Bedload transport efficiency of forested sand-bed streams in the seasonally wet tropics of northern Australia

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ABSTRACT: The purpose of this research was to apply the bedload transport efficiency approach of Bagnold (1973) to a new bedload data set for two sand-bed streams in the seasonally wet tropics of northern Australia. Hand-held, pressure difference, Helley-Smith bedload samplers were used to measure bedload fluxes for the 1998/1999, 1999/2000, 2000/2001 and 2001/2002 wet seasons at the East Tributary and Swift Creek gauging stations in the Ngarradj Creek catchment at Jabiluka, NT, Australia. The East Tributary gauge is characterized by slightly higher stream powers than Swift Creek gauge and hydraulic geometry relations show that both stations respond to increasing discharge differently. Bedload ratings were defined as those that were not only statistically significant ($\rho \leq 0.05$) but also explained at least (Adjusted $R^2 \geq$) 0.60 of the variance in bedload flux. They were established between adjusted submersed bedload weight per unit width and time, and both unit and excess unit stream power for raw and $\log_{10}$-transformed data. Bagnold (1973) defined the capacity of a river to transport bedload at various percentage efficiencies. Most stream kinetic energy is expended overcoming internal resistance to flow within the fluid and only a very small proportion is expended in moving bedload. For East Tributary, bedload transport efficiency increased with increasing excess unit stream power but never exceeded 0.1%. For Swift Creek, bedload transport efficiency approximately followed a linear trend at a constant slope at about 0.3% efficiency. This indicates that bedload transport at Swift Creek is at least three times more efficient than at East Tributary, most likely because of the wider cross section and less dense loading of large wood. This would permit a greater proportion of excess unit stream power to be expended on the bed. Furthermore, at-a-station hydraulic geometry equations differ between the stations, supporting the differences in bedload efficiency. Bagnold’s (1973) approach seems to apply to the two gauges.

1 INTRODUCTION

Bedload data from rivers worldwide are exceedingly sparse (Leopold and Emmett, 1976; 1997; Gomez and Church, 1989; Gomez, 1991; Ryan and Emmett, 2002; King et al., 2004) and are needed for more
effective river management, sediment control and improved understanding of contaminated coarse sediment transport and dispersal (Hean and Nanson, 1987). Bedload transport has been rarely measured in Australia despite its practical importance for river and environmental management (Hean and Nanson, 1987). The present work formed part of a comprehensive geomorphic research program by the Environmental Research Institute of the Supervising Scientist (ERISS) in the Ngarradj Creek catchment (Erskine et al. 2001), where the Jabiluka project area (uranium mine) is located in the seasonally wet tropics of northern Australia (Figure 1). The purpose of our research was to measure sediment transport before the commencement of mining. This paper applies Bagnold’s (1973) approach of determining the rate at which bedload is transported to the rate of energy expenditure in the channel to a new, high quality, bedload data set collected by the authors. Bagnold’s (1973) approach for evaluating bedload transport efficiency has not been previously tested. We have adopted Bagnold’s (1977; p. 303) definition of bedload which is:

“Bedload is….the solid material transported in a statistically dispersed state above the bed surface but which is not, however, suspended, i.e. its immersed weight is supported, on average, not by upwards currents of fluid turbulence but by a combination of fluid and solid reactive forces exerted at intermittent contacts with the bed solids.”

Bedload particles move at a speed less than the velocity of the transporting flow (0.01 to 0.1 % of mean flow velocity (Emmett et al., 1983)) and are confined to a layer, a few grain diameters thick, immediately above the river bed (Gomez, 1991). Stream power and flow turbulence determine the sediment size that moves as bedload (Abbott and Francis, 1977). Bedload rarely includes sediment finer than 0.1-0.2 mm in diameter because, once disturbed, these sizes go directly into suspension (Sundborg, 1956).

