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TESTING AND IMPROVING PREDICTIONS OF SCOUR AND FILL DEPTHS IN A NORTHERN CALIFORNIA COASTAL STREAM

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ABSTRACT

Seasonal scour and fill from bankfull flows were measured in Freshwater Creek, a gravel-bed coastal stream of northern California, to test a previously developed approach predicting the reach-average and distribution of scour or fill depths based on Shields stress and the exponential function. Predictions of reach-average scour and fill depths were within 4–60% of measured depths. Three of the four predicted distributions of scour and fill depths were statistically different ($p < 0.05$) from measured distributions. Differences between predicted and measured values were likely due to scour and fill patterns in Freshwater Creek that were influenced by sediment supply and location within the channel network, channel form roughness, and possibly multiple peak flows. Consequently, the predictive approach may be better suited for individual peak flows on straight reaches that are in equilibrium between sediment supply and transport, and with form roughness similar to the creeks where the approach was developed. Improved predictions of scour and fill are possible with adjustments for aggrading reaches and form roughness. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: scour; fill; prediction; Shields stress; exponential distribution; form roughness; local scour; aggradation

INTRODUCTION

The prediction of scour and fill depths in gravel-bed rivers is a growing interest among wildlife agencies and researchers as a potential tool to assess effects on aquatic life (e.g. Lapointe *et al.*, 2000; Railsback and Harvey, 2001) and in estimating sediment transport rates when combined with tracer particles (e.g. Haschenburger and Church, 1998). The distribution of scour and fill depths measured in gravel-bed rivers is generally right-skewed (negative exponential), where a small portion of the channel experiences deeper scour and fill relative to the majority of the channel (e.g. Montgomery *et al.*, 1996; Haschenburger, 1996, 1999; Rennie and Millar, 2000). Observed patterns of lateral scour and fill across the width of a channel range from high scour and fill near the thalweg (Yee, 1981) to random (Rennie and Millar, 2000). Where scour and fill are measured over long (10^3 m) or multiple (three or more) gravel-bed reaches, bed elevations of different subreaches often alternately aggrade, degrade, or remain stable (e.g. Hassan, 1990; Matthaei *et al.*, 1999).

While a basic understanding of scour and fill has evolved from previous studies, the physical factors influencing the process can vary. Some studies indicate a strong correlation between flow strength (or shear stress) and scour and fill depths (Carling, 1987; Wilcock *et al.*, 1996; Haschenburger, 1999), while others have found weak correlation with shear stress (Hales, 1999; DeVries, 2000) and suggest that scour and fill are controlled strongly by sediment supply and particle size (DeVries, 2000). Differences between scour and fill patterns observed in various studies are likely due to the location, cause, and magnitude of scour and fill observed, including (in order of increasing magnitude): (1) uniform entrainment of the armour layer (thickness = *c.* D_{90}) primarily from bedload movement (e.g. Wilcock *et al.*, 1996; DeVries, 2002); (2) scour and fill due to stage-dependent variations of shear stress in pools and riffles (e.g. Keller, 1971; Lisle, 1979); (3) localized scour and fill from flow over and around channel obstructions (e.g. Lisle, 1986; Rennie and Millar, 2000); (4) reach-scale bedload fluxes or gravel sheets that cause net aggradation or degradation over one or a few high flow events (e.g. DeVries *et al.*, 2002); (5) a

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progressive change in channel morphology, for example, resulting from channel avulsion, bank erosion, or movement of large wood (e.g. Lisle, 1989; Schuett-Hames *et al.*, 2000); and (6) large-scale aggradation or degradation (e.g. Griffiths, 1979; Madej and Ozaki, 1996).

A recent approach developed by Haschenburger (1999) appears promising for predicting both the reach-average and distribution of scour and fill depths at smaller magnitudes (i.e. magnitudes 1, 2, and possibly 3 outlined above) based on Shields stress and the exponential function, respectively. The objectives of this study were to test the predictive approach proposed by Haschenburger (1999) on a northern California coastal stream and provide potential improvements for such predictions.

SCOUR AND FILL DEPTH PREDICTION

Haschenburger (1999) developed an approach to predict reach-average scour or fill depths based on Shields stress (dimensionless shear stress), a parameter used to express the ratio of the tractive and gravitational forces acting on a representative bed particle:

$$\tau^* = \frac{\tau_0}{g(\rho_s - \rho_w)D_{50}} \tag{1}$$

where $\tau_0 = g\,\rho_w\,R\,S$ is the boundary shear stress ($N\,m^{-2}$), g is gravitational acceleration ($m\,s^{-2}$), ρ_w is the density of water ($kg\,m^{-3}$), R is the hydraulic radius (m), S is the water surface slope (over a length of 70 to 900 m in the primary study reaches used by Haschenburger, 1999), ρ_s is the density of sediment ($kg\,m^{-3}$), and D_{50} is the surface median particle size (m).

Based on the relation between Shields stress and reach-average scour and fill depths measured on gravel-bed streams (British Columbia, Canada and England), Haschenburger (1999) developed the following equation that can be used to estimate the reach-average scour or fill depths for peak flows to a first approximation (undefined) for similar streams (pool–riffle–bar and plane-bed channel morphology):

$$\theta = 3.33e^{-1.52\tau^*/\tau_r^*} \tag{2}$$

where $1/\theta$ is the predicted reach-average scour or fill depth (cm), τ^* is the measured Shields stress, and τ_r^* is the reference Shields stress for incipient grain entrainment (the threshold or critical Shields stress needed to initiate particle movement). A value of 0.045 is generally accepted as a good approximation of critical Shields stress in natural streams (Komar, 1988) and was used for τ_r^* by Haschenburger (1999) and in this study. Equation 2 was derived primarily from individual events over a range of flows. Equation 2 is hereafter referred to as the mean depth–Shields stress relation.

The distribution of scour or fill depths of the reach is then predicted by the exponential function:

$$f(x) = \theta e^{-\theta x} \tag{3}$$

where $f(x)$ equals the proportion of stream bed scour or fill to a given depth x (cm), and θ is the inverse of the reach-average scour or fill depth (cm). See Haschenburger (1999) for details on using this approach to predict the reach-average and distribution of scour and fill depths and development of the method. It should be noted that scour or fill distributions presented by Haschenburger (1999) and in this study are modified relative frequencies of binned data, where the relative bin frequency is divided by the bin interval (Olkin *et al.*, 1980).

