# PREDICTABILITY OF BEDLOAD RATING AND FLOW COMPETENCE CURVES FROM BED ARMORING, STREAM WIDTH AND BASIN AREA

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**Abstract:** In mountain gravel- and cobble-bed streams, relationships between discharge, bedload transport rates and the largest bedload particle size are typically not well predictable from bedload transport or shear stress equations. This study explored the prediction of gravel transport rates and particle sizes from watershed and streambed characteristics. Exponents and coefficients of the rating and flow competence curves obtained from bedload trap samples were significantly correlated to easily measurable parameters such as stream width, basin area size and the area-gradient product. High correlations indicating good predictability were obtained from the degree of bed armoring.

## INTRODUCTION

Prediction of the bedload transport – discharge relationship in mountain gravel- and cobble bed streams is problematic. Transport rates for specified flows are typically predicted from a bedload transport equation that is applied to measured cross-sectionally averaged flow hydraulics (e.g., mean flow depth) and local bed material size. However, for coarse-bedded mountain streams, predictions from different bedload equations commonly vary by orders of magnitude, and only rarely do modeled results match measured gravel transport rates with satisfactory accuracy (e.g., Bathurst et al. 1987; Gomez and Church 1989; Weinhold 2001; Bravo-Espinosa et al. 2004; Barry et al. 2004). A similar problem exists with the prediction of flow competence, i.e., the largest bedload particle size transported at a specified flow. Shear stress or dimensionless critical shear stress equations often do not predict critical flow for the onset of motion of a specified particle size with sufficient accuracy. Given this, one may reasonably ask whether relationships of bedload transport and flow competence with flow can be predicted using a different approach.

Our field data measured in several mountain streams suggested that bedload rating and flow competence curves in mountain streams vary with parameters that scale streambed and stream size. This led us to pursue an approach that predicts bedload rating and flow competence curves from these characteristics. Observations and suggestions regarding the variability of bedload rating curves in streams of different sediment sizes, geological conditions, sediment supply, armoring, and channel gradient are also beginning to emerge from other sources (e.g., Barry et al. 2004; Ryan et al. 2002, 2005; as well as in several contributions to the 2005 Gravel-Bed Rivers Meeting (e.g., Hassan et al.; Diplas; and Lisle).

## METHODS

**Field procedures:** Over the past 8 years, we have measured 10 data sets of bedload transport rates and flow competence by intensive sampling of gravel bedload over the snowmelt runoff season at 9 study sites in 8 Rocky Mountain gravel- and cobble-bedded streams. All streams were relatively undisturbed and had step-pool, cascade, plane-bed and pool-riffle morphologies. Basin area sizes ranged from 8 to 105 $km^2$, channel gradients from 1 to 9%, bankfull flows from 0.8 to 6.2 $m^3/s$, bankfull widths from 3.7 to 15 m, bed material surface $D_{50}$ particle sizes from 45 to 108 mm, and subsurface $D_{50s}$ sizes from 26 to 42 mm. The streams were typically incised, such that flows of 1.5 times bankfull caused very little overbank flooding. Samples were collected using bedload traps and a similarly designed large net-frame sampler. Bedload traps consist of an aluminum frame 0.3 by 0.2 m in size that is fastened onto a ground plate that is anchored to the stream bottom. Bedload is collected in a 0.9-1.6 m long net with a 3.5 mm mesh width. Four to six bedload traps are typically installed across the stream spaced 1-2 m apart (Bunte et al. 2003, 2004, 2005) (Figure 1). The net-frame sampler has a 1.5 by 0.3 m opening to which a 3 m long net with a 1 cm mesh width is attached (Bunte 1996) (Figure 2). Both samplers have large openings and a large sampler capacity that permits sampling over a long duration (typically 1 hr).