2 STUDY AREA

The Ngarradj Creek catchment is located partly in the Jabiluka Mineral Lease and partly in the world-heritage listed Kakadu National Park (Figure 1). The climate, geology, landforms, soils, vegetation and land systems of the Ngarradj Creek catchment have been described in detail by Erskine et al. (2001) and Saynor et al. (2004a, 2006), and will not be repeated here. However, it is important to emphasize the environmental characteristics that relate to the properties and field measurement of bedload. The tropical climate is characterized by distinct wet and dry seasons. Generally hot and humid conditions prevail from October to March, when heavy periodic rains associated with afternoon thunderstorms are interspersed with periods of monsoonal activity (McQuade et al., 1996). Dry, slightly less humid and warm to hot conditions with little rain occur from April to September (McQuade et al., 1996). April is often a transitional month between wet and dry seasons. All bedload measurements were undertaken during either rainfall-runoff events or baseflow discharges between December and May. Sand is supplied to the channels of the Ngarradj Creek catchment from resistant quartz sandstone of the Palaeoproterozoic (Statherian) Mamadawerre Sandstone of the Kombolgie Subgroup (Needham, 1988; Carson et al., 1999) which forms the Arnhem Land plateau and escarpment, and the Jabiluka outlier in Figure 1. Sand is also supplied from a range of uniform sandy soils developed on the lowlands below the Arnhem Land plateau and escarpment (Wells, 1979) and from bank erosion and channel incision on the lowlands (Erskine et al., 2001; Saynor et al., 2004a, 2004b). The regolith of the lowlands is comprised largely of quartz sand and overlies deeply weathered lateritic saprolites (Bettenay et al., 1981).

3 BEDLOAD TRANSPORT IN NGARRADJ CREEK CATCHMENT, NORTHERN AUSTRALIA

Hand-held, pressure difference, Helley-Smith bedload samplers (Helley and Smith, 1971, Emmett, 1980; 1981) were used for all field measurements at the gauging wire at the East Tributary and Swift Creek gauges (Figure 1). The square orifice internal diameter was 76.2 mm and the polyester monofilament bag had a mesh diameter of 0.2 mm. The sampler has an expansion ratio of 3.2 in the throat which causes a reduction in pressure and hence deposition. The sample bag can be filled with sediment larger than the mesh size to about 40 % capacity without a reduction in hydraulic efficiency which is the ratio of the mean flow velocity through the sampler to mean flow velocity at the same point in the absence of the
Figure 1 Ngarradj Creek catchment in the Alligator Rivers Region of northern Australia. The two gauging stations discussed in this paper are ET (East Tributary) and SC (Swift Creek). The other abbreviations refer to Tributary North (TN), Tributary Central (TC), Tributary South (TS), Tributary West (TW) and Upper Swift Creek gauge (UM).
sampler (Emmett, 1980; 1981). Sediment with diameters close to the sample bag mesh size plugs the bag and escapes through the mesh, resulting in an unpredictable decrease in hydraulic efficiency and loss of sample (Emmett, 1980, 1981). The sampling trap efficiency of a bedload sampler is the ratio of the weight of collected bedload to the weight of bedload that was transported at the same point in the absence of the sampler (Hubbell, 1964). Emmett’s (1980) calibration of the sediment trapping characteristics of the Helley-Smith bedload sampler found that for particle sizes coarser than 0.5 mm but finer than 16 mm, the sediment trap efficiency is essentially 100 % with no change in efficiency with changes in transport rate. For particle sizes finer than 0.5 mm, the Helley-Smith sampler has a high bedload sediment trap efficiency because part of the retained sediment has been transported in suspension but cannot be quantified separately from bedload. For bedload particle sizes less than 0.25 mm, Emmett (1981) recommended that data should be discarded. As Emmett’s (1981) recommendation referred to a 0.25 mm diameter bag, the relevant grain size for this study is 0.2 mm. Beschta’s (1981) detailed experimental measurements found that organic matter and fine sand can clog the 0.2 mm mesh bag, hence reducing the sampler trap efficiency. Johnson et al. (1977) also documented reduced sediment trap efficiency due to collection bag clogging. However, this was not a problem at our two gauging stations because of coarse sand and low particulate organic matter loads and is discussed further below.