METHODS

Study area

The study was conducted on two reaches of Freshwater Creek, a coastal stream just north of Eureka, California (Figure 1). The upper reach drains a 22.5 km^2 basin of managed redwood (*Sequoia sempervirens*) timberland,

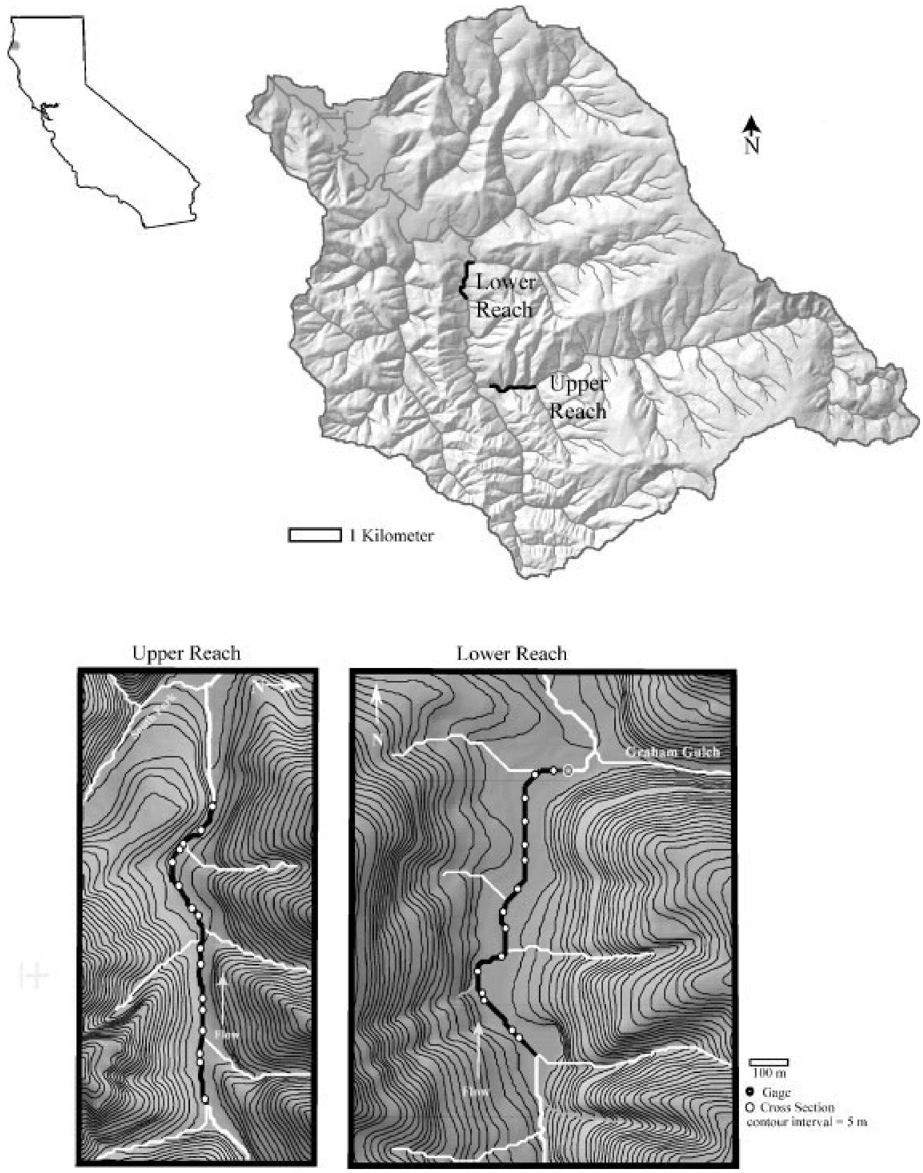


Figure 1. Freshwater Creek watershed and study reaches, gauge, and approximate cross-section locations

while the lower reach drains a basin of 34 km^2 and is in a rural residential area where the vegetation may have been historically dominated by redwood, but is now mostly red alder (*Alnus rubra*) and willow (*Salix lasiandra*). The Mediterranean climate of the area is characterized by high annual precipitation (150–200 cm) that falls primarily between October and April. The 840–900 m long study reaches are fourth-order single-thread gravel-bed streams that are moderately confined, low gradient (0.7–1.1%), and contain a combination of plane-bed, pool–riffle, and forced pool–riffle channel morphology (Montgomery and Buffington, 1997). Most of the lower reach is underlain by poorly consolidated sandstones and mudstones with some adjacent terrace deposits, while the upper reach is underlain by resistant sandstone with interbedded shales (Knudsen, 1993) and contains intermittent adjacent terraces. The most characteristic physical differences between the reaches are: (1) the higher amount of resistant bedrock, boulders, and large wood in the upper reach, resulting in more forced pool–riffle channel morphology; (2) the higher proportion of riparian deciduous trees and scarcity of large wood in the lower reach; and (3) the wider valley width of the lower reach (Figure 1). Table I summarizes the physical characteristics of the study reaches and

Table I. Summary of Freshwater Creek physical characteristics, sampling intensity, and measured and predicted scour and fill depths. Characteristics from primary study reaches (Carnation Creek) used to develop the predictive approach (Haschenburger, 1999) are included for comparison

Variable	Freshwater Creek		Carnation Creek	
	Upper reach	Lower reach	Reach 1	Reach 2
Reach length (m)	900	840	900	70
No. cross-sections	16	15	22	3
No. chains[a] recovered/installed	88/98	60/67	56–108/108	17–19/19
Drainage area (km^2)	22.5	34.1	11	11
Peak discharge (m^3/s)	17.1[b]	25.9	3.6–48.8[c]	3.6–48.8
Mean slope (%)	1.1	0.7	0.9	0.7
Mean width (m)	13	12	15	16
Surface D_{50} (mm)	33/45[d]	44/49[d]	47[d]	29[d]
Surface D_{90} (mm)	138	110		
Hydraulic radius (m)	0.76	1.07		
Shields stress[e] (τ_*)	0.14/0.10[d]	0.14/0.08[d]		
Grain Shields stress[f] (τ_{G*})	0.044	0.049		
Predicted mean depth $1/\theta$[g] (cm)	9.8	5.3		
Measured mean scour depth (cm)	10.6	6.0		
Measured mean fill depth (cm)	10.2	13.3		

