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ASSESSMENT OF METHODS FOR MEASURING EMBEDDEDNESS: APPLICATION TO SEDIMENTATION IN FLOW REGULATED STREAMS[1]

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ABSTRACT: Five commonly used methods for measuring embeddedness – the degree to which fine particles surround coarse substrate on the surface of the streambed – are assessed and used to evaluate the sedimentation pattern resulting from impoundment on tributaries of the Connecticut River. Results show that the U.S. Environmental Protection Agency (USEPA) method best reflects the sediment regime on these rivers. On the Ompompanoosuc River, regulated by a run-of-the-river/flood control dam, embeddedness increases significantly directly downstream of the dam. On the unregulated White River, no downstream trends in embeddedness are observed. The USEPA results on the Ompompanoosuc River reflect the movement of a local decrease in embeddedness, interpreted as a moving region of scour, with a calculated transport rate of approximately 5 to 25 m/day. Observed transport rates are similar to previously measured sediment transport rates and consistent with results from a multifraction sediment transport model. Application of the USEPA method to an additional regulated tributary demonstrates the effects of dam management on embeddedness. Flow regulation with high sediment trapping efficiency results in a decrease in embeddedness downstream of the dam. Results provide insight into the utility of available methods for evaluating the effects of management practice on streambed composition.
(KEY TERMS: dams; flow regulation; deposition; fluvial processes; sediment transport; watershed management.)

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INTRODUCTION

Flow regulation alters the magnitude, timing, and frequency of river flows, with subsequent effects on sediment dynamics and channel morphology (Williams and Wolman, 1984; Elliott and Parker, 1997; Hadley and Emmett, 1998; Magilligan and Nislow, 2001; Grant *et al.*, 2003). Depending on the style of dam management, changes in flow can produce a range of geomorphic adjustments (Brandt, 2000; Juracek, 2000; Phillips, 2001; Schmidt *et al.*, 2001). In some cases, flow regulation may increase sedimentation and embeddedness – the degree to which fine particles surround coarse substrate on the surface of the streambed (Sylte and Fischenich, 2002). Numerous studies have correlated high embeddedness with degraded benthic habitat and a decline in macroinvertebrate diversity and abundance (Waters, 1995; Angradi, 1999; Lowe and Bolger, 2000).

Owing to the ecological impacts of fine sediment deposition and its relationship to land use changes such as logging and agriculture, many management agencies, such as the U.S. Forest Service and U.S. Bureau of Land Management, routinely measure embeddedness in their attempts to characterize streambed conditions. However, there is no single standard methodology for quantifying this phenomenon; in fact, the precise definition of embeddedness differs between methods. Consequently, there may be significant variability between different measures and it is therefore difficult to compare results across studies when different techniques are used.

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This creates the potential for significant error to be introduced into the management of river systems.

The primary purpose of this study is to apply and compare five commonly used techniques for measuring embeddedness and to evaluate their ability to identify changes in streambed condition across a range of fluvial and geomorphic conditions. In particular, this study assesses their ability to detect the impact of a dam known to alter sediment supply and transport capacity (Salant *et al.*, 2006a,b). Moreover, to help establish the most appropriate technique for determining embeddedness, results from each method are compared to previously reported, independently determined changes in bed aggradation and increased bed sand fraction above and below the dam. A context for using these methods is then provided by considering how dam management style (permanent reservoir storage versus seasonal run-of-the-river) impacts the spatial and temporal variation of embeddedness.

SITE DESCRIPTIONS

The White, Ompompanoosuc, and Black rivers are all mixed gravel sand tributaries of the Connecticut River in eastern Vermont (Figure 1). Physical characteristics of each river are provided in Table 1. While the White River is unregulated, the Ompompanoosuc River is regulated by the Union Village Dam (built in