There is considerable temporal variability inherent to the bedload transport process (Leopold & Emmett 1976, 1977, Emmett 1980, Pitlick 1988, Gomez et al 1989, Leopold & Emmett 1997, Kleinhans & Ten Brinke 2001), with bedload transport rates for dune bedforms at a fixed sampling point during constant water discharge ranging from near zero to approximately four times the mean rate and with about 60 % of the sampled values being less than the mean (Carey 1985). Pitlick (1988) found that section-averaged sand bedload flux for constant discharge varied twofold over a 10 hour period for dune bedforms. Furthermore, lateral variations in bedload transport rates for dune bedforms at a cross section are also highly variable due to lateral variations in bedforms (Carey 1985, Pitlick 1988, Kleinhans & Ten Brinke 2001). Temporal variations in transport rates are greater at points with higher transport rates (Pitlick 1988, Leopold & Emmett 1997, Kleinhans & Ten Brinke 2001). Emmett (1980, 1981) recommended that the bedload sampling procedure for a Helley-Smith sampler should involve the completion of two traverses of the channel with at least 20 measurement points on each traverse no further than 15 m apart and no closer than 0.5 m. We adopted the double traverse method. The minimum, maximum and mean (± standard error) spacing between measurement points were 0.4 m, 1.4 m and 0.9 ± 0.02 m at East Tributary and 0.77 m, 1.64 m, 1.05 ± 0.02 m at Swift Creek. Our sampling intervals are consistent with Gomez et al’s (1991) recommendations that on small streams (<30 m wide) samples should be collected at more than 0.5 m intervals and less than 2–3 m intervals. The sample at each measurement point should be collected over 30-60 s (Emmett 1981). Our minimum sample collection time was 120 s and the maximum was 660 s. These variations were determined by bedload flux so that no more than 40 % of the sample bag was filled at a time. As all site access was by helicopter during the wet season and our field program also involved the collection of water samples from a pump sampler (Evans et al 2004), there were significant weight and time constraints on our field work, which prevented the collection of additional bedload samples.

4 BEDLOAD TRANSPORT EFFICIENCY

Total stream power (Ω in kg/s) is the total supply of kinetic power per unit length of channel (Bagnold, 1973; 1977) and is denoted by:

\[
\Omega = \rho Q S
\]

where ρ is fluid density (kg/m³), Q is discharge (m³/s) and S is slope of the energy grade line (m/m).

Specific or unit stream power (ω in kg/m.s) is total power supply per unit bed area (Bagnold, 1973; 1977) and is denoted by:

\[
\omega = \Omega / W = \tau V
\]

where W is channel width (m), τ is bed shear stress (kg/m²) and V is mean flow velocity (m/s).

Unit stream power is often closely correlated with bedload transport (Bagnold, 1973; 1977; 1980; 1986; Leopold and Emmett, 1976; Reid and Frostick, 1986; Laronne and Reid, 1993; Blizzard and Wohl, 1998; Gomez, 2006). Bagnold (1973; 1977; 1979; 1980) noted that unit stream power is not a measure of the power directly available to transport bedload and found that excess unit power is the best predictor of bedload fluxes, a result consistent with the findings of Inbar and Schick (1979) and Leopold and Emmett
(1997). Excess unit stream power ($\omega'$) is defined as:

$$\omega' = \omega - \omega_0$$  \hspace{1cm} (3)

where $\omega_0$ is threshold unit stream power for first displacement of bedload.

Bagnold (1980) proposed that $\omega_0$ can be approximately defined as:

$$\omega_0 = 290 D^{1.5} \log_{10}(12Y/D)$$  \hspace{1cm} (4)

where $D$ is modal grain size (m) and $Y$ is flow depth (m).

While other formulations for threshold unit stream power have been published (Leopold and Emmett, 1997), they produce values similar to equation 4. The transport rate of unsuspended bedload by immersed weight per unit width and time (ib) varied as $\omega'^{1.5}$ for constant $D$ and $Y$ (Bagnold, 1980). Leopold and Emmett (1997) and Inbar and Schick (1979) found a similar result.

Bagnold (1986) proposed an overall conversion to adjust for the effect of grain size and flow depth on immersed weight of bedload (ib'). The resultant equation was:

$$ib' = ib(Y/Y_r)^{0.66}(D/D_r)^{0.5}$$  \hspace{1cm} (5)

where the subscript $r$ refers to a reference value.

