are needed to achieve a suitable spatial measurement. Spacing between verticals in our studies ranged from 0.3 m in small channels to 0.6 m in larger systems, which was approximately 15% of the channel width. However, such close spacing is impractical for larger rivers where hundreds of verticals would be needed to cover 15% of the channel bottom. The 40 vertical and percentage criteria are guidelines to ensure that a sufficient portion of the channel bottom is sampled; a study to determine more precisely the effects of the number of verticals on the measured transport rates is in progress.

For most purposes, the spacing between the verticals should be equal; the spacing *must* be equal if the sample is to be composited. Some have recommended an initial effort to identify cross-sectional patterns of transport, then focusing effort in the zones of heavy transport, usually in the center of the channel (e.g., Hubbell, 1987). This assumes however that the zones of high transport are readily identified and remain constant; cross-sectional data from our small mountain streams indicate zone position is inconsistent and unpredictable (USFS, unpublished data). Also, while focusing effort in zones of high transport may provide a better estimate of the mean in those areas, it ignores the zones of low transport, which are as important in determining an appropriate transport rate for the entire cross-section. Consequently, if one is interested in the mean transport rate over the entire bed, samples must be collected at equidistances over the full wetted width.

2.2c Sampling Time

Sampling time is the total time that the sampler is held on the stream bed at each vertical. Longer sampling times provide better measurements of mean transport at that point. However, the longer the sampling time, the longer it takes to sample a cross-section. If too much time is given to each vertical, then flow conditions for the duration of sampling may fluctuate excessively. Ideally, a bedload sample is collected in 1/2 to 1 hour during moderately fluctuating flow conditions; while feasible in small mountain streams, this may be impossible where there are many verticals and they are bagged separately.

USGS Office of Surface Water Technical Memorandum No. 90.08 (1990) recommends a sampling time of 30 to 60 seconds for each vertical in gravel bed streams. We incorporated a longer sampling time because of the highly sporadic nature of bedload transport in our cobble- and boulder-bed channels. Each vertical was sampled for 2 minutes, except for composite-only samples where sampling times were 1 minute per vertical, but 2 channel traverses were made. In this manner, the total time was the same whether a sample was separated or composited. Furthermore, sampling time should be the same at each vertical to prevent bias within a particular zone. If transport rates are high, the bag may need to be emptied 2 or more times until the total sampling time is reached.

2.2d Sampling Frequency

Sampling frequency determines the total number of samples collected for a site; sufficient numbers should be collected in order to develop valid transport relationships. From our experience, a minimum of 25 composite samples, measured over a wide range of flows (i.e., low flow to roughly bankfull), were needed to define a transport function. More are desirable for defining error terms, but the goodness-of-fit did not change substantially after more than 25 samples (Troendle, et al., 1996); this result, however, may not be universally applied. Because the variability of transport is greater at higher flows, increased sampling under those conditions is advantageous, whenever possible.

The number of samples and range of sizes is constrained by the length of runoff and level of peak flow reached, which in snowmelt systems is driven by the amount of snow available for melting and insolation intensity. One can determine from snow survey records measured in the spring whether it will be a relatively wet year; it is usually not worth the expense and effort necessary to sample bedload if the snowpack is less than average because the range of flows will be restricted. During a typically wet year, high discharge may occur over 4-6 weeks, with bankfull or greater flows achieved on 4 to 5 days. If a site is measured 5 times a week for 6 weeks, then 30 bedload samples are collected, meeting the minimum needed for developing a suitable bedload function for a wide range of flows. Sampling frequency can be adjusted based on the anticipated duration of runoff.

2.3 Other Concerns

2.3a Bridges vs. Wading

It is strongly recommended that bedload samples be collected from bridges or platforms, not only to ensure operator safety at high flows, but also to maintain the integrity of the channel bed (i.e., no rocks are kicked up by persons wading nearby). Relatively inexpensive platforms ($200 - $1000) which will support 3-4 adults can be constructed on-site over small mountain streams using wooden supports or bar joists, plywood, and hand tools (Martinez and Ryan, manuscript in progress). However, if samples must be collected by wading, a guide cable should be strung across the channel for the operators to grasp while crossing during high flow. In this case, every effort should be made to maintain the character of the stream bed, and all movement should be downstream of the cross-section. If flow is too deep for wading and no platform is available, samples may be collected from boats or rafts stabilized by guidewires; cable mounted samplers may be more appropriate for these conditions.

2.3b Operator Consistency

Another frequently overlooked factor in bedload sampling is the potential error due to operator inconsistency. Some variation in sample size due to differences in technique is inevitable. In our experience, some operators handle the samplers more cautiously or aggressively and the sample size varies as a result. To minimize this factor, operators need to be well-trained in sampling protocol, particularly in the placement of the bedload sampler. The sampler should be placed on the bottom with the nose slightly elevated, then gently rotated to lie flat on the bed. This helps prevent the displacement of stable particles near the opening. However, accidental disturbance or "scooping" of the stable bed may occur, especially at high flows when the sampler is more difficult to place and maintain on the stream bed. *Operators need to be reassured that it is better to toss a questionable sample and re-do it than to accept one that has been scooped from the bed.* If an operator is uncertain about the validity of a sample, a second measurement may be taken to see if the first appears reasonable; the first is retained if a second sample of comparable size is acquired. The problem of operator error is probably minimal at lower flows when sampler placement is relatively easy. How much of the variability of transport measurements at higher flows is due to operator error is unknown.

