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Bedload transport, hydrology and river hydraulics in the Ngarradj Creek catchment, Jabiluka, Northern Territory, Australia

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Executive summary

Rainfall, discharge and bedload were measured at three gauging stations in the Ngarradj Creek catchment at Jabiluka, Northern Territory. These gauging stations were East Tributary, Upper Swift Creek and Swift Creek, and all had catchment areas less than 45 km^2. 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. The bedload sampling procedure involved the completion of two traverses of the channel with at least four measurement points on each traverse at East Tributary, five at Upper Swift Creek and six at Swift Creek. Minimum sample collection time was 120 seconds and the maximum was 660 seconds. These variations were determined by bedload flux so that no more than 40% of the sample bag was filled at a time.

Rainfall is strongly seasonal over the Ngarradj Creek catchment, being concentrated in the wet season between November and April. Mean annual point rainfall between 1998 and 2007 for the water year (September to August inclusive) varied over the Ngarradj Creek catchment from 1731 ± 98 mm (SE) at Upper Swift Creek gauge to 1737 ± 105 mm at Swift Creek to 1754 ± 116 mm at East Tributary. Using the Thiessen polygon method, mean annual catchment (areal) rainfall for the same time period was 1735 ± 100 mm based on four stations in the Ngarradj Creek catchment. The recent time period has been characterised by above average rainfall with annual catchment rainfall being much greater than the mean for six of the nine years. CUSUM analysis of the long-term nearby Oenpelli rainfall record (1910–2010) found that there are alternating wet and dry periods that usually persist for at least a decade. The wet periods have a mean annual rainfall between 1537 and 1648 mm whereas the dry periods have a mean between 1267 and 1287 mm. Rainfall oscillates between these two different states, with one exception, 1955–1972, when rainfall was essentially constant at an intermediate value of 1436 mm. These different rainfall states are statistically significantly different from each other and all bedload measurements were completed during the last wet period. Between 190 and 440 mm of rainfall are required before streamflow commences in December in most years. Streamflow persists until at least April. Mean annual runoff, as a percentage of mean annual rainfall, decreases slightly with catchment area from 48 ± 8% at East Tributary to 46 ± 11% at Upper Swift Creek to 39 ± 9% at Swift Creek. Bankfull discharge usually occurs at least once during each wet season.

At-a-station hydraulic geometry equations were calculated for the velocity-area gauging data at each station. At East Tributary, the exponents exhibited the trend m>f>b whereas at Upper Swift Creek it was f>m>b and at Swift Creek, f>b>m. East Tributary is a type 4 river whereas both Upper Swift Creek and Swift Creek are type 10 rivers according to the Rhodes classification scheme. For type 4 rivers, width-depth ratio and velocity-area ratio decrease while Froude Number and slope-roughness ratio increase with increasing discharge. For type 10 rivers, all the above morphologic and hydrodynamic parameters decrease with increasing discharge. This indicates that the East Tributary gauge is characterised by higher stream powers than the other two stations and that all three stations respond to increasing discharge differently.

A total of 52 double traverses at East Tributary, 57 at Upper Swift Creek and 60 at Swift Creek were completed over the four wet seasons. Bedload ratings were calculated for four data sets, namely the whole data set at each gauge, the above threshold data set at East Tributary, the reliable data set at each gauge and the censored data set at Upper Swift Creek and Swift Creek. The 'whole data sets' comprised every mean bedload flux for each paired bedload transect at each gauge. The 'above threshold data set' at East Tributary only included the bedload fluxes for discharges greater than 0.223 m^3/s because at lower discharges the fluxes clustered around zero flux. The ‘reliable data sets’ comprised all mean bedload fluxes where paired transect values differed by less than 4 times and where the gauge height change during the paired transect gaugings was ≤ 0.02 m at each gauge. The ‘censored data sets’ involved those bedload fluxes measured during equilibrium conditions when there was no pronounced scour or fill at Upper Swift and Swift Creek gauges.