Bagnold (1986) adopted $Y_r = 0.1$ m and $D_r = 1.1$ mm from Williams (1970) flume experiments. Immersed specific bedload flux is obtained by multiplying dry specific bedload flux by $(\gamma_s - \gamma)/\gamma_s$ where $\gamma_s$ is specific gravity of sediment and $\gamma$ is specific gravity of the fluid. Martin and Church (2000) found that equation 5 works remarkably well over a wide range of data. Leopold and Emmett (1997) concluded that, for the East Fork River, Wyoming the general relation of Bagnold’s (1986) adjusted specific bedload flux is given by:

$$ib' = 0.28 \omega'^{1.5}$$  \hspace{1cm} (6)

Bagnold (1973) also related the rate at which bedload is transported to the rate of energy expenditure in the channel such that:

$$ib = \omega_e \epsilon_b / \tan \alpha$$  \hspace{1cm} (7)

where $\epsilon_b$ is the bedload transport efficiency and $\tan \alpha$ is a friction coefficient for the bed material.

Bedload transport efficiency is obtained by rearranging equation 7 and declines with increasing particle size as the overall rate of energy dissipation involved in the transfer of stress from fluid to solids increases (Gomez, 2006). The amount of stream power used in bedload transport is very small, generally being less than about 1 % (Mantz and Emmett, 1985) but very little data exist to confirm the usual percentage. The remainder of the stream power is used in transporting water and suspended sediment over the varying boundary roughness (Mantz and Emmett, 1985). These relationships are now explored for the Ngarradj Creek bedload data set.

5 RESULTS AND DISCUSSION

5.1 Bedload grain size

Vericat et al (2006) recommended that a bedload sampler intake opening should always be greater than 5 times the diameter (strictly the ‘a’ and not the ‘b’ axis) of the largest clasts likely to move in the stream to maintain sediment trapping efficiency. At East Tributary, 95 grain size distributions of bedload samples bulked on a transect basis, were evaluated and at Swift Creek, 118 grain size distributions were evaluated. The coarsest bedload particle had a b-axis diameter of 6 mm at East Tributary and 9 mm at Swift Creek. Therefore the internal diameter of the Helley Smith bedload sampler should be at least 30 mm for East Tributary and 45 mm for Swift Creek, to maintain sediment trap efficiency. This diameter is in fact 76.2 mm (see above) and hence the Helley Smith bedload samplers will have performed as designed for all samples at both sites in the Ngarradj Creek catchment. As the quartz grains are rounded, b- and a-axis diameters are similar.

As also noted above, a 0.2 mm diameter bag was used for the Helley Smith sampler. Finer sediment can clog the bag and hence reduce sampler trap efficiency (Beschta 1981, Emmett 1981). Of the 95 bedload grain size distributions obtained for East Tributary, only one had a 95th percentile (cumulative percent coarser by weight) finer than 0.2 mm. Of the 118 grain size distributions obtained for Swift Creek, only two had a 95th percentile finer than 0.2 mm. Therefore, it seems unlikely that the sampler bags were clogged by fine sediment to such a degree as to reduce the sampler trap efficiency.

At East Tributary, there is no significant difference in graphic mean size ($\rho = 0.05$) between bedload and bed material for the period 1998-2002 (0.90 $\Phi$ or 0.53 mm versus 0.89 $\Phi$ or 0.54 mm). The phi ($\Phi$)
notation system is used for grain size by sedimentologists and is a logarithmic scale in which each grade limit is twice as large as the next smaller grade limit (Folk, 1974). The same result was obtained for Swift Creek (0.88 Φ or 0.54 mm versus 0.89 Φ or 0.54 mm). Most of the dry season bed material is transported as bedload during each wet season. Size selective transport seems to occur with bedload being better sorted at both stations. Therefore, bedload is a slightly finer fraction of the total bed material but the differences are mainly in the extreme coarse fraction which may be mobile only under extreme events.