[a] Carnation Creek study (Haschenburger, 1999) used scour monitors and scour chains.
[b] Upper reach discharge estimated by using discharge at lower reach (where the gauge is located) prorated by drainage area.
[c] Haschenburger (1999) measured scour and fill over a range of 15 different peak flow events.
[d] Value excludes particles <8 mm for predictions; in Freshwater Creek reaches, value to left of slash includes all particles.
[e] Calculated using a sediment density of 2800 kg m^{-3}, typical for metasedimentary and metamorphic rocks, which constitute the majority of the substrate in the upper and lower study reaches.
[f] Calculated using equations 2, 7, and 9 in Parker and Peterson (1980).
[g] Prediction parameter: $\theta = 3.33e^{-1.52\tau*/\tau r*}$; a value of 0.045 was used for τ_{r*} by Haschenburger (1999) and in this study and is generally accepted as a good approximation of critical Shields stress for incipient motion in natural streams (Komar, 1988).

includes characteristics of Carnation Creek for comparison, the primary study reaches used to develop the predictive approach (Haschenburger, 1999) being tested in this study.

Sampling design

Because scour and fill were measured at numerous locations, chains (Leopold *et al.*, 1964; Laronne *et al.*, 1994) were selected for ease of installation rather than sliding bead/wiffle ball scour monitors (Tripp and Poulin, 1986; Nawa and Frissell, 1993) and scour cores that require more time for installation. Chains yield similar results to monitors (Haschenburger, 1999) and cores of painted gravel (Hales, 1999).

Scour and fill were measured at random locations in both reaches. Scour chains were installed on two cross-sections randomly located within every 100 m section of the reach, totalling 31 cross-sections in the two study reaches (Figure 1). On each cross-section, chains were installed at 1.5 m intervals across the active width. In contrast to selecting idealized cross-section locations within a study reach (e.g. straight, avoiding channel complexity) commonly sought in many sediment transport studies, this sampling design ensures that cross-sections are randomly located but distributed over the whole reach with the goal of characterizing representative scour and fill of a reach.

Because recovery of scour chains is time intensive and can substantially loosen the bed (potentially affecting subsequent measurements), chains were only recovered once, at the end of the peak flow season. At each chain, maximum scour depth was determined by the difference between the pre- and post-flood season horizontal chain length, net fill was measured as the vertical distance above the elbow (approximately 90° bend; see Laronne *et al.*, 1994) in the chain to the post-flood season bed surface. All scour chains were installed by November 1999 (prior to peak flows) and recovered in July 2000 (after all peak flows).

In the 900 m upper reach (Figure 1), 88 of the 98 chains installed on 16 cross-sections were recovered. Minimum scour depths were inferred at three locations in a pool where chains scoured out entirely and minimum fill depths were inferred at three locations where extensive fill precluded recovery (total $n = 91$: 88 recovered chains plus 3 inferred scour and fill depths). In the 840 m lower reach (Figure 1), 60 of the 67 chains installed on 15 cross-sections were recovered. Five cross-sections in a 300 m stretch immediately below the lower reach could not be included in the study because extensive fill (>40 cm) prevented chain recovery at these cross-sections. Reach-average seasonal scour and fill were calculated using all 91 and 60 chain locations in the upper and lower reaches, respectively.

To relate observed patterns of scour and fill to generalized types of channel morphology (e.g. Schuett-Hames *et al.*, 2000), the area of each scour chain was identified at low flow as: (1) *bars* that were storage areas of gravel or larger substrate; (2) *pools* that had a scoured pool head, definitive tailout at the bottom of the pool (narrow riffle), flat unbroken water surface, and a residual depth greater than 0.5 m; (3) *riffles* that had a dominant particle size of gravel or larger, turbulent broken water surface, and shallow water depths less than 0.5 m; or (4) *plane-bed* areas that had a relatively flat planform channel bed, homogeneous substrate, unbroken water surface, and residual depths less than 0.5 m.

Shields stress parameters

Reach-average Shields stress parameters (mean water depth, water surface slope, median particle size) for the peak flow were measured to predict the reach-average and distribution of scour and fill depths using the mean depth–Shields stress relation (Equation 2) and the exponential function (Equation 3), respectively. Stream discharge was continuously recorded at a gauging station at the bottom of the lower reach (Salmon Forever, 2001) (Figure 1). Cross-sections with flood marks (leaf litter) were surveyed at the end of the peak flow season with an auto level and stadia rod using standard techniques (e.g. Benson and Dalrymple, 1967; Harrelson *et al.*, 1994) to determine the mean water depth and water surface slope for the peak flow. Only flood marks that were flagged within one to two days of peak flows were considered reliable and included in the mean depth and slope calculation. Surface median grain size was determined from surface pebble counts (Wolman, 1954) performed at each cross-section and combined to estimate a reach average. At least 100 particles were measured at each cross-section. Particles less than 8 mm were excluded from the median particle size analysis to be consistent with methods used by Haschenburger (1999) as detailed in her dissertation (Haschenburger, 1996).

Analysis

To test the accuracy of predicting the reach-scale distribution of scour and fill depths (using measured Shields stress, the mean depth–Shields stress relation, and the exponential function), measured and predicted distributions were compared using a Cramér–von Mises (CvM) goodness-of-fit test (W^2 test statistic, Spinelli and Stephens, 1997). This test was selected because it weights differences by the predicted proportion of a group (bin) rather than weighting differences between groups equally (e.g. chi-squared test). Haschenburger (1999) used a CvM method (A^2 test statistic; Spinelli, 2001) that tests the fit between the measured distribution and the exponential function that best fits the measured distribution (derived using maximum likelihood estimators), and therefore could not be used in this study since the objective was to directly test the fit between predicted and measured distributions.

To determine if there were differences in scour and fill depths between types of channel morphology, measured depths were compared using a one-way analysis of variance (ANOVA) with a pair-wise comparison using the Tukey method. Comparisons for all statistical tests were considered different at a significance level (p-value) of 0.05.