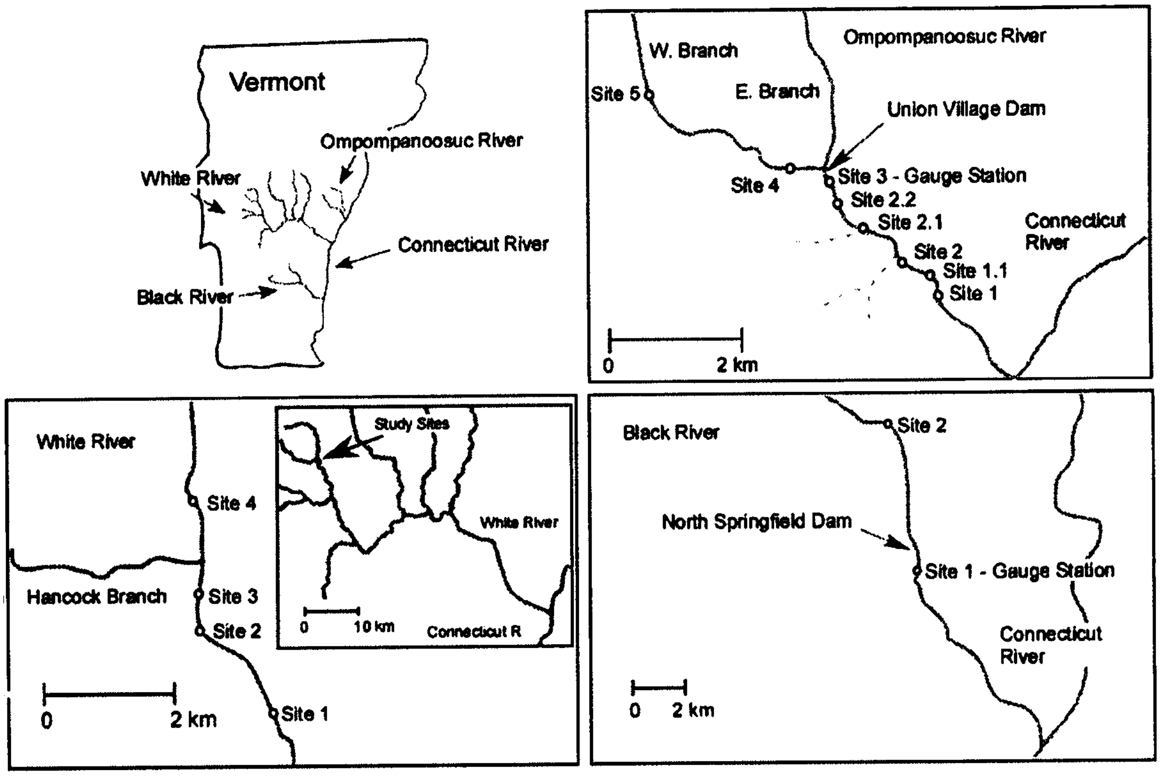

Figure 1. Location of Embeddedness Measurement Sites on the Ompompanoosuc, White, and Black Rivers, Tributaries of the Connecticut River in Eastern Vermont.

TABLE 1. Physical Characteristics for Sites Directly Downstream of the Union Village and the North Springfield Dams on the Ompompanoosuc and Black Rivers, Vermont, Respectively, as Well as for Sites on the White River, Vermont.

	Ompompanoosuc River	Black River	White River
Drainage Area (km^2)	282	409	80 to 160
Mean Annual Discharge (m^3/s)	~6	~9	
Gradient (percent)	< 0.1	< 0.1	< 0.1
Channel Width (m)	25	45	11 to 21
Median Grain Size D_{50} (cm)	10	13	10 to 11

1950) and the Black River is regulated by the North Springfield Dam (built in 1960). Flow regulation has similarly reduced the magnitude and frequency of flows on both the Ompompanoosuc and Black rivers; for both rivers, the post-dam two-year flood discharge just below the dams is about two-thirds of the pre-dam two-year flood discharge (Magilligan and Nislow, 2001). In addition, discharges during the more than three-decade post-dam period have never exceeded the pre-dam two-year flood discharge on either river. Both dams were primarily designed for flood control, but dam operation differs considerably between the two. The dam on the Ompompanoosuc River maintains a storage reservoir only during the winter and early spring. For the rest of the year, the dam gates are usually open, allowing the reservoir to drain during mid-spring and for run-of-the-river discharges from late spring to early winter. In 2004, the year when this study was conducted, the dam gates were opened in late March and closed in late October. Most of the sediment trapped in the reservoir during the winter and early spring was flushed downstream when the reservoir was drained (Salant *et al.*, 2006b). In contrast, the dam on the Black River maintains a large storage reservoir throughout the year. Water discharge from the dam generally matches upstream flows, maintaining a relatively constant reservoir, except during large precipitation events and spring snowmelt. In the latter cases, storage behind the dam temporarily increases to prevent downstream flooding. Owing to the large reservoir size (0.4 km^2), the majority of sediment settles out in the upstream end of the reservoir and little is drawn into the water release, effectively trapping the upstream sediment flux.

To capture spatial changes in embeddedness above and below the Union Village Dam, eight sites on the Ompompanoosuc River were selected, representing a progression of flow regulation impact: two unregulated sites upstream of the dam (Sites 4 and 5); a highly regulated site immediately downstream of the dam (Site 3); and five progressively less regulated sites located at increasing downstream distances from the dam (Sites 2.2, 2.1, 2, 1.1, and 1). Under typical flow conditions, Site 1, farthest downstream, represents the last free flowing section of river before the backwater effect of the regulated Connecticut River. Four additional sites were chosen on the White River as representative of unregulated streambed conditions. These sites have similar catchment areas to the upstream sites on the Ompompanoosuc River (~100 km^2). Two sites on the regulated Black River, one above (Site 1) and one below (Site 2) the North Springfield Dam, were chosen to compare changes in embeddedness between two differently managed rivers.

METHODS

To capture the effects of seasonal variations in flow and sediment transport on streambed conditions, embeddedness was measured on the Ompompanoosuc and White rivers in mid-May, mid-July, mid-September, and early November 2004. The Black River was sampled only once, in mid-January 2005. On the Ompompanoosuc and White rivers, embeddedness was measured using five different methods at each sampling site and date. These methods are representative of the wide array of proposed methods in the literature and are referred to as Platts/Bain, EPA EMAP, USFWS DTE, USGS NAWQA and Burns. Where appropriate, slight modifications were made to some methods as described below. Summary values were computed for each method as follows: for methods in which measurements are taken along multiple transects, the average transect values were used to compute a reach mean embeddedness and standard error (SE). For methods without replicate transects, reach summary values are simply the mean embeddedness and SE calculated using all measurements. One-way ANOVA and ad hoc Tukey-Kramer HSD tests, separated by sampling date and site, were used to determine method specific differences in average embeddedness and, therefore, the variability between methods. Similarly, one-way ANOVA and Tukey-Kramer tests, separated by sampling date and method, were used to determine site specific and river specific differences in embeddedness. The same analyses were also used to determine differences between sites and rivers averaged over all dates. Based on the ANOVA results, which reveal a high degree of variability between sites, average embeddedness values between grouped upstream and downstream sites on all three rivers were compared using Student's t-tests. Because the risk of a false positive or Type II error increases when multiple t-tests are performed, a Bonferroni correction (Dunn, 1961) was used to adjust the required probability level for each test in the set of n comparisons. Accordingly, for a desired significance level α, a p-value less than α/n is required for the means in any single t-test to be considered significantly different.