5.2 Bedload flux and transport efficiency

For the whole data sets at both stations, the only significant relationships ($\rho < 0.05$ and Adjusted $R^2 > 0.6$) between bedload immersed weight and the various measures of stream power were for East Tributary. Bedload immersed weight was significantly related to unit stream power for both raw and log$_{10}$-transformed data and the following least squares equations were obtained:

$$ib = 0.0127 \omega - 0.0041$$  \hspace{1cm} (8)

$F$ ratio = 138.2; $\rho = 5.29 \times 10^{-16}$; Adjusted $R^2 = 0.729$; Standard Error (SE) = 0.0061 kg/m.s; N = 52 (East Tributary)

$$\log_{10}ib = 1.8909 \log_{10}\omega - 2.2979$$ \hspace{1cm} (9)

$F$ ratio = 148.0; $\rho = 1.47 \times 10^{-16}$; Adjusted $R^2 = 0.7425$; $SE = 2.65$ kg/m.s; N = 52 (East Tributary)

Significant relationships were also derived between bedload immersed weight and excess unit stream power and their log$_{10}$-transformed values, and the following least squares equations were obtained:

$$ib = 0.0127 \omega' - 0.0039$$ \hspace{1cm} (10)

$F$ ratio = 137.6; $\rho = 5.75 \times 10^{-16}$; Adjusted $R^2 = 0.7281$; $SE = 0.0061$ kg/m.s; N = 52 (East Tributary)

$$\log_{10}ib = 1.8056 \log_{10}\omega' - 2.29$$ \hspace{1cm} (11)

$F$ ratio = 144.48; $\rho = 2.31 \times 10^{-16}$; Adjusted $R^2 = 0.7378$; $SE = 2.67$ kg/m.s; N = 52 (East Tributary)

However, the highest adjusted $R^2$ values were derived for the relationships between adjusted immersed weight, and both unit and excess unit stream power, and their log$_{10}$-transformed values, as shown in Figures 2 and 3. The following least squares equations were derived:

$$ib' = 0.1431 \omega - 0.0724$$ \hspace{1cm} (12)

$F$ ratio = 157.7; $\rho = 4.40409 \times 10^{-17}$; Adjusted $R^2 = 0.7545$; $SE = 0.0643$ kg/m.s; N = 52 (East Tributary)

$$ib' = 0.1432 \omega' - 0.0706$$ \hspace{1cm} (13)

$F$ ratio = 157.1; $\rho = 4.78 \times 10^{-17}$; Adjusted $R^2 = 0.7537$; $SE = 0.0644$ kg/m.s; N = 52 (East Tributary)

$$ib' = 0.0474 \omega'^{2} - 0.0212 \omega' - 0.0057$$ \hspace{1cm} (14)

$F$ ratio = 70.16; $\rho < 0.0001$; Adjusted $R^2 = 0.897$; $SE = 0.0416$ kg/m.s; N = 52 (East Tributary)

$$ib' = 0.0475 \omega'^{2} - 0.0203 \omega' - 0.0056$$ \hspace{1cm} (15)

$F$ ratio = 69.31; $\rho < 0.0001$; Adjusted $R^2 = 0.896$; $SE = 0.418$ kg/m.s; N = 52 (East Tributary)

$$\log_{10}ib' = 2.5539 \log_{10}\omega' - 1.6177$$ \hspace{1cm} (16)

$F$ ratio = 252.71; $\rho = 3.4396 \times 10^{-21}$; Adjusted $R^2 = 0.8315$; $SE = 0.4367$ kg/m.s; N = 52 (East Tributary)

$$\log_{10}ib' = 2.5366 \log_{10}\omega' - 1.0549$$ \hspace{1cm} (17)

$F$ ratio = 246.3; $\rho = 5.86243 \times 10^{-21}$; Adjusted $R^2 = 0.8279$; $SE = 2.875$ kg/m.s; N = 52 (East Tributary)

The test of Chayes (1970) showed that a second order polynomial regression on raw data (Equations 14 and 15) significantly increased the explained variance over the first order polynomial for adjusted bedload immersed weight (Equations 12 and 13). This is shown in Figure 2. However, there is little difference between Equations 14 and 15, indicating the close similarity in values between $\omega$ and $\omega'$. This is expected where the threshold unit stream power is low for medium-coarse sand.

Equation 7 defines the capacity of a water stream to transport bedload at various percentage efficiencies (Bagnold 1973). Lines for 100 and 0.1 % efficiencies have been added to Fig 3. Most stream kinetic energy is clearly taken up over coming internal resistance to flow within the fluid and only a very small proportion is expended in moving bedload. Furthermore, for East Tributary, the bedload transport efficiency increases with increasing excess unit stream power (Fig 3). Such a result has been commonly reported (Bagnold 1973, Leopold & Emmett 1976, Reid & Frostick 1986, Laronne & Reid 1993)

The power function between adjusted immersed weight and excess unit stream power at East Tributary is simply derived by rearranging equation 17 and taking the antilog of the y intercept (see Carlston 1969).