RESULTS

Study flows

Three peak flows occurred during the study period. The largest flow recorded during the study was 25.9 m^3/s on 11 January 2000, followed by flows of similar magnitude on 14 January (25.2 m^3/s) and 14 February (23.2 m^3/s) (Figure 2). Flood marks from the flows were above bankfull indicators (i.e. break in bank slope, base of perennial

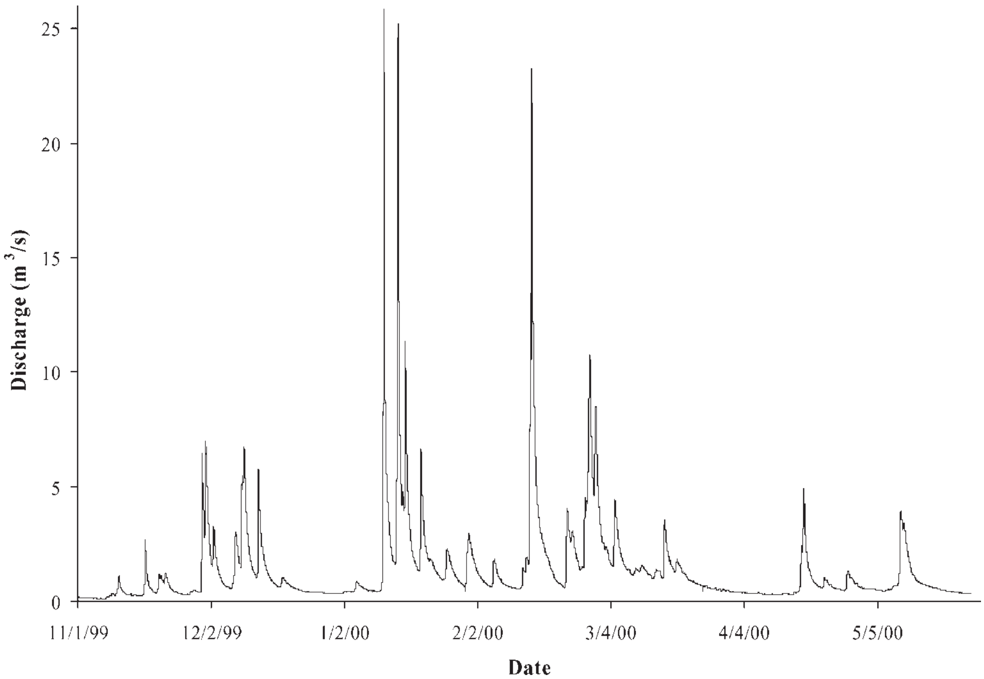


Figure 2. Discharge in Freshwater Creek from 1 November 1999 to 30 May 2000, recorded at the Salmon Forever (2001) gauge at the bottom of the lower reach

vegetation). Based on a 19-year record for an adjacent basin and prorated by drainage area (see Bigelow, 2003), the estimated recurrence intervals for these flows are roughly 1.2 to 1.3 years, within the estimated range of recurrence intervals for regional bankfull flows (Rosgen and Kurtz, 2000).

Reach scour and fill

Upper reach. Table I includes the measured Shields stress (i.e. prediction input), reach-average scour and fill depth predictions based on the measured Shields stress and the mean depth–Shields stress relation (Equation 2), and the measured reach-average scour and fill depths for both reaches. The predicted reach-average scour and fill depths (9.8 cm) were within 8 to 4% of the measured reach-average scour (10.6 cm) and fill (10.2 cm) depths ($n = 91$), respectively. The distribution of scour depths measured in the upper reach was right-skewed and approximated a negative exponential form, while the distribution of fill depths was less skewed (Figure 3). The predicted distribution (using measured Shields stress, the mean depth–Shields stress relation, and the exponential function) was statistically similar to the measured distribution of scour depths (CvM goodness of fit test, $p > 0.25$, $W^2 = 0.046$), but was statistically different from the measured distribution of fill depths ($p < 0.005$, $W^2 = 0.32$).

To potentially explain differences between predicted and measured scour and fill distributions and improve predictions, it is worthwhile to evaluate patterns at cross-sections and in different types of channel morphology. By averaging the net elevation change recorded at each chain, the average change in streambed elevation was calculated for each cross-section. In Figure 4, the average streambed elevation change is plotted against reach distance and slope (long profile) to observe net scour or fill patterns over the reach. In the upper reach, eight cross-sections experienced small amounts of net fill (average +4.0 cm) and seven cross-sections experienced shallow net scour (average −2.7 cm), with an overall reach-average bed elevation change of +0.9 cm (Figure 4A).

The distribution of types of channel morphology (see Methods section) within the upper reach consisted primarily of bars (49%), followed by riffles (21%), pools (19%), and plane-bed areas (11%) (Figure 5A). Scour depths were statistically deeper in pools than plane-bed and bar areas ($p < 0.05$, one-way ANOVA with Tukey's pairwise comparison), while fill was statistically deeper in pools than plane-bed areas ($p < 0.05$) (Figure 5B).