Platts / Bain Visual Method

Platts/Bain is a visual estimate of the fraction of the streambed within a reach covered by fine sediment. Embeddedness is classified in representative habitats including riffle, glide, and pool. The visual estimate describes embeddedness as one of five embeddedness classes: 0 to 5 percent, 5 to 25 percent, 25 to 50 percent, 50 to 75 percent or 75 to 100 percent (Platts *et al.,* 1983). For ease of comparison with other methods that focus primarily on riffle sections, only the Platts/Bain "riffle" values are discussed here.

EPA EMAP (USEPA) Visual Method

The EPA EMAP method is a visual estimate typically made at 11 cross sections spaced at four times the channel width. In this study, only four cross sections were measured at each site. Along each cross section, sampling is done at five points: 0, 25, 50, 75, and 100 percent of the wetted channel width. At each sampling point, all particles larger than sand in a 10 cm diameter circle surrounding the sampling point are visually examined (Peck *et al.,* 2000). Embeddedness of each particle is defined as the fraction of a particle's upper surface surrounded by fine sediment (< 2 mm). Sand and finer substrates are considered 100 percent embedded.

USFWS Depth to Embeddedness (DTE) Method

The USFWS DTE method measures the depth to embeddedness, differentiating it from most other methods that are generally related to the fraction of surface area composed of fine sediment. Twenty measurements are taken at each site by laying one hand flat on top of the cobble surface layer, placing the other hand adjacent to the first, and extending the fingers downward until the tip of the index finger reaches the layer of embeddedness. The embeddedness layer is identified when more than a moderate effort is necessary to push the middle finger deeper into the substrate (Osmundson and Scheer, 1998). These measurements are all taken near-shore, along a transect parallel to the bank. Different particle sizes can change the height of the cobble layer and thus the DTE measurement. To normalize for this effect, each measurement is divided by the median bed particle size in the region where the measurements are taken, converting each to a percentage.

USGS NAWQA (USGS) Method

The USGS NAWQA (National Water-Quality Assessment Program) method visually estimates embeddedness as the average percentage of a large particle's total height buried by fine sediment (< 2 mm). The percentage of each particle's total height buried in sediment is estimated from discoloration of the particle surface. In the original method described by Fitzpatrick *et al.* (1998), embeddedness is measured at three points along 11 cross channel transects. For this study, only three transects were measured, but the number of measurements along each transect was increased; five gravel-to-boulder-sized particles were randomly selected and examined along each transect, producing a total of 15 measurements.

Burns Quantitative (BSK) Method

The Burns method (Burns and Edwards, 1985) involves a random 60-cm-diameter hoop toss within an area that has a water depth less than 45 cm, with a float time across the hoop between 0.9 and 2.5 seconds. In this study, these criteria were approximated by tossing the hoop in areas that are both shallow and slow moving enough to make measurements feasible. Within the 60-cm hoop, both the depth of embeddedness (D_e) and particle height (D_t) of each single matrix particle larger than sand (> 2 mm) are measured. Hoops are thrown until at least 100 particles are measured; all particles in the last hoop thrown are measured even if this exceeds 100 particles. Embeddedness of free matrix particles is defined as zero. Three different computational methods developed for application to the Burns method [and the modified Burns, Skille, and King (BSK) method (Skille and King, 1989)] are used to compute embeddedness from these measurements. These include the original BSK expression for embeddedness E_{BSK}, which excludes free matrix particles

$$E_{BSK} = 100 \times \left(\sum D_e \Big/ \sum D_t \right) \tag{1}$$

where D_e is the depth of the pebble buried by sediment in mm and D_t is the total height of the pebble in mm. In contrast, the *BSK-n* equation takes into account total rock count (n) and therefore free matrix particles. For this method, the embeddedness E_{BSKn} is defined as

$$E_{BSKn} = 100 \times \frac{\left(\sum D_e \Big/ \sum D_t \right)}{n} \tag{2}$$

Finally, the weighted BSK equation accounts for conditions where a large portion (> 10 percent) of the hoop area is composed of fine particles (< 2 mm) by weighting this area into the equation as 100 percent embedded (Sylte and Fischenich, 2002). The equation for weighted embeddedness $E_{weighted}$ is

$$E_{weighted} = 100F_{fines} + (1 - F_{fines})E_{BSKn} \tag{3}$$

where F_{fines} is fraction of the hoop area covered in fine sediment. The weighted *BSK-n* computation is used in all figures.

Sediment Transport Model

Changes in embeddedness reflect changes in sediment supply and transport capacity, processes that are commonly quantified using sediment transport models. Embeddedness is fundamentally a comparison between the small and large grain-size fractions; therefore, a multifraction transport model (Parker *et al.*, 1982; Parker, 1990; Andrews, 2000) is required to provide insight into the relationship between sediment transport dynamics and streambed composition. In the model used here, the unit bedload flux of each grain size class, i, per unit width is given as (Parker *et al.*, 1982)

$$q_{bi} = \frac{W_i^* f_i \sqrt{g}(dS)^{3/2}}{R}$$

where f_i is the fraction of size class i on the bed, g is gravity, d is water depth, S is slope, R is the submerged specific gravity of sediment, and W_i is a dimensionless transport function, defined as

$$W_i = \begin{cases} 0.0025\exp[14.2(\phi_{50} - 1) - 9.28(\phi_{50} - 1)^2 & \text{for } 0.95 \le \phi \le 1.65 \\ 11.2\left(1 - \dfrac{0.822}{\phi_{50}}\right) & \text{for } \phi > 1.65 \end{cases} \tag{5}$$

where

$$\phi_i = \frac{\tau_i^*}{\tau_{ri}^*} \tag{6}$$

$$\tau_i^* = \frac{\tau}{\rho R g D_i} \tag{7}$$

and

$$\tau_{ri}^* = \tau_{r50}\left(\frac{D_i}{D_{50}}\right)^{-0.982} \tag{8}$$

where, τ_i^* is the dimensionless Shields stress, τ is the bed shear stress (ρghs), D_i is the mean particle size of size class i, and D_{50} is the median particle size of the bed. The reference median grain shear stress in Equation (8) is empirically defined as τ_{r50} = 0.0876 (Parker *et al.*, 1982). Mean water depth determined from monthly cross section measurements was regressed against discharge and used to determine flow depth h from hourly discharge records (Salant, 2005).