It is much different to equation 27 for the East Fork River derived by Leopold and Emmett (1997) with a much larger exponent:

$$ib' = 0.0247 \omega^{-2.5366}$$ \hspace{1cm} (18)
Figure 2  Relationships between adjusted immersed bedload weight and (A) unit stream power, and (B) excess unit stream power for the East Tributary gauge.
Figure 3  Relationships between log_{10} adjusted immersed weight and (A) log_{10} unit stream power, and (B) log_{10} excess unit stream power for the East Tributary gauge.
Next, the data set for the Swift Creek gauge was analysed for relationships between bedload immersed weight and the various measures of unit stream power. No relationships for raw and \( \log_{10} \)-transformed data were significant and had an adjusted \( R^2 > 0.60 \). Therefore, Swift Creek data were subjected to greater scrutiny in an attempt to find a significant bedload rating. The bedload data were checked for gaugings when either the cross section at the gauge wire was deeply scoured to a root mat during and after a large flood or when there was rapid infill with sand after both a large flood and scour to the above root mat. From discussions with the field parties who conducted the bedload gaugings, such conditions were believed to reflect very low and very high sand supply, respectively. These conditions violate the assumption of equilibrium bedload fluxes implicit in such analyses (Dietrich et al. 1989, Gomez & Church 1989, Gomez 2006). Therefore, these bedload gaugings (\( n = 18 \) at Swift Creek) were deleted from the total data set and the rating curves recalculated. These data were called the ‘censored data set’ for differentiation from the ‘whole data set’ analysed above. For the censored data set at Swift Creek, two regressions were significant. For the \( \log_{10} \)-transformed censored data at Swift Creek, the two significant least squares regression equations related adjusted bedload immersed weight to unit and excess unit stream power (Fig 4A & 4B):

\[
\begin{align*}
\log_{10}b' &= 1.2347 \log_{10}Q - 0.3656 \\
F \text{ ratio} &= 64.38; \rho = 7.34 \times 10^{-10}; \text{Adjusted } R^2 = 0.6072; \text{SE} = 2.23 \text{ kg/m.s}; N = 42 \text{ (Swift Creek)} \\
\log_{10}b' &= 1.0337 \log_{10}Q - 0.4616 \\
F \text{ ratio} &= 63.0; \rho = 9.61 \times 10^{-10}; \text{Adjusted } R^2 = 0.6020; \text{SE} = 2.24 \text{ kg/m.s}; N = 42 \text{ (Swift Creek)}
\end{align*}
\]

Unlike the relationships for East Tributary (Fig 3), the relationships between \( \log_{10} \)-transformed adjusted bedload immersed weight and both unit stream power and excess unit stream power at Swift Creek in Fig 4A and 4B approximately follow a linear trend at about 0.1 % efficiency. This indicates that bedload transport at the Swift Creek gauge is more efficient than at the East Tributary gauge, most likely because of the wider cross section and less dense loading of large wood. This would permit a greater proportion of unit stream power to be expended on the bed.

Hydraulic geometry equations were determined on the velocity-area gauging data for each station by the method of Carlston (1969) and the following equations were derived:

\[
\begin{align*}
W &= 4.9276 Q^{0.1075} \\
F \text{ ratio} &= 231.99; \rho = 3.99296 \times 10^{-23}; \text{Adjusted } R^2 = 0.778; \text{SE} = 1.07 \text{ m}; N = 67 \text{ (East Tributary)} \\
W &= 7.6472 Q^{0.2332} \\
F \text{ ratio} &= 231.01; \rho = 2.59 \times 10^{-24}; \text{Adjusted } R^2 = 0.757; \text{SE} = 1.15 \text{ m}; N = 75 \text{ (Swift Creek)} \\
Y_m &= 0.4373 Q^{0.4335} \\
F \text{ ratio} &= 1068.6; \rho = 4.5322 \times 10^{-42}; \text{Adjusted } R^2 = 0.942; \text{SE} = 1.14 \text{ m}; N = 67 \text{ (East Tributary)} \\
Y_m &= 0.3301 Q^{0.567} \\
F \text{ ratio} &= 812.0; \rho = 2.72432 \times 10^{-41}; \text{Adjusted } R^2 = 0.916; \text{SE} = 1.20 \text{ m}; N = 75 \text{ (Swift Creek)} \\
V &= 0.464 Q^{0.459} \\
F \text{ ratio} &= 823.4; \rho = 1.2588 \times 10^{-38}; \text{Adjusted } R^2 = 0.926; \text{SE} = 1.17 \text{ m/s}; N = 67 \text{ (East Tributary)} \\
V &= 0.3962 Q^{0.1998} \\
F \text{ ratio} &= 200.8; \rho = 1.20392 \times 10^{-22}; \text{Adjusted } R^2 = 0.730; \text{SE} = 1.14 \text{ m/s}; N = 75 \text{ (Swift Creek)}
\end{align*}
\]

All terms have been defined above. Rhodes (1977) used the exponents of the at-a-station hydraulic geometry equations (b for width, f for mean depth and m for mean flow velocity) to classify different channel types on a ternary diagram. At East Tributary \( m > f > b \) whereas at Swift Creek \( f > b > m \). East Tributary is a type 4 river whereas Swift Creek is a type 10 river (Rhodes 1977). For type 4 rivers, width-depth ratio and velocity-area ratio decrease while Froude Number \( (V/(g.Y)^{0.5}) \) where \( g \) is gravitational acceleration constant and slope-roughness ratio \( (S^{0.5}/n \text{ where } S \text{ is slope and } n \text{ is Manning's roughness coefficient}) \) increase with increasing discharge (Rhodes 1977). For type 10 river, all the above morphologic and hydrodynamic parameters decrease with increasing discharge (Rhodes 1977). This indicates that the East Tributary gauge is characterized by slightly different hydraulic and morphological features than Swift Creek and should exhibit different bedload transport characteristics. This is indeed the case.
Figure 4  Significant regressions on censored bedload data for Swift Creek gauge with an adjusted $R^2 > 0.60$. (A) Log$_{10}$-transformed adjusted bedload immersed weight and unit stream power and (B) Log$_{10}$-transformed adjusted bedload immersed weight and excess unit stream power

6 CONCLUSIONS

Bedload transport efficiency declines with increasing grain size as the overall rate of energy dissipation involved in the transfer of stress from fluid to solids increases (Gomez, 2006). The amount of stream power used in bedload transport is thought to be very small, generally being less than about 1 % (Mantz and Emmett, 1985) but very little data exist to confirm the usual percentage. The remainder of the stream power is clearly taken up overcoming internal resistance to flow within the fluid. For East Tributary, the bedload transport efficiency increases with increasing excess unit stream power but never exceeds 0.1 % (Fig 3). Such a result has been commonly reported (Bagnold 1973, Leopold & Emmett 1976, Reid & Frostick 1986, Laronne & Reid 1993). However, bedload transport at the Swift Creek gauge is more
efficient than at the East Tributary gauge at about 0.3 % and is essentially constant with increasing excess unit stream power (Fig 4B), most likely because of the wider cross section and less dense loading of large wood. This would permit a greater proportion of unit stream power to be expended on the bed. At-a-station hydraulic geometry equations differ between both stations to such an extent that the two stations are classified as different stream types according to Rhodes’ (1977) classification. Different stream types support the differences in bedload efficiency. The Ngarradj Creek bedload data set validates Bagnold’s (1973) approach to defining bedload transport efficiency in the seasonally wet tropics of northern Australia. Bedload transport efficiency differs significantly between these two gauging stations and, therefore, sand discontinuities between river reaches should be expected (Erskine 2008).

7 ACKNOWLEDGEMENTS

For their assistance with various aspects of this work, we thank Bryan Smith, Elice Crisp, Xavier Finlayson, Michael Grabham, Guy Boggs, Gary Fox and Renee Fergusson. We also thank the Northern Lands Council and Parks Australia for the necessary access permits. Maureen Townley-Jones, University of Newcastle- Ourimbah Campus provided statistical advice.

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