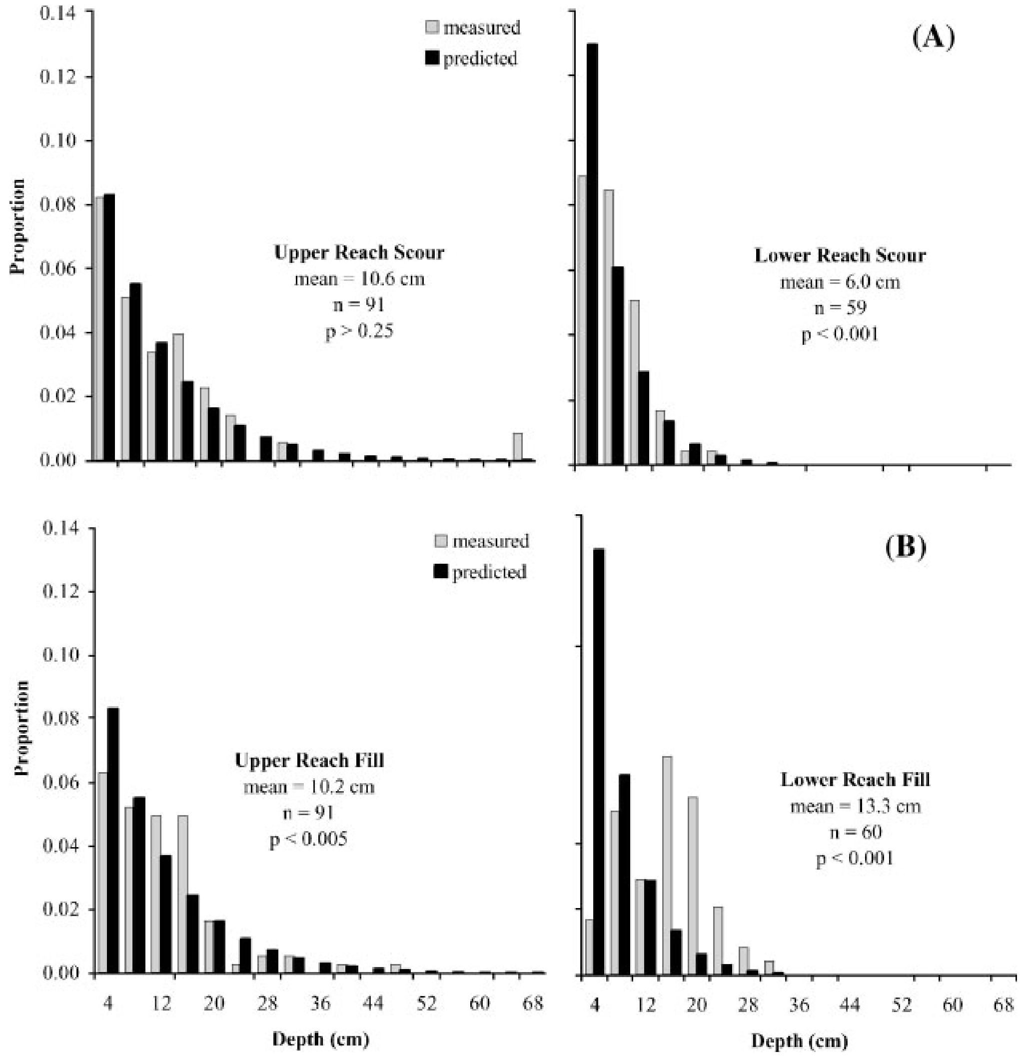
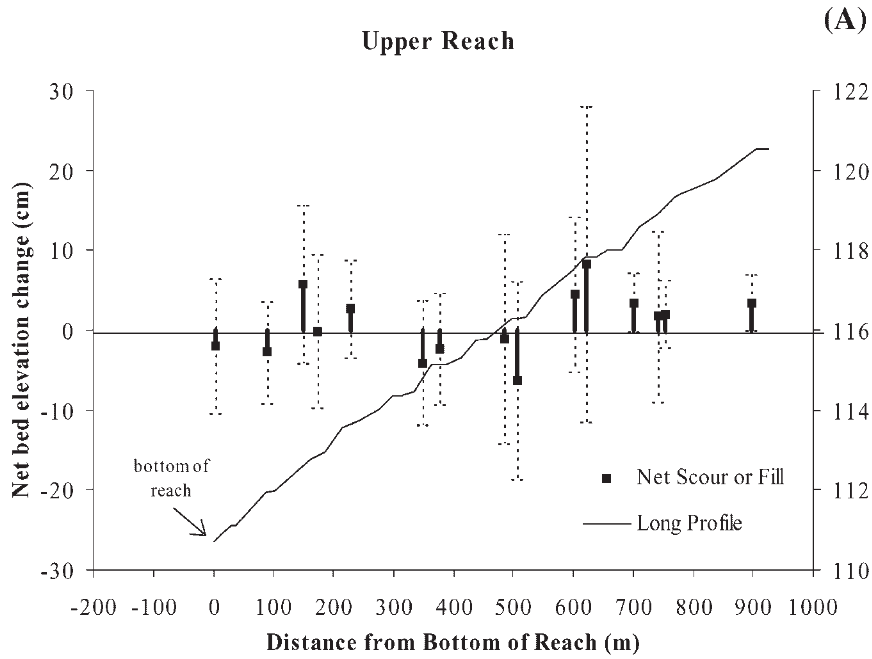


Figure 3. Modified relative frequency histograms of predicted and measured (A) scour, and (B) fill depths for the upper and lower reach. Goodness of fit between measured and predicted distributions is indicated by *p*-values. Histograms are modified by dividing the relative frequency of each bin by the bin interval (Olkin *et al.*, 1980)

Lower reach. The predicted mean scour and fill depth (5.3 cm) was within 12% of the measured mean scour depth (6.0 cm), but underestimated the measured mean fill depth (13.3 cm) by 60%. The distribution of measured scour depths in the lower reach ($n = 60$) was right-skewed, while the distribution of fill was less skewed and approximated a normal distribution (Figure 3). The predicted distributions were statistically different from the measured distributions of scour ($p < 0.001$, $W^2 = 1.0$) and fill ($p < 0.001$, $W^2 = 6.6$).

As indicated by a measured reach-average fill depth that was over twice the reach-average scour depth, sediment supply to the lower reach was greater than sediment transport out of the reach, resulting in net fill at 13 of the 15 cross-sections (average +7.2 cm) (Figure 4B). The aggradation is due to sediment supply from above the reach, as substantial local sediment supply from bank erosion or streamside landslides was not apparent within the lower reach.

In contrast to the bar-dominated upper reach, the distribution of channel morphology in the lower reach consisted primarily of riffles (42%), followed by plane-bed areas (34%), and bars (24%) (Figure 5A). Pools were conspicuously absent from the random sample of channel locations. The range of scour or fill depths in each type of