Unit bedload flux (m^2/s) is simply the volume (per unit width) of sediment moving at a certain velocity (m/s). Given that the flux of a given size class is proportional to the size of the particles in that class, converting the flux to a velocity requires scaling the flux to particle size, or the depth of the bedload layer. Bedload depth has been previously estimated as $2D_c$, where D_c is a characteristic grain size such as D_{90} (DeVries, 2002). Since each class is considered independently and the unknown grain size distribution likely varies between classes, here the characteristic grain size is approximated as the midpoint grain size (D_i) of each class, recognizing that this may slightly underestimate the bedload layer thickness and thus overestimate the velocity.

RESULTS

Ompompanoosuc River

Embeddedness values in the Ompompanoosuc River for two of the sampling dates, July and September, are representative of the range of results (Figure 2). In general, results varied considerably both between methods and sampling dates. In July, all the methods qualitatively show a similar downstream trend, but there is great variation between the absolute values determined by each method (Figure 2a). In contrast, in September, there is less variation between values determined by the different methods, especially directly below the dam (Figure 2b). Statistical (ANOVA) results support this qualitative assessment: for all sites except Site 2.1, there are less significant variations in values determined by the different methods in July than in September, demonstrating higher variability among methods in July. The difference between embeddedness values determined by the different methods at the same location highlights the difficulty of comparing results between methods. The ANOVA analyses confirm that significant discrepancies between all embeddedness measures persist even when values for each method are averaged over the entire sample period (Figure 3).

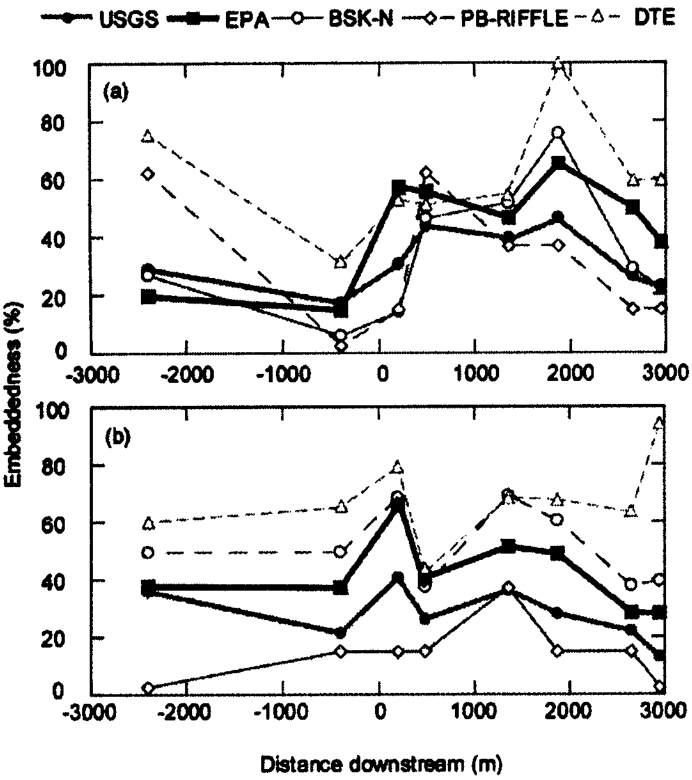

Figure 2. Embeddedness Values Upstream and Downstream of the Union Village Dam on the Ompompanoosuc River, Vermont, for Five Methods: USGS NAWQA, EPA EMAP, Burns (BSK-n weighted), Platts/Bain-Riffle, and USFWS DTE in (a) July and (b) September 2004. A distance downstream of 0 m indicates the location of the dam. Negative values are distances upstream of the dam, while positive values are distances downstream of the dam. See text for description of each method.

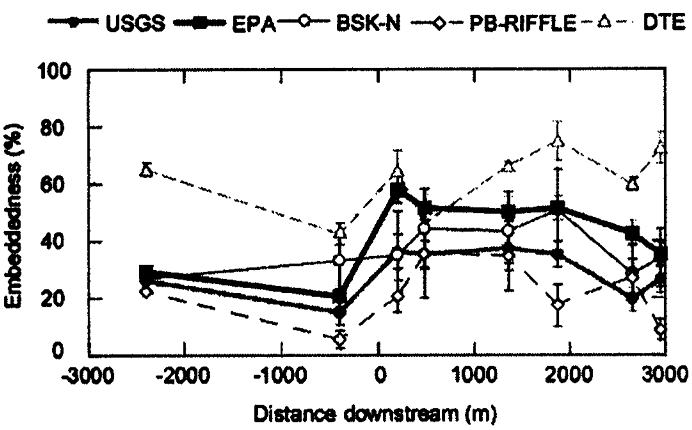

Figure 3. Embeddedness Values Upstream and Downstream of the Union Village Dam on the Ompompanoosuc River, Vermont, Averaged Over All Sample Dates, 2004, for Five Methods: USGS NAWQA, EPA EMAP, Burns (BSK-n weighted), Platts/Bain-Riffle, and USFWS DTE. A distance downstream of 0 m indicates the location of the dam. Negative values are distances upstream of the dam, while positive values are distances downstream of the dam. Error bars represent the standard error around the reach averaged mean. See text for description of each method.