2.4 Strengths and Weaknesses of Portable Samplers

Portable samplers may be used at a number of sites and are easily transported to remote areas. The sampling scheme can also be designed to meet the objectives of an individual study, whether the interest is in mean transport rates or variation in transport patterns within a cross-section. Transport databases may be developed within a year or two, depending on flow levels reached during the sampling periods. Their main weakness is that the confidence in the estimate of mean transport is lowered for many reasons, many of which are described above. Also, there is a limit to the size of material that may be sampled with a relatively small nozzle, so estimates of flow competence are suspect; still, 85% or more (by weight) of the grain sizes excavated from the weir ponds would fit into a sampler with a 3x3 inch opening (Wilcox, et al., 1996) so even small samplers are capable of trapping a majority of grain sizes moved (consistently) as bedload. Finally, sampling procedures using portable samplers are highly labor intensive and, as such, can be quite expensive.

(3) OBSERVATION OF COARSE BEDLOAD MOVEMENT USING TRACER GRAINS

In addition to describing methods of seeding stream beds with painted tracers, we also describe painting grains *in situ*, thereby eliminating the problem of preferential positioning that is problematic with seeding procedures (Laronne and Carson, 1976).

3.1 Seeded Grains

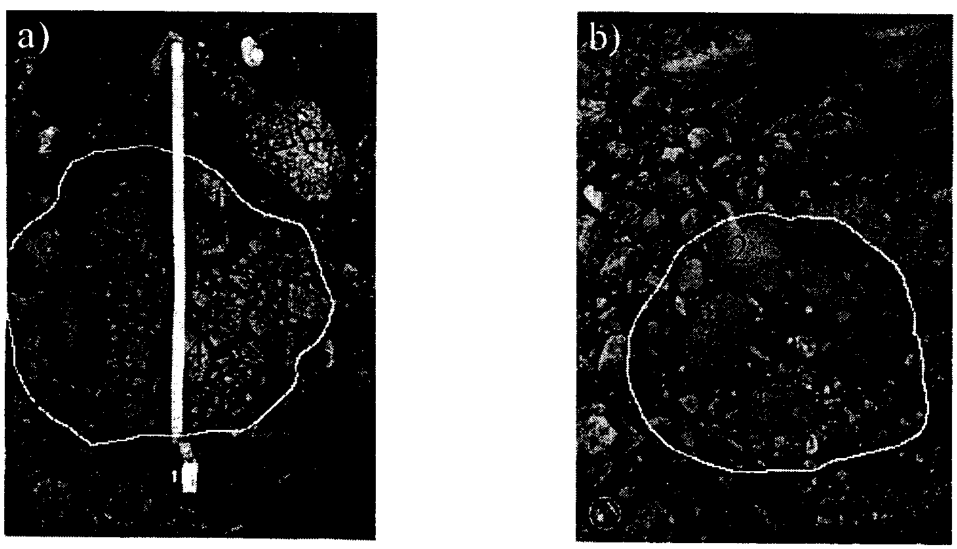
Individual cobbles are collected, dried, painted, and replaced on the channel bed, usually during low flow. Selected particles should represent a range of those found in the particle-size distribution of the channel bed (d_{35} to d_{84}, for example), as determined from Wolman pebble counts (Wolman, 1954). Between 30 and 50 roughly equally-spaced particles were placed in lines upstream of our bedload sampling sites, in areas of the bed with comparably sized particles. Particles may also be randomly distributed on the bed, although straight lines facilitate relocation of initial positions. Line direction is usually perpendicular to the direction of the flow (at narrower sites the lines may be oblique to the flow to fit more particles). Line endpoints are marked by rebar to re-locate the position of the line at a later date. The b-axis of each grain is measured and the distance from an endpoint recorded. Particles should be pressed into the bed (where possible) with the ball of the foot, rather than be permitted to sit on top of the surface.

Particle movement is determined after recession of runoff by the presence or absence of a seeded grain from its initial position. Some particles were observed to have moved short distances (1-2 m) at low-to-moderate flows (less than 3/4 bankfull). This is probably due to their preferential position on the stream bed and isn't a good measure of flow competence. However, once the particle moved from its initial unstable position, it usually settled into a more stable configuration, having been moved by the flow rather than placed by hand. Therefore, seeded grains which move more than once are better indicators of sizes moved by the range of flows observed.