Figure 1 Bedload traps installed in a stream

Figure 2: Net-frame sampler installed

Power function regressions were fitted to the relationships between measured gravel transport rates ($Q_B$, in g/s) and discharge ($Q$, in $m^3/s$) as well as to the relationships between the largest measured bedload particle sizes ($D_{max}$, in mm) and discharge. This yielded bedload rating curves and flow competence curves in the form of

$$Q_B = a \cdot Q^b \quad \text{and} \quad D_{max} = f \cdot Q^g$$

Exponents ($b$ and $g$) indicate the curve steepness. Steeper curves have a higher rate of increase in transport rates or in the $D_{max}$ particle size with flow. Coefficients ($a$ and $f$) indicate the vertical position of the curves and thus the magnitude of transport or the size of $D_{max}$ particles. Bedload rating curves fitted to transport rates obtained from bedload trap samples were generally steep with exponents of 8 to18. Flow competence curves had exponents of 1.5 to 4.3. All rating curves used in this study were well established, with $r^2$-values of 0.49 to 0.90 and a mean of 0.77. Flow competence curves were likewise well established ($0.40 < r^2 < 0.90$, mean $r^2 = 0.65$).

**Regression analyzes:** Exponents and coefficients of the bedload rating curves ($b$ and $a$) and flow competence curves ($g$ and $f$) established for the 10 data sets were regressed against several watershed and streambed parameters that included: basin area size ($A$, from maps), bankfull stream width ($w_{bkf}$, field measured), stream gradient ($S$, field survey), bankfull flow ($Q_{bkf}$, field determined or from 1.5-year recurrence interval flood), bankfull stream power (simplified to $Q_{bkf}$

$\cdot S$), median surface bed material size ($D_{50}$, reach-spanning pebble count exceeding 400 particles), surface bed material sorting (Inman sorting coefficient $\sigma_I = |\phi_{16}-\phi_{84}|/2$), median subsurface bed material size ($D_{50s}$, several volumetric samples with a mass exceeding 10 times the mass of the sample $D_{max}$ particle, typically 150-200 kg), the percent sand and fines in the subsurface sediment (from volumetric samples) and the degree of bed armoring (ratio of surface $D_{50}$ to subsurface $D_{50s}$ size). Power function regressions in the form of $b = \alpha_1 \cdot X^{\beta 1}$, $a = \alpha_2 \cdot X^{\beta 2}$, $f = \alpha_3 \cdot X^{\beta 3}$, and $g = \alpha_4 \cdot X^{\beta 4}$ generally obtained the best fit (where $X$ denotes a watershed or streambed parameter, and $\alpha$ and $\beta$ are the coefficients and exponents of the fitted functions).

## RESULTS

Results from our study showed that exponents and coefficient of the rating and flow competence curves where significantly and in some cases very well correlated to parameters describing the bed material and the stream size. Exponents decreased with the degree of bed armoring, percent sand and fines in the subsurface sediment, surface bed material sorting coefficient, $D_{50}$ surface and $D_{50s}$ subsurface bed material size, and stream gradient. Exponents increased with bankfull stream width, basin area, bankfull stream power, as well as bankfull flow. Since exponents and coefficients of bedload rating and flow competence curves are inversely related, stream parameters that have positive relationships with the exponents have negative ones with the coefficients and vice versa. Exponents and coefficients had only weak relationships with stream gradient, the $D_{50}$ surface and $D_{50s}$ subsurface bed material sizes, and the surface bed material sorting coefficient.

**Exponents of bedload transport rating and flow competence curves:** Exponents of bedload transport rating and flow competence curves were found to be highly correlated to the degree of bed armoring (Table 1) (Figure 3). Both, bedload rating and flow competence curves were less steep in more heavily armored streams. The matching trends of the bedload rating and flow competence curves, and the well defined negative functions (with $r^2$-values of 0.91 and 0.82, and p-values of 0.0001 and 0.005, respectively) with bed armoring are not unexpected when one considers that the degree of armoring is a direct result of the interaction between flow and bedload transport. Streams that are lightly or not armored (i.e., $D_{50}/D_{50s} \approx 1$) transport particle size-distributions that are similar to the subsurface bed material size-distribution near bankfull flow (Lisle 1995), while heavily armored streams (i.e., $D_{50}/D_{50\ sub} \geq 2$) transport bedload that is

Table 1 Regression parameters α and β and the $r^2$-value for relationships between exponents of the bedload rating and flow competence curves and parameters describing the streambed and stream size. $r^2$-values > 0.80 are printed in bold, and those between 0.50 and 0.80 in bold italics.