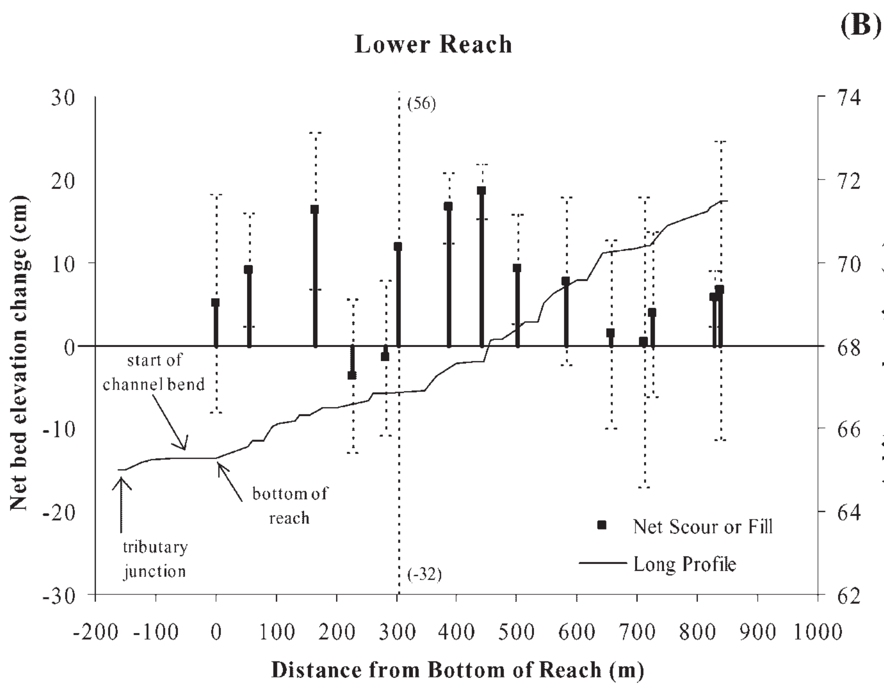


Figure 4. Average streambed elevation change at each cross-section (left y-axis) and low flow water surface profile (right y-axis) for the (A) upper and (B) lower reach. Bed elevation change is based on an average of six and four scour chains per cross-section on the upper and lower reaches, respectively. Dashed line is 95% confidence interval; 95% confidence interval for sixth cross-section from bottom in lower reach shown in parentheses to maintain a useful vertical scale

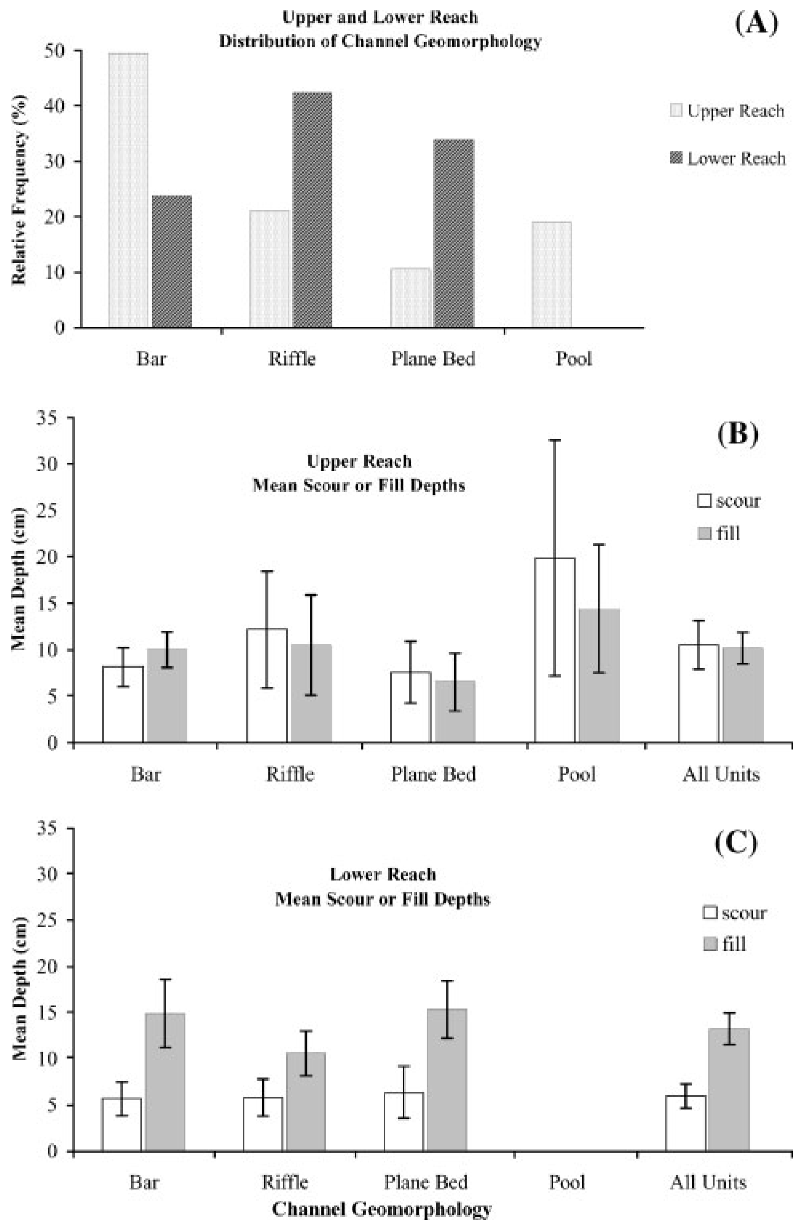


Figure 5. (A) Distribution of channel geomorphology in both reaches, and mean scour or fill depths (and 95% confidence interval) within each type of geomorphology in the (B) upper reach and (C) lower reach

channel morphology was fairly uniform. Scour and fill depths were statistically similar between all types of channel morphology (bars, riffles, and plane-bed) with the exception that fill depths were deeper in plane-bed areas than riffles ($p < 0.05$, one-way ANOVA with Tukey's pairwise comparison) (Figure 5C).

DISCUSSION

Scour and fill patterns

A closer look at the difference in scour and fill patterns between the two reaches helps clarify limitations and reveal potential improvements for predicting scour and fill. The right-skewed distribution of scour depths in both reaches (Figure 3A) is consistent with other studies (Montgomery *et al.*, 1996; Haschenburger, 1999; Rennie and Millar, 2000). The right-skewed distribution of scour depths reflects that the majority of streambed was scoured to shallow depths during the peak flows, while a small portion of the channel scoured relatively deeply (e.g. Haschenburger, 1996). In contrast, the distribution of fill depths in the lower reach was more symmetric, crudely approximating a normal or lognormal distribution (Figure 3B). Distributions of scour are often skewed because only a narrow zone of the channel is scoured deeply (e.g. thalweg or portion of a bar), while fill distributions are more symmetric and less skewed because fill is deposited more uniformly across the channel (e.g. filling depressions), particularly during bedload pulses or sheets causing aggradation of a reach.

The differences in channel morphology and resulting scour and fill patterns between the upper and lower reaches are also striking. The complex bar-dominated upper reach experienced more localized deep scour and fill at channel obstructions (large wood, boulders, bedrock) resulting in more forced pools. Conversely, the uniform riffle- and plane-bed-dominated channel of the lower reach with few channel obstructions experienced fairly uniform and shallower scour depths resulting in a conspicuous absence of pools (in the areas randomly sampled) (Figures 3 and 5). Similar influences of channel morphology and obstructions on scour and fill patterns have also been observed by others (Schuett-Hames *et al.*, 2000).