Also evident, at least qualitatively, in Figure 3 are the differences in downstream trends for the different methods. Results from one-way ANOVAs comparing embeddedness between sites for each method confirm the variations in downstream trends for the different methods. For example, the ANOVA results from the EPA method averaged over all dates are presented in Table 2a: values are site means; sites not sharing the same statistical group are significantly different ($p < 0.001$). For this method, the embeddedness values of the two upstream sites (Sites 4 and 5) are significantly different from values at the four sites (Sites 2, 2.1, 2.2, and 3) immediately downstream of the dam. In contrast, for the DTE method, no consistent downstream trend exists (Table 2b).

TABLE 2. Average Embeddedness Values (SE) and ANOVA Results for All Sites on the Ompompanoosuc River, Vermont, for All Sampling Dates, as Measured by the (a) EPA method and (b) DTE method. Sites are listed in upstream to downstream order where Sites 5 and 4 are above the Union Village Dam. Sites not sharing the same statistical group are significantly different ($p < 0.001$).

Location	Embeddedness (percent)	Statistical Group				
	(a) EPA Method					
Site 5	29.9 (2.7)	A				E
Site 4	19.6 (2.2)	A				
Site 3	57.3 (2.3)		B			
Site 2.2	50.0 (2.4)		B	C		
Site 2.1	53.2 (2.4)		B			
Site 2	51.0 (2.4)		B	C		
Site 1.1	42.8 (2.1)			C	D	
Site 1	35.8 (2.1)				D	E
	(b) DTE Method					
Site 5	67.6 (6.4)	A	B			
Site 4	46.7 (5.0)		B			
Site 3	75.8 (5.3)	A				
Site 2.2	46.6 (4.7)		B			
Site 2.1	64.2 (6.4)	A	B			
Site 2	99.4 (4.6)			C		
Site 1.1	57.2 (4.3)	A	B			
Site 1	69.8 (4.7)	A				

These, and similar results for the other methods, can be summarized in a simpler format by grouping the upstream and downstream sites. This grouping is based on the expectation, based on physical arguments and independent analyses, that the dam alters the sediment supply and transport capacity of the river, inducing changes in bed aggradation and bed sand fraction below the dam (Salant *et al.*, 2006a,b). We therefore expect a corresponding increase in embeddedness below the dam. Accordingly, values for each method at all sites upstream of the dam are averaged and compared, using a Student's t-test, to the average of all downstream sites, excluding Site 1. The most downstream site (Site 1) is excluded because of the potential influence of backwater from the Connecticut River when discharge is high. Averaged over all dates, only the EPA method reveals significantly higher embeddedness at sites downstream of the dam at $p < 0.01$. At $p = 0.02$, the USGS method results are only marginally insignificant, while the other methods show no significant difference between sites (Table 3).

TABLE 3. Average Embeddedness Values (SE) and Student' t-Test Results for Upstream and Downstream Sites on the Ompompanoosuc River, Vermont, for All Sampling Dates, 2004, as Determined Using Five Different Methods. See text for descriptions of each method.

Method	Upstream	Downstream	P
BSK-n Weighted	30.26 (10.06)	37.07 (12.17)	0.50
Platts/Bain Riffle	12.79 (3.13)	23.90 (9.31)	0.22
USGS NAWQA	19.76 (4.39)	31.65 (4.94)	0.02
EPA EMAP	24.25 (3.78)	48.11 (4.49)	< 0.001
USFWS DTE	52.16 (4.04)	63.94 (7.80)	0.1663

White River

Minimal knowledge exists about the historical downstream bed sediment composition on the Ompompanoosuc River, particularly prior to the emplacement of the dam. However, differences in bed composition between unregulated and regulated locations that are similar in other aspects (i.e., drainage basin area, lithology) can be used to elucidate dam-induced changes. Thus, results from the White River, as representative of unregulated conditions, serve as a comparison to the results from the regulated Ompompanoosuc River. Average embeddedness values on the White River for all methods are consistently low, between 3 and 35 percent, and are similar to values obtained upstream of the dam on the Ompompanoosuc River by all methods (except USFWS DTE). In particular, we find that average embeddedness values for both the USGS and EPA methods on the White River are not significantly different from average embeddedness for upstream sites on the Ompompanoosuc River. White River average embeddedness values obtained by these methods are, however, significantly different from the average values obtained by the same methods for sites downstream of the dam (again excluding Site 1 on the Ompompanoosuc) (Table 4).

TABLE 4. Average Embeddedness Values (SE) and ANOVA Results for the White River, and Both Upstream and Downstream of the Union Village Dam on the Ompompanoosuc River, Vermont, for All Sampling Dates, 2004, as Determined by the USGS NAQWA and EPA EMAP Methods. Sites not connected by the same letter are significantly different ($p < 0.001$). See text for description of each method.