| | Exponents ***b*** of bedload transport rating curve | | | | Exponents ***g*** of flow competence curve | | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | α | β | r² | p-value | α | β | r² | p-value |
| $D_{50}$ surface/$D_{50}$ subsurf. [-] | 30.2 | -1.89 | **0.91** | 0.00097 | 7.34 | -2.10 | **0.82** | 0.0049 |
| Bankfull stream width [m] | 3.86 | 0.483 | ***0.55*** | 0.014 | 0.716 | 0.557 | ***0.54*** | 0.016 |
| % subsurface fines <8 [%] | 465 | -1.17 | ***0.58*** | 0.048 | 142 | -1.28 | ***0.50*** | 0.074 |
| Basin area [km$^2$] | 5.11 | 0.199 | 0.31 | 0.096 | 0.976 | 0.233 | 0.31 | 0.093 |
| Stream power [$Q_{bkf} \cdot S$; m$^3$/s] | 51.1 | 0.621 | 0.43 | 0.040 | 11.3 | 0.614 | 0.31 | 0.095 |
| Bankfull flow [m$^3$/s] | 8.41 | 0.184 | 0.23 | 0.16 | 1.77 | 0.205 | 0.21 | 0.18 |

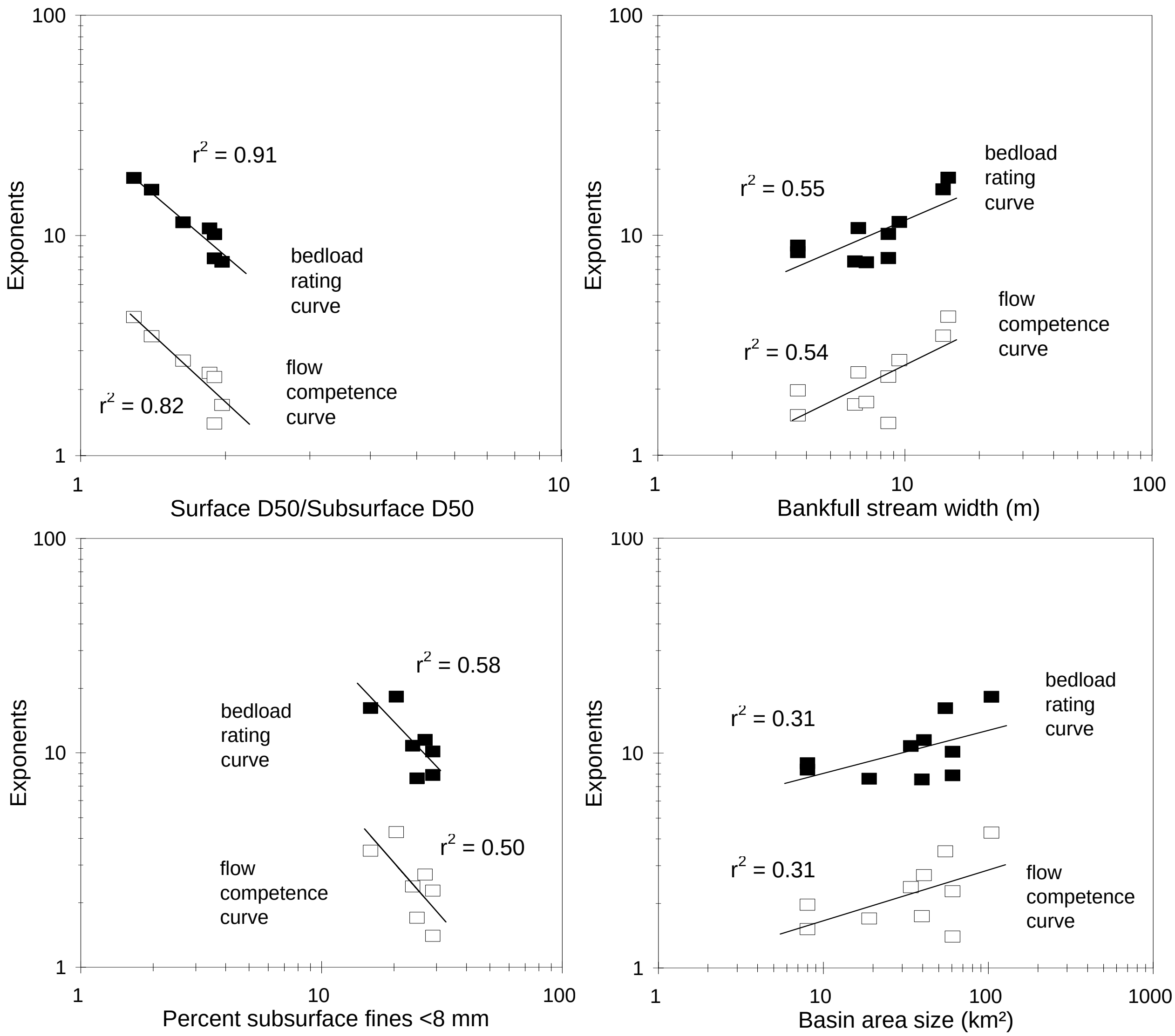


Figure 3 Relationship of exponents of bedload rating and flow competence curves with streambed and stream size parameters.