Significant bedload ratings were defined as those that were not only statistically significant ($\rho \leq 0.05$) but also explained a ‘meaningful’ amount of the variance in bedload flux. At least 0.60 of the variance in bedload flux had to be explained for a bedload rating to be accepted as reliable. For the three stations, twenty-three bedload ratings complied with the above criteria. Sixteen equations were accepted for East Tributary, thirteen for the ‘whole data set’, two for the ‘above threshold data set’ and one for the ‘reliable data set’. For Upper Swift Creek, four bedload ratings were accepted for the ‘censored data set’ and for Swift Creek, three bedload ratings were accepted for the ‘censored data set’. Significant bedload ratings were established between bedload flux and discharge, unit bedload flux and discharge, transport rate of unsuspended bedload by immersed weight per unit width and time and both unit and excess unit stream power, and adjusted submersed bedload weight and both unit and excess unit stream power for raw and $\log_{10}$-transformed data.

Bedload yields were calculated by thirty-nine methods at East Tributary, nine methods at Upper Swift Creek and eleven methods at Swift Creek. These methods involved combining the above bedload rating curves with either the hourly or daily hydrographs or the flow duration curves for the period 1 September 1998 to 31 August 2005. Ferguson’s (1986) and Duan’s (1983) corrections for bias were used with all methods based on $\log_{10}$-transformed ratings. Mean annual bedload yields varied by three orders of magnitude at East Tributary and by two orders of magnitude at Upper Swift Creek and Swift Creek. Hourly discharges usually produced higher yields than daily discharges. The bedload rating-flow duration curve technique overestimates yields and bias correction methods always produce even higher yields. Ratings using both immersed bedload weight and adjusted immersed bedload weight always underpredict yields because they contain an implicit threshold of motion condition that is at least four times greater than that predicted by Bagnold (1980). Such a result questions the applicability of Bagnold’s (1980) threshold to the Ngarradj Creek catchment. The best estimates of mean annual bedload yield at East Tributary, Upper Swift Creek and Swift Creek are 575 ± 65 (SE), 1000 ± 120 and 1625 ± 180 t/yr respectively.

Bedload sediments are similar at all sites. At East Tributary, bedload is a moderately sorted, coarse skewed, leptokurtic, coarse sand. At Upper Swift Creek, bedload is a moderately sorted, coarse skewed, mesokurtic, medium sand. At Swift Creek, bedload is a moderately sorted, coarse skewed, leptokurtic, coarse sand. There is little difference in grain size statistics between wet season bedload and dry season bed material. The differences that were significant suggest that most of the bed material is transported as bedload during the wet season. There may be some size selective transport at all three gauging stations with bedload being better sorted. At East Tributary, bedload samples are also less coarse skewed than the bed material. All these differences in grain size statistics indicate that bedload may be 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.

Key Words: Bedload flux, bedload yield, Jabiluka, threshold of motion, unit stream power, immersed bedload weight

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1 Introduction

Bedload data from rivers worldwide are exceedingly sparse (Leopold & Emmett 1976, 1997, Gomez & Church 1989, Gomez 1991, Ryan & 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 & Nanson 1987). Bedload transport has been rarely measured in Australia (Hean & Nanson 1987) and, where it has, no consistent correlation with discharge has been found (Erskine et al 1996, Locher 1997). Furthermore, calculated bedload transport rates using various equations were much different from the measured rates for two sites on the King River, Tasmania (Locher 1997), a result also found for rivers in other countries (Gomez & Church 1989, Barry et al 2004). Erskine et al (1996) measured bedload fluxes by irrigation flows on the Goulburn River, Victoria, and concluded that they transported little bedload at measured fluxes of less than 2 t/d. On a continental scale, bedload usually accounts for less than 10% of the fluvial sediment transferred from continental uplands to continental margins (Meade et al 1990). However, bedload constitutes at least 40% of the total sediment load for tropical seasonal rivers in the Alligator Rivers Region (ARR) of the Northern Territory, Australia, where sediment yields are some of the lowest in the world (Erskine & Saynor 2000).