Location	USGS	USEPA
White River	18.68 (4.67) A	28.32 (4.15) A
Ompompanoosuc River Upstream	19.76 (4.39) A	24.25 (3.78) A
Ompompanoosuc River Downstream	31.65 (4.94) B	48.11 (4.49) B

Furthermore, there is no evidence of a trend or significant difference between embeddedness measured at different sites on the White River when using the USGS or USEPA methods. Assuming that the White River and upstream Ompompanoosuc River embeddedness values are representative of typical values for unregulated streams, the length scale of dam impact can be estimated. Specifically, embeddedness values for the Ompompanoosuc River site furthest downstream of the dam that experiences no backwater effect (Site 1.1) are similar to the White River and upstream Ompompanoosuc River sites (Figure 3). In contrast, the average embeddedness values of all Ompompanoosuc River sites between the dam and Site 1.1 are significantly different from the average value of the White River or the average upstream value of the dam on the Ompompanoosuc River. These results suggest that the dam's effect on embeddedness does not extend beyond Site 1.1, located approximately 2.5 km downstream of the dam.

Seasonal Variations in Embeddedness

The USEPA method detects an interesting spatial trend in the seasonal variation of embeddedness that is not captured by any other method. Figure 4 (filled symbols) compares the USEPA measured embeddedness of the four sites directly below the dam on the Ompompanoosuc River at four different times of the year. The two furthest downstream sites (Sites 1 and 1.1) are not included in this analysis, as they are beyond the length scale of impact of the dam (see previous section). During May, the embeddedness values for all sites, except the first one immediately below the dam, are very similar (~60 percent; Figure 4a). In

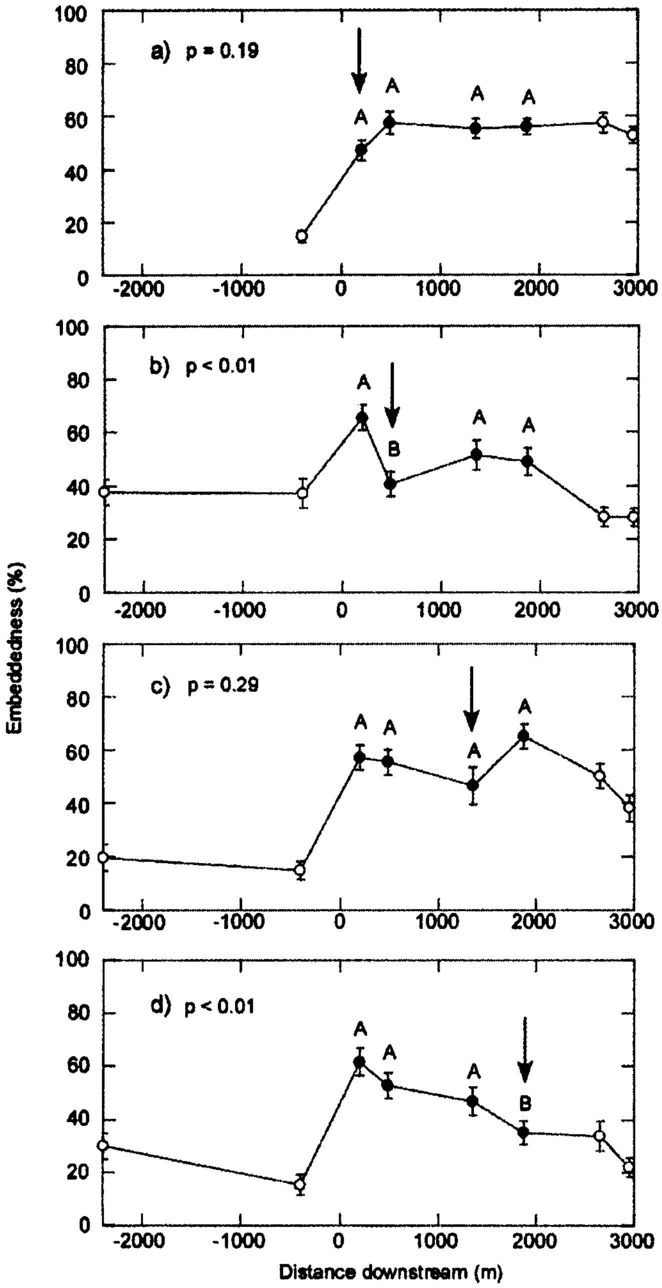

Figure 4. Embeddedness Values Upstream and Downstream of the Union Village Dam on the Ompompanoosuc River, Vermont, for the USEPA Method in (a) May, (b) July, (c) September, and (d) November 2004. Arrows indicate position of the low embeddedness region. P-values for each date are based on a one-way ANOVA between sites; sites not connected by the same letter are significantly different. A distance downstream of 0 m indicates the location of the dam. Negative values are distances upstream of the dam, while positive values are distances downstream of the dam. Error bars represent the standard error around the reach averaged mean. See text for description of the USEPA method.

contrast, the embeddedness at the first site is noticeably lower, although this decrease is not significant ($p = 0.19$). In July, the embeddedness at the site immediately below the dam has increased, while embeddedness at all the remaining sites has decreased (Figure 4b). However, the decrease at the second site downstream from the dam (at ~200 m) is noticeably larger than at the further downstream sites. In fact, the embeddedness at the second site in July (~40 percent) is both statistically lower ($p < 0.01$) than observed at the other three sites and similar to the embeddedness that was observed at the first site during May. This suggests that a region of low embeddedness first observed at the site below the dam in May translated downstream to the next site by July.

The translation of the low embeddedness region can be traced further downstream in the September and November measurements. In September, the embeddedness at all sites except the third downstream site is similar to that observed in May at the furthest downstream sites (~60 percent; Figure 4c). The embeddedness at the third site is similar to that found at the first site in May and the second site in July (~40 percent), although the difference between the third site and the other sites is not significant ($p = 0.29$). Finally, in November, the lowest embeddedness occurs at the fourth downstream site, which is significantly lower ($p < 0.01$) than the three upstream sites (Figure 4d). Thus, at each sampling date, the region of low embeddedness appears to translate one site downstream. From the position of low embeddedness at each sample date, the rate of translation is calculated as approximately 5 to 25 m/day.