finer than the bed. Highly armored coarse-bedded mountain streams have only a limited number of transportable particles available on the stream bed such that increasing flow is not likely to find particles of transportable sizes on the bed. The result is a relatively flat rating curve with a low exponent. By contrast, lightly armored streams are likely to have more transportable coarse surface particles, and transport rates can easily respond to increasing flow.

Exponents were also found to decrease with the percent fines <8 mm in the subsurface sediment, which is positively correlated to bed armoring. Streams with a high percent of subsurface fines have an ample supply of small gravel particles available for transport at low flows at the very onset of fine gravel motion. This low-flow transport elevates the lower end of the rating and flow competence curves, thus reducing the overall slopes and resulting in lower exponents. However, with $r^2$-values of 0.58 and 0.50, respectively, the percent surface fines is not as good a predictor of the exponents as the degree of armoring. Exponents were also found to increase with bankfull stream width. Wider streams typically have a larger mobile bed area in which transport rates and bedload particle sizes can increase strongly with flow. Although the $r^2$-values are only 0.55 and 0.54, respectively, the bankfull stream width is easy enough to measure in the field that it could serve as a first estimator of the rating and flow competence curve exponents. Exponents also increase with basin area, stream power, and bankfull flow, but the relationships are not as tightly defined.

**Coefficients of bedload transport rating and flow competence curves:** Coefficients of bedload transport rating and flow competence curves were generally better correlated with streambed and stream size parameters than the exponents (Table 2). Coefficients were highly and positively correlated to bed armoring ($r^2$ values of 0.95 and 0.96, and p-values of 0.0002 and 0.0001, respectively) (Figure 4). The tight relationship of both exponents and coefficients with bed armoring indicates that the degree of armoring reflects gravel transport processes quite well. Armoring is thus a good predictor of both the rating curve and flow competence curve response to increasing flows in coarse-bedded mountain streams. Coefficients are also related to the percent subsurface fines, but the correlations ($r^2$ of 0.60 and 0.62) are only moderate. In contrast to exponents, coefficients are highly, but negatively, correlated to the bankfull stream width ($r^2$-values of 0.91 and 0.88, respectively and p-values <0.0001) and thus predictable from an easy to measure field parameter. Coefficients also decrease with parameters indicating stream size such as bankfull flow, basin area, and adjusted basin area. However, with $r^2$-values of 0.52 to 0.71, the relationships are not as well defined as those for armoring and stream width and are less well suited as predictors.

Table 2 Regression parameters α and β and the $r^2$-value for relationships between coefficients of the bedload rating and flow competence curves and parameters describing the streambed and stream size. $r^2$-values > 0.80 are printed in bold, and those between 0.50 and 0.80 in bold italics.

| | Coefficients *a* of bedload transport rating curve | | | | Coefficients *f* of flow competence curve | | | |
|---|---|---|---|---|---|---|---|---|
| | α | β | $r^2$ | p-value | α | β | $r^2$ | p-value |
| $D_{50}$ surface/$D_{50}$ subsurf. [-] | 3.04E-18 | 45.9 | **0.95** | 0.00017 | 4.04E-03 | 10.1 | **0.96** | 0.00012 |
| Bankfull stream width [m] | 7.54E+12 | -20.3 | **0.91** | <0.0001 | 1.33E+04 | -4.31 | **0.88** | <0.0001 |
| Basin area [km$^2$] | 1.13E+10 | -9.93 | ***0.71*** | 0.0022 | 2.97E+03 | -2.06 | ***0.67*** | 0.0039 |
| Bankfull flow $Q_{bkf}$ [m$^3$/s] | 0.619 | -10.2 | ***0.67*** | 0.0040 | 21.7 | -2.12 | ***0.62*** | 0.0070 |
| % subsurface fines <8 [%] | 6.17E-47 | 28.4 | ***0.60*** | 0.040 | 1.59E-09 | 6.31 | ***0.62*** | 0.036 |
| Stream power, $Q_{bkf} \cdot S$ [m$^3$/s] | 5.64E-25 | -17.1 | 0.30 | 0.099 | 2.51E-04 | -3.51 | 0.28 | 0.12 |