The most noticeable difference in the observed scour and fill patterns between the two reaches was the aggradation in the lower reach, where the mean fill depth (13.3 cm) was over twice the mean scour depth (6.0 cm) due to increased sediment supply and location of the reach within the channel network. Sediment supply to the lower reach was much higher relative to the upper reach. Further, net fill increased downstream in the lower reach (Figure 4B) with proximity to a major entrenched channel bend (approximately 180°, where bedrock is exposed along the outside bend) and the Graham Gulch tributary junction (Figure 1). The entrenched meander bend and tributary junction are a knick point in the channel (defined as any abrupt change in the longitudinal profile; American Geological Institute, 1984) that created a backwater effect and associated sediment deposition (Figure 4B). The magnitude of this effect is further underscored considering that five cross-sections below the lower reach could not be included in the study due to extensive fill that prevented chain recovery (see Methods section). Similar sediment deposition has been observed by others at channel bends (e.g. Lisle, 1986; Matthaei *et al.*, 1999) and tributary junctions (e.g. Benda *et al.*, 2003, 2004a).

Sources of differences between predicted and measured depths

Differences between predicted and measured scour and fill in Freshwater Creek (Figures 3, 4 and 5) were influenced by (1) sediment supply and location within the channel network (proximity to major entrenched channel bend and tributary junction), (2) form roughness from different channel morphology as well as large wood, boulders and bedrock outcrops, and possibly (3) a series of peak flows rather than a single event. These differences are described below along with potential modifiers for improved predictions of scour and fill.

Sediment supply. Both reaches of Freshwater Creek show imbalances in sediment supply and transport, which is especially evident in the substantial aggradation of the lower reach (Figure 4). However, equivalent scour and fill depths are predicted using the mean depth–Shields stress relation, in part, because the relation was developed primarily from streams with relatively stable bed elevations (Haschenburger, 1999) and may not be applicable to streams with fluctuating bed elevations. This potential limitation was noted by Haschenburger (1999) cautioning that; ‘scour distributions that incorporate localized net change related to significant adjustments of bed morphology were not fitted by the exponential function . . . ’.

To improve predictions in reaches affected by sediment supply, the net mass sediment balance of a reach (aggrading, degrading, equilibrium) could be incorporated. Since sediment supply is a stochastic and largely unpredictable process, empirical observations would be necessary. For example, observations could include measuring sediment transport at the top and bottom of a reach, or more simply by surveying a set of cross-sections before and after the period of interest. The influences of reach location within the network could also be evaluated, where reaches upstream of a major channel knick point, such as a tributary fan or entrenched channel bend, may tend to aggrade if sediment supply is high.

If the channel is indeed aggrading, the reach-average and distribution of scour and fill depths predicted using the mean depth–Shields stress relation and the exponential function can be adjusted for the increased sediment load.

Based on the measured reach-average fill depth in the aggrading lower reach of Freshwater Creek that was roughly twice the predicted value (Table I), increasing the predicted fill depth by a factor of two (i.e. fill depth will be twice that predicted by the mean depth–Shields stress relation), improves the approximation to within 25% of the measured value (formerly within 60%). The site-specific factor by which to adjust predictions of fill depths would depend on empirical observations. Empirical observations of aggradation diminish the usefulness of a 'predictive' approach. However, the addition of a few scour chains or cross-sections prior to a period of interest is nominal relative to the primary measurements necessary for the predictions (surveys of water surface slope, cross-sections, and particle size). Areas upstream of tributary junctions, major channel bends, and other knick points prone to aggradation could also be avoided; however, such areas often have high physical diversity (Benda *et al.*, 2003, 2004a) and associated biological diversity and productivity (Rice *et al.*, 2001; Benda *et al.*, 2004b).

As indicated by measured fill depths in the lower reach, aggrading reaches may have a less skewed distribution of fill depths. Consequently, using a normal (or lognormal) probability distribution function may provide a better approximation of fill depths in aggrading reaches:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} \mathrm{e}^{-(x-\mu)^2/2\sigma^2} \tag{4}$$

where $f(x)$ equals the proportion of stream bed scour or fill to a given depth x (cm), μ is the predicted reach-average fill depth (cm) (as adjusted for aggradation described above), and σ is the standard deviation (cm) that can be estimated *a priori* by $\sigma = \mu/5$, based on properties of a normal probability distribution function where 99% of the population is within 2.5 standard deviations of the mean. In the aggrading lower reach, using the normal probability distribution function provides a better fit (CvM test statistic $W^2 = 0.36$) of the distribution of fill depths than the exponential function ($W^2 = 6.6$). Although the predicted and measured distributions are still statistically different ($p = 0.001$), over half the difference is derived from one bin in particular (12 cm bin, Figure 6), where differences are weighted by the predicted proportion of a given bin (see methods section).

Channel form roughness. The predictive approach (Haschenburger, 1999) is based on Shields stress that includes force exerted on bed particles as well as channel form roughness elements such as banks, bars, bends,

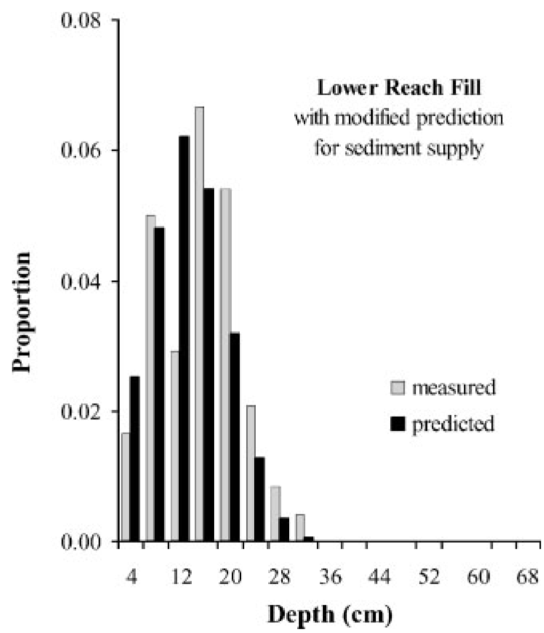


Figure 6. Modified relative frequency histogram of measured fill depths for the lower reach and predicted depths using a normal probability distribution function. Histogram is modified by dividing the relative frequency of each bin by the bin interval (Olkin *et al.*, 1980)

bedrock outcrops, large boulders, large wood, and riparian vegetation. Consequently, the Shields stress exerted only on bed particles can vary greatly between gravel-bed streams depending on channel form roughness.