When possible, particles are recovered and the distance moved off line recorded. Our recovery rate, however, was less than 30%. Color of paint is an important factor in the likelihood of particle recovery. White, red, and orange particles, for example, quickly take on the tinge of unpainted bed particles due to abrasion, fading, and colonization of the surface by algal growth. By contrast, particles with blue, teal green, and bright yellow are more easily recovered, even when the rock is heavily abraded or partially buried; some were relocated after 2 or 3 runoff seasons, allowing the fate of the particles to be tracked for several years. Particles with tree-marking paint retain color and resist abrasion longer than those marked with ordinary household-type spray paint.

3.2 Painted Areas

Circles 1 to 1.5 ft. in diameter have been painted on channel surfaces to document grain movement within the marked area. Surfaces are painted as close to the wetted edge of the channel as possible during late summer or early fall when flows are lowest. The location within the channel will depended largely on the level of baseflow at the time of painting; baseflow during fall 1994, for example, was particularly low, allowing painting of surfaces well into the active channel. A description of the location (such as edge of riffle, in pool, etc.) is recorded at the time of painting. Labeled stakes, driven into a nearby bank, mark the position of the circle, making the area easier to relocate in the future. The painted area is then photographed by positioning a camera directly over the painted surface (Figure 1a). Most of our circles were located in pool-riffle or plane bed channels; step-pool channels have few surfaces exposed, even at low flows, to permit paint adherence. Over 100 painted areas have been marked and monitored in this manner.



Figures 1a and b. Scanned photographs of circle painted on exposed channel surface (a) before seasonal runoff (painted in fall of 1991) and (b) after seasonal runoff (re-photographed in fall 1992). White line indicates limit of painted area; numbers mark 4 stable grains identified in both photographs. Similarly sized particles (gravels) were moved on and off painted area; cobbles remained stable during moderate flows in 1992. Tape case in (a) is 2.5 inches in length and lens cap in (b) is 52 mm in diameter.

After runoff, the circles are rephotographed with a scale featured in the picture (Figure 1b). Particles with paint are considered stable, while particles without paint have moved onto the painted circle. While some unpainted particles may be subsurface particles exposed by the removal of overlying grains, the majority probably originate from outside the area because the subsurface is typically finer than the surface and no particle fining was evident between the 2 photographs. A grid is drawn on the photograph and grains located under the intersection of grid points are measured, similar to a Wolman (1954) count for sampling particles on the bed surface; between 50 and 100 grains are usually assessed for each photo pair. A measuring scale drawn on clear film is overlaid onto the photo to directly measure particle size; the scale for each photo will depend based on the dimension of the scale in the picture. The b-axis (intermediate) is measured and classified using 1/2 phi interval classes.

3.3 Strengths and Weaknesses of Painted Tracer Methods

Painted tracers are most valuable for detecting motion of coarsest particles on the stream bed, sizes often larger than those caught in most portable samplers. However, the results are qualitative in nature because we are unable to estimate transport rates from painted tracers to an acceptable degree of reliability.

Several authors have used painted grains to monitor the movement of coarse bedload (e.g., Laronne and Carson, 1976; Hassan, et al., 1992). While it is a relatively quick and inexpensive method of characterizing grain motion, there are limitations to an analysis of flow competence. First, seeded grains may be moved at relatively low flows, probably due to preferential position on the stream bed (i.e., on top of other grains, rather than within the surface layer) (Laronne and Carson, 1976). Second, the actual flow which moves the grain is unknown, but is frequently assumed to be the highest achieved during the period of observation; this connection may be invalid in many cases (Wilcock, 1992). Third, there is usually low success in particle recovery due to abrasion of the paint and burial by other particles. Because of these limitations, seeded grains are best used in conjunction with other sampling procedures.

The advantage of the painted area method is that the naturally occurring particle geometry remains intact. Additionally, most of the analysis can be done in an office, with the displacement of particles recorded through photographs. The disadvantage is that only bars or higher, exposed surfaces may be sampled; these surfaces, while interesting, are usually composed of grains smaller than those in the wetted channel. Also, measurements obtained from photographs introduce some error because the size of the particle may be obscured by overlying grains or distorted by the position of the particle relative to the photo plane (Church, et al., 1987). Finally, painting the stream bed requires pre-season planning to mark dry surfaces during low flow.

SUMMARY

While a single method for quantifying the full complexity of bedload transport processes would be best, we are simply not at this level of assessment for steepland environments. Because of the difficulties encountered in obtaining incontestable data from standard measurement procedures, several methods may be necessary to obtain a good picture of transport processes. This paper described 3 methods used for monitoring bedload movement at Forest Service research facilities in Colorado and Wyoming. While additional methods for documenting the movement of coarse bedload are employed elsewhere, these are methods with which we have had direct experience. Surveys and samples from weir ponds provide information on annual sediment yield and the composition of material moved primarily as bedload. Values of total sediment yield from the weir ponds have been corroborated by estimates of total yield from bedload collected in portable samplers; additionally, data from the portable samplers provide information on transport patterns within channels for a range of discharges. Finally, motion of the coarsest particles can be observed through seeded grains and painted surfaces. The range of information and the level of detail from these studies allow us to extend the utility of any one method, and is helping to build a reasonable level of confidence in our understanding of how coarse-grained systems operate.

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