The multifraction sediment transport model described above permits comparison of this translation rate to the predicted rate of movement of a particular grain size along the bed. The results from the transport modeling show that all particle size classes on the bed move at a rate similar to the rate of low-embeddedness translation (~1-19 m/day). Furthermore, the middle range of observed bed particle sizes (~16 to 181 mm) is mobilized at average rates consistently within the range of those calculated for the movement of the scour patch (~10 to 19 m/day).

DISCUSSION

Comparison of Methods

The Union Village Dam on the Ompompanoosuc River provides a fixed location of impact (Magilligan and Nislow, 2001; Salant *et al.*, 2006a) with which to assess the ability of each method to capture changes in embeddedness due to flow regulation. Our results indicate a large degree of variability among methods, which may be due to the subjectivity inherent to the visual methods used. This bias can affect the replication and accuracy of estimates, compared to more quantitative, objective techniques (Whitman *et al.*, 2003). Nevertheless, the results from the visual USEPA method appear to best reflect the expected change in embeddedness above and below the dam. The USEPA method is the only one that detects a significant increase in embeddedness below the dam, which is expected for several reasons. First, dam operation has reduced the magnitude of large flows that likely mobilized most of the sediment in the pre-dam period, but does not permanently trap sediment, therefore maintaining sediment supply. An oversupply of sediment relative to transport capacity should result in deposition (Nolan and Marron, 1995; Montgomery *et al.*, 1999) and thus increase embeddedness. Second, bed elevation data at the site directly below the dam show significant aggradation since dam construction (Salant et al., 2006a), a phenomenon closely linked to sediment deposition and greater embeddedness. Third, an independently calibrated two-fraction transport model predicts an increase in sand fraction downstream of the dam during the post-dam regime (Salant *et al.*, 2006b), a process that is likely to increase embeddedness. Finally, visual observations in the field clearly indicate that embeddedness is much greater below the dam. These reasons, as well as generally consistent results over time, suggest that the USEPA method best captures the variation in embeddedness on the Ompompanoosuc River. Although the downstream increase in embeddedness measured by the USGS method is not significant at $p < 0.01$, a p-level of 0.02 suggests, but cannot confirm, that the USGS method might also detect expected changes in embeddedness.

One factor that may help explain why the USGS and USEPA methods appear to perform best among the five methods is that both methods are the only ones that measure embeddedness along cross channel transects. Multiple cross channel transects capture both the lateral and longitudinal variability that exists between stream morphologies in a given reach. Thus, embeddedness measurements will not be biased by the characteristics specific to a particular morphology or area within the reach.

Translation of Low Embeddedness Region

Of all the methods considered here, only the USEPA method is able to detect the translation of the region of low embeddedness downstream of the dam during the study period. The failure of the USGS method to detect the localized scour may be due to the relatively long time required for the discoloration of partially buried sediment to appear or disappear. The translation of this region of low embeddedness is somewhat analogous to the concept of a sediment wave (Lisle *et al.*, 1997; Sutherland *et al.*, 2002), except that it reflects the movement of a region of sediment scour rather than a wave of sediment excess (Figure 4). Although the region of low embeddedness is not significantly lower for all sampling dates, this does not invalidate this interpretation of the data; it is highly probable that the timing and location of measurements did not always coincide with the center, or deepest portion, of the region of scour. Thus the sampling locations during May and September may have only captured the front or tail end of the scoured region as it passed through the reach, measuring embeddedness values that are only slightly less than adjacent sites.

Scour is associated with either an increase in transport capacity related to a change in flow pattern (i.e., an increase in flow depth) (Andrews, 1979; Howard and Dolan, 1981) or a decrease in upstream sediment supply (Howard and Dolan, 1981). Lower embeddedness immediately below the dam in May could be due to scouring flows associated with the opening of the dam gates and draining of the reservoir in April. The opening of the dam gates in late March provides the main source of sediment to this system, which is then transported downstream by large flows in April and early May. Initially, a large sediment supply leads to deposition downstream of the dam, but with time, this supply decreases as accumulated sediment is gradually flushed out of the system. Meanwhile, discharge and transport capacity remain relatively high while the reservoir continues to drain, eroding the deposited sediment and scouring the bed. A similar process was observed during the 1996 Grand Canyon flood experiment, where initial aggradation during peak flow was followed by scour prior to and during the receding limb of the flood; this scour was attributed to the depletion of upstream sediment supply (Topping *et al.*, 2000). Thus, scour on the Ompompanoosuc River following the initial flux of water and sediment from the dam may be due to a decrease in upstream sediment supply. Previous studies have used the volume of fine sediment in pools, as well as its inverse, the scoured residual pool volume, as an index of sediment supply (Lisle and Hilton, 1992, 1999). Similarly, we suggest that embeddedness may reflect changes in the upstream sediment supply.

It may appear contradictory to suggest that scour occurs in a river that has experienced significant aggradation since dam construction, as noted above. However, these two processes are not mutually exclusive because they occur on very different timescales. Aggradation following construction of the dam has occurred on decadal timescales, as shown by Salant *et al.* (2006a), due to reductions in the magnitude and frequency of high flows that moved most of the sediment in the pre-dam period. However, scour following the high flows when the dam gates are opened moves through the reach relatively quickly and is not linked to long-term changes in the balance between sediment supply and transport.