## DISCUSSION AND CONCLUSION

Results from intensive sampling of gravel bedload transport using bedload traps in several Rocky Mountain gravel- and cobble-bed streams showed that exponents and coefficients of both bedload transport rating and flow competence curves vary systematically with stream size and bed material characteristics. Exponents have a strong negative correlation with the degree of bed armoring, and to a lesser extent with the percentage of subsurface sand and fines, and there is a moderate positive correlation with stream width. Coefficients have a significantly positive relationship to the degree of bed armoring and are negatively related to stream width. There are moderate, negative relationships with bankfull flow, basin area, and percent subsurface sand. It

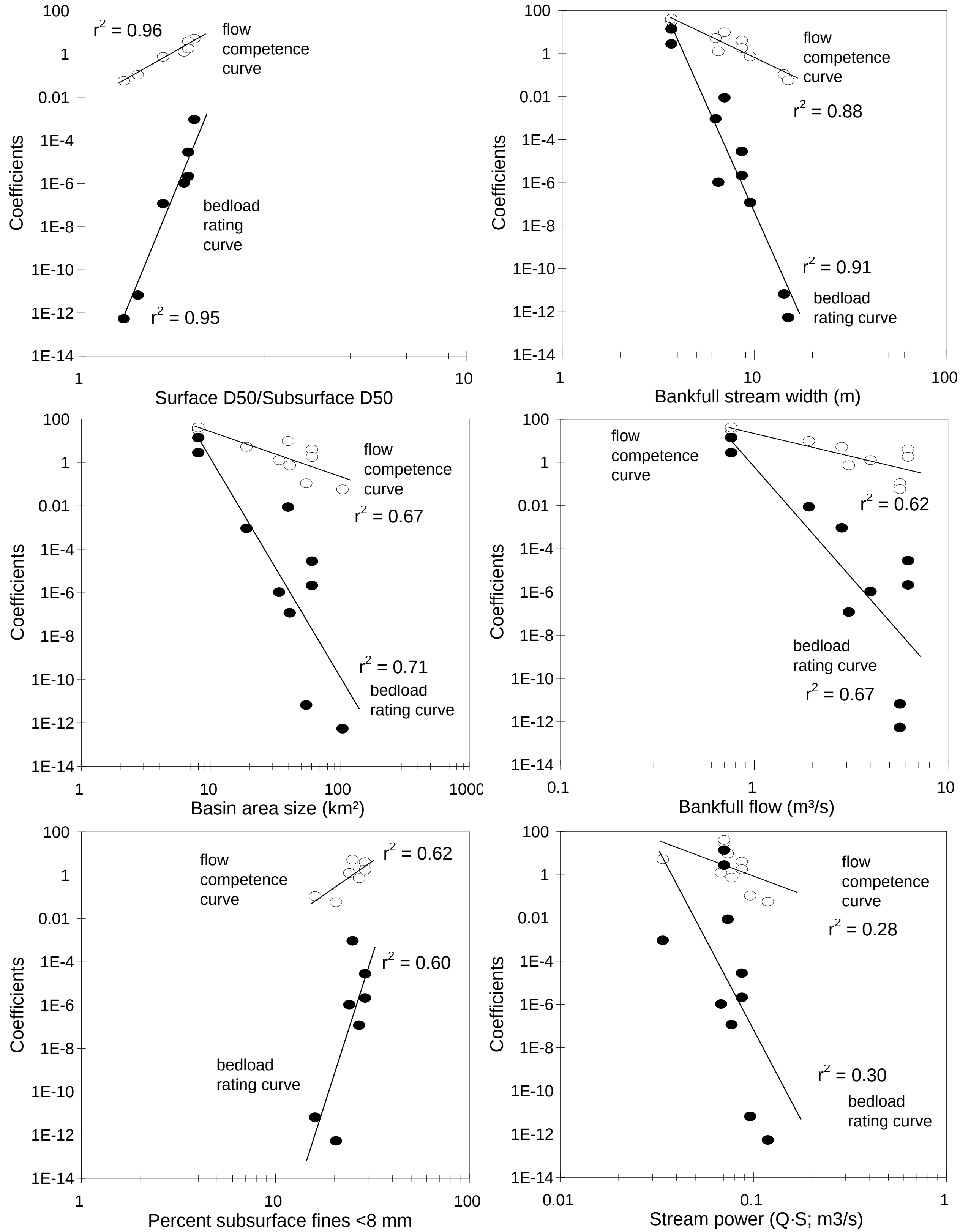


Figure 4 Relationship of the bedload rating and flow competence curve coefficients with streambed and stream size parameters.

is notable that exponents and coefficients of both the bedload rating and the flow competence curves follow the same trend, suggesting that the mobility of the bedload $D_{max}$ particle size and high bedload transport rates are positively correlated.

**Computational, procedural, and natural variability in bedload rating curves:** Ideally, a large number of streams should be used for an analysis of this type to show that results apply to gravel-bed streams in general. A large sample size can also include and highlight variability between streams or watersheds of different characteristics. However, including data sets from the literature in the analyses is problematic because exponents and coefficients of bedload rating and flow competence curves are affected by computational differences, natural variability, and sampling methods. Computational difference that arise from computations of transport rates, the $D_{max}$ particle size, and discharge using different units can easily be fixed. Those arising from the curve fitting procedure and the measured data range pose larger problems. Exponents and coefficients vary depending on whether measured zero-transport values were excluded from a power function regression or included after a small numerical value (e.g., 0.1 times the smallest measured transport rate) has been assigned to them. The range of flow over which transport rates are measured also affects the fitted rating curve due to the scatter of transport rates around discharge. Exponents are higher and coefficients lower in large data ranges (e.g., with flows from 30 and 130% $Q_{bkf}$) compared to small data ranges with flows of 30 to 80% or 80 to 130% of bankfull. These factors may change a rating curve exponent by up to approximately ±20% and a coefficient by a factor of up to ±5. Attempts to determine correlations of exponents and coefficients with stream parameters are necessarily compromised by this uncertainty.