The predictive approach was developed from scour and fill data collected from cross-sections on relatively straight subreaches with pool–riffle–bar and plane bed morphology in Carnation Creek (British Columbia, Canada) and flat areas in Great Eggleshope Beck (England) (Haschenburger, 1999), often excluding localized effects on scour and fill from channel bends and large wood (see Haschenburger, 1996) which can be substantial (e.g. Matthaei *et al.*, 1999; Rennie and Millar, 2000; Schuett-Hames *et al.*, 2000; DeVries *et al.*, 2002). Cross-sections on Freshwater Creek were randomly selected and reflect both scour and fill from localized obstructions as well as unobstructed bedload transport. Differences in form roughness between Freshwater Creek and Carnation Creek are another likely source for the differences in the measured and predicted scour and fill distributions. Consequently, the predictive approach without site-specific adjustments may only be applicable to sites with similar form roughness to areas sampled in Carnation Creek and Great Eggleshope Beck.

Improved predictions for channels with different form roughness may be possible by considering both Shields stress exerted only on bed particles and form roughness that causes localized scour and fill. Parker and Peterson (1980) developed an equation to partition Shields stress applied to the bed (Shields grain stress τ_G^*) and form roughness that was primarily from bars in their study reaches. The reach-average Shields grain stress in Freshwater Creek was roughly estimated using equations 2, 7, and 9 detailed in Parker and Peterson (1980), with inputs of channel and flow characteristics in Table I, and back calculations of water velocity using WinXSPro (US Forest Service, 1997) with Jarrett's equation to calculate roughness (Jarrett, 1984). The estimated reach-average Shields grain stress was 0.044 in the upper reach and 0.049 in the lower reach, approximately half of the estimated total Shields stress (Table I). However, form roughness in the upper reach was primarily from large wood, bars and boulders that produced deeper localized scour and fill depths, while form roughness in the lower reach was primarily from an encroaching deciduous riparian thicket that did not cause deeper localized scour and fill depths. Consequently, to apply a scour and fill model between different channels, some evaluation of the effect of form roughness on scour and fill may be necessary (i.e. whether it creates deeper localized scour and fill or not).

Approaches to accomplish this could include complex partitioning of form roughness (e.g. Einstein and Banks, 1950; Manga and Kirchner, 2000) or modelling local variation in Shields stress (e.g. Lisle *et al.*, 2000). A simpler approach might include modifying the predicted distribution of scour and fill depths based on the distribution of the reach channel morphology that can reflect deeper localized scour and fill from form roughness. For example, in the upper reach of Freshwater Creek, localized scour and fill at channel obstructions such as boulders and large wood generally created forced pools, and pools constituted a portion (19%) of the reach area. The scour and fill depths in pools were statistically deeper than other channel morphology in the upper reach, where scour and fill depths in pools were nearly twice the reach average (Figure 5). The predicted distribution can be adjusted for deeper localized scour and fill in pools by assigning 19% of the distribution with twice the predicted value using the mean depth–Shields stress relation (i.e. two times Equation 2) and the exponential function and combining it with 81% of the unadjusted predicted distribution. This adjustment does not alter the statistical fit between predicted and measured scour depths, but does improve the fit to measured fill depths slightly (CvM test statistic $W^2 = 0.21$, $p = 0.025$; formerly $W^2 = 0.32$, $p < 0.005$). While the predicted distribution is still statistically different from the measured distribution, the approach indicates that predictions can be improved by considering effects of form roughness on scour and fill distributions. The specific proportion of the distribution to adjust will depend on the site-specific distribution of channel morphology (e.g. the proportion of channel consisting of pools) and while a factor of 2 observed in this study does not appear unreasonable to apply to deeper scour and fill for pools in general, site-specific empirical observations will improve accuracy of predictions. Again, while a few empirical observations of differences in scour and fill between types of channel morphology diminish the usefulness of a 'predictive' approach, it is a small effort relative to the primary surveys needed to calculate Shields stress for the predictions.

Individual and multiple peak flows. It was not possible to recover chain data after each peak flow event in Freshwater Creek, consequently the chain data were only recovered at the end of the high flow season that included three peak flow events of similar magnitude (Figure 2). The predictive approach (Haschenburger, 1999) was developed from scour and fill measured primarily for individual peak flows and may not be applicable to scour and fill over multiple events (J. Haschenburger, personal communication, 2001). Although the effect of multiple peak flows on Freshwater Creek was not evaluated, the exponential function still appears to be the best available function to describe the distribution of seasonal scour and fill depths for a series of peak flows. In some cases, the distribution of fill depths may be better approximated by a normal probability distribution function, such as aggrading reaches.

CONCLUSIONS

In Freshwater Creek, the predicted reach-average scour depths were within 8 to 12% of measured values and predicted fill depths were within 4 to 60% of the measured values. In addition, three of the four predicted distributions of scour and fill were statistically different from the measured distributions. Based on the accuracy of the predictions in Freshwater Creek and the scour and fill patterns observed, the relation between Shields stress and scour and fill depths appears most reasonable under ideal conditions. The relations become weaker when complexity is imposed in the form of increased sediment supply, channel knick points (e.g. entrenched meander bends, tributary junctions) that causes sediment deposition, and channel form roughness that causes localized deeper scour and fill. In summary, differences between predicted and measured values of scour and fill in Freshwater Creek were influenced by sediment supply and location within the channel network, channel form roughness, and possibly multiple peak flows. Accordingly, the tested predictive approach may be better suited for individual peak flows on reaches that are straight, in equilibrium between sediment supply and transport, and have form roughness similar to the creeks where the approach was developed. Simple adjustments are proposed to compensate for increased sediment supply and channel form roughness that improve predictions slightly (e.g. predictions formerly within 60% of measured mean fill depths and improved to within 25% in aggrading reaches). Further improvements to channel scour and fill depth predictions are possible given consideration of fluvial geomorphic complexity.

Finally, results of this study provide some bounds on the approximation of predictions for end users such as watershed managers (i.e. within 4 to 25% of mean depths, approximate distributions but often statistically different). Watershed analyses often evaluate the effect of land management on peak flows (e.g. Washington Department of Natural Resources, 1997) and the predictive approach provides a ‘coarse’ tool (as defined above) to estimate the effect of increased peak flows from land management on aquatic life that utilizes stream substrate, such as incubating salmon embryos or aquatic insects.

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