The calculated rate of translation (5 to 25 m/day) for the presumed scour patch is between those previously reported elsewhere for bedload sediment (0.3 to 4.5 m/day) (Beechie, 2001) and suspended sediment (150 to 600 m/day) (Bonniwell *et al.,* 1999). This rate is similar to, but slightly less than, the fine bed material velocities measured on the Ompompanoosuc River using fallout radionuclides (30 to 80 m/day) (Salant *et al.,* 2006b). The faster velocities measured using fallout radionuclides may reflect the preferential sorption of radionuclides to the finest – and generally fastest moving – bed particles. The multifraction sediment transport model predicts that all particle-size classes on the bed generally move at a rate similar to the rate of scour translation (~1 to 19 m/day) with the middle range of size classes moving at rates consistently within the range of the scour patch (~10 to 19 m/day). Although the modeled transport rates lend insight into sediment transport in this system, they are probably inaccurate for the smallest size classes because the particle size distribution does not accurately represent the smallest portion of the bed. Nonetheless, the results obtained from the model do suggest that tracking changes in embeddedness can provide insight into the transport of the intermediate grain sizes in this system.

Embeddedness and Dam Management

The results from the Ompompanoosuc River indicate that embeddedness provides one measure of the impact of flow regulation on streambed composition. The results presented above indicate a relatively short length scale of regulation impact. A similarly short length scale of impact has been found in previous studies (Collier, 2002), suggesting that increased flow from small downstream tributaries (Figure 1) may efficiently mediate the effect of the dam. To further demonstrate the utility of embeddedness measurements as an indicator of flow regulation impact, we apply the USEPA method to the regulated Black River to determine how differences in dam management affect embeddedness. On the Black River, reach-averaged embeddedness values for the USEPA method decrease slightly downstream of the dam relative to the upstream site, in contrast to a significant increase in average embeddedness for all sites downstream of the run-of-the-river Union Village Dam, excluding Sites 1.1 and 1 (Figure 5). No significant change in embeddedness is observed between the two upstream sites and two downstream sites on the unregulated White River. This slight decrease in embeddedness below the dam on the Black River is consistent with the idea that a reduction in sediment supply due to permanent storage dam management leads to a decrease in embeddedness, demonstrating that the USEPA method provides a fast, quantitative, and effective assessment of dam impact and the differences between management styles.

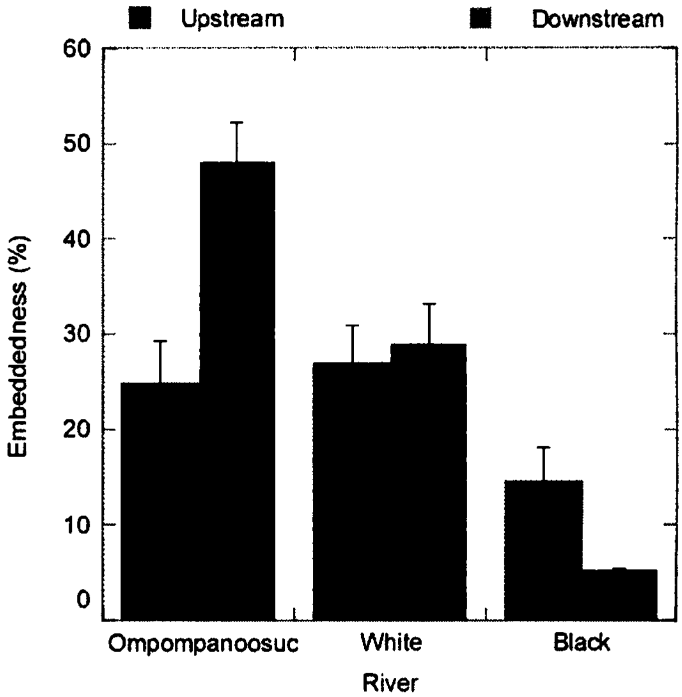

Figure 5. Average Embeddedness Values for the Sites Upstream and Directly Downstream of the Union Village and North Springfield Dams on the Ompompanoosuc and Black rivers, Respectively, and for Two Upstream and Two Downstream Sites on the White River, Vermont, as Determined Using the USEPA method. See text for description of the USEPA method. Error bars represent the standard error around the reach averaged mean.

CONCLUSION

Current methods for measuring embeddedness are often inconsistent and difficult to compare. The disparities between results acquired using the different methods make it difficult to distinguish trends and make comparisons across rivers and methods. Among the methods we used in this study, the USEPA method most effectively captures the expected impact of flow regulation on embeddedness in the Ompompanoosuc River.

Comparing embeddedness values between an unregulated and two differently managed regulated rivers suggests markedly different sediment regimes. Embeddedness is nearly constant along the unregulated river, but increases significantly downstream of the flood control/run-of-the-river dam on the Ompompanoosuc River, while decreasing downstream of the permanent storage dam on the Black River. These results indicate that dam management can have a measurable influence on bed composition.

Last, this work has important implications for broader aspects of channel management and restoration. For the past several decades, management agencies have collected an array of hydrologic and geomorphic data across a range of scales – from the habitat unit (e.g., pool frequency) to the cross section to the channel reach – to ascertain channel conditions and the effectiveness of management strategies. These agencies employ numerous protocols and methods such that a significant body of literature has emerged on assessing channel conditions and determining the best methods to measure channel characteristics (Juracek, 2000; Roper *et al.*, 2002). Protocols have evolved considerably over time through efforts to be both consistent and scientific (Montgomery and MacDonald, 2002). Results from this study suggest that certain measures of embeddedness may be best able to accurately represent sediment dynamics and correspond to sediment rates determined by independent, physically-based techniques. Furthermore, this study shows that embeddedness can differentiate regulated from unregulated conditions, as well as differences in dam management. Future research may be able to use embeddedness to evaluate anthropogenic effects other than dams that are less physically distinct and exist on other spatial or temporal scales.

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