By far the greatest variability in measured rating curve exponents and coefficients is due to the difference in transport rates obtained from using different samplers. For example, transport rates collected during low transport at 50% bankfull flow with a 0.076 m Helley-Smith sampler are several orders of magnitude higher than those collected with bedload traps, while both samplers produce similar results when a large number of bedload particles are moving near bankfull flow. Bedload rating curves computed from Helley-Smith samples are thus less steep. Exponents typically range from 2 to 5 in coarse-bedded mountain streams (compare to exponents from bedload trap rating curves of 8 to 18 (Bunte et al. 2004)). Helley-Smith rating curve coefficients, by contrast, are many orders of magnitude higher than those obtained from bedload traps. To avoid sampler specific differences in bedload transport rates and particle sizes, our study was solely based on data obtained from bedload traps and the similarly designed net-frame sampler. Results from a comparable study that used a different bedload sampler deviate to some degree from results in our study. Based on a large data set of Helley-Smith samples compiled primarily by King et al. (2004), Barry et al. (2004) found a significant negative correlation between bedload rating curve coefficients and basin area size ($r^2$ = 0.79) which is a similar but better defined relationship than in this study. They also found a moderately well defined relationship between exponents and the dimensionless bedload transport rate $q^*$ (Dietrich et al. 1989) ($r^2$ = 0.56). The parameter $q^*$ includes some ratio of the $D_{50}$ and $D_{50s}$ particle sizes, however, no relationship was found with the field-measured degree of bed armoring.

Using bedload traps, our field study showed relationships between rating curve exponents and coefficients with the degree of bed armoring that are sufficiently well developed to predict bedload rating and flow competence curves. This finding could lead to tremendous savings in time and labor. The field and lab work required for a careful analysis of the degree of bed armoring can be completed within several days (Bunte and Abt 2001). This is much faster and more convenient than intensive bedload sampling over a snowmelt highflow season. Bankfull stream width is even more easily measurable stream and is well suited to predict coefficients of the rating and flow competence curves, but is only moderately well suited to estimate exponents (steepness of the rating curve). A first estimate of exponents and coefficients of the bedload transport rating and flow competence curves can be obtained from the basin area size which is obtainable from detailed topographic maps.

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