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 is located in the seasonally wet tropics of northern Australia (Figure 1). The Jabiluka project area comprises the headworks, infrastructure, water retention pond and disturbed area at the Jabiluka mine. Erskine et al (2001) recommended that, among other things, bedload fluxes should be measured at a series of gauging stations upstream and downstream of the Jabiluka mine to complement runoff, and suspended and solute load measurements. Clearly such research would redress Hean and Nanson's (1987) conclusion that there are no meaningful bedload data sets in Australia. This paper reports the results of measurements of bedload and its grain size at three gauging stations during four consecutive wet seasons between 1998 and 2002 (Figure 1). Bedload rating curves were constructed and used to calculate bedload yields by combining the bedload ratings with the discharge record at each gauging station. Erskine et al (2006) previously published preliminary bedload results for one gauging station on East Tributary (Figure 1).

We have adopted Bagnold's (1977, p303) 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, ie 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.

This definition is consistent with that proposed at about the same time by Leopold and Emmett (1976, p1000), which is:

> Though bedload may best be defined as that part of sediment load supported by frequent solid contact with the unmoving bed, in practice it is the debris moving on or near the streambed rather than in the main bulk of the flowing water.

Einstein et al (1940), on the basis of detailed field measurements in the Enoree River in South Carolina, USA, defined bed-material load as the coarser part of the total sediment load that is composed of particles found in the bed material in appreciable quantities and that is transported at a rate dependent on stream discharge. This definition includes both bedload, as measured by a traditional bedload sampler, and suspended bed material, as measured by a depth integrated suspended sediment sampler (Erskine 2005). Although the Einstein et al (1940) definition is commonly adopted for sediment transport studies, it has not been adopted herein because we do not sample suspended bed material. 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 & Francis 1977). Bedload rarely includes sediment finer than 0.1 to 0.2 mm in diameter because, once disturbed, these sizes go directly into suspension (Sundborg 1956). In the present study, we compared the grain sizes of the bed material with bedload. Saynor et al (2006) have previously published the results of the grain size statistics for bed-material samples for the period 1998–2003 at the three gauging stations in the Ngarradj Creek catchment used in this report.

The channels at the East Tributary, Upper Swift Creek and Swift Creek gauging stations are low energy, forested, laterally stable, unconfined, meandering, sand-bed streams (Erskine et al 2005). Saynor et al (2006) found that the bed material at eight cross sections at the East Tributary gauge had a dominant mean size of medium sand in 1998 that increased to coarse sand from 1999 to 2003. The sediments were usually moderately well sorted to poorly sorted and coarse to strongly coarse skewed. The graphic grain size statistics of Folk and Ward (1957) and the Wentworth grain size scale (Folk 1980) were used in both the earlier report of Saynor et al (2006) and in this report. At the Upper Swift Creek and Swift Creek gauges, bed-material mean size increased from medium and coarse sand in 1998 to coarse sand from 1999 to 2003 at all eight cross sections at each site. The sediments at both gauges were predominantly moderately to poorly sorted and near symmetrical to coarse skewed.

Bedload is rarely measured in Australia because it is time consuming, often inaccurate, difficult and expensive (Erskine et al 1985, Hean & Nanson 1987, Locher 1997). Traps or sumps are usually employed on a local scale (eg large erosion plots) in the Australian tropics to retain bedload (Evans et al 1999, Hancock et al 2000, Saynor & Evans 2001, Bartley et al 2006), but at the catchment scale bedload is either ignored or estimated by crude methods of unknown but dubious accuracy (eg Bartley et al 2007) or by the use of very unreliable bedload equations (Hean & Nanson 1987, Gomez & Church 1989, Locher 1997). Our work partly redresses this deficiency for streams in the seasonally wet tropics of northern Australia. There is virtually no information on bedload transport processes for the seasonally wet tropics of northern Australia, although Roberts (1991) and Jansen and Nanson (2004) are significant exceptions.

The Ngarradj Creek catchment is located partly in the Jabiluka Mineral Lease and partly in the World Heritage Listed Kakadu National Park (Fig 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 are not repeated here. However, it is important to emphasise the environmental characteristics that relate to the properties and field measurement of bedload. The tropical climate is characterised by distinct wet and dry seasons. Generally hot and humid conditions prevail from October to April, which encompasses the wet season months of December to March, inclusive, when heavy periodic rains associated with afternoon thunderstorms are interspersed with periods of monsoonal activity (McQuade et al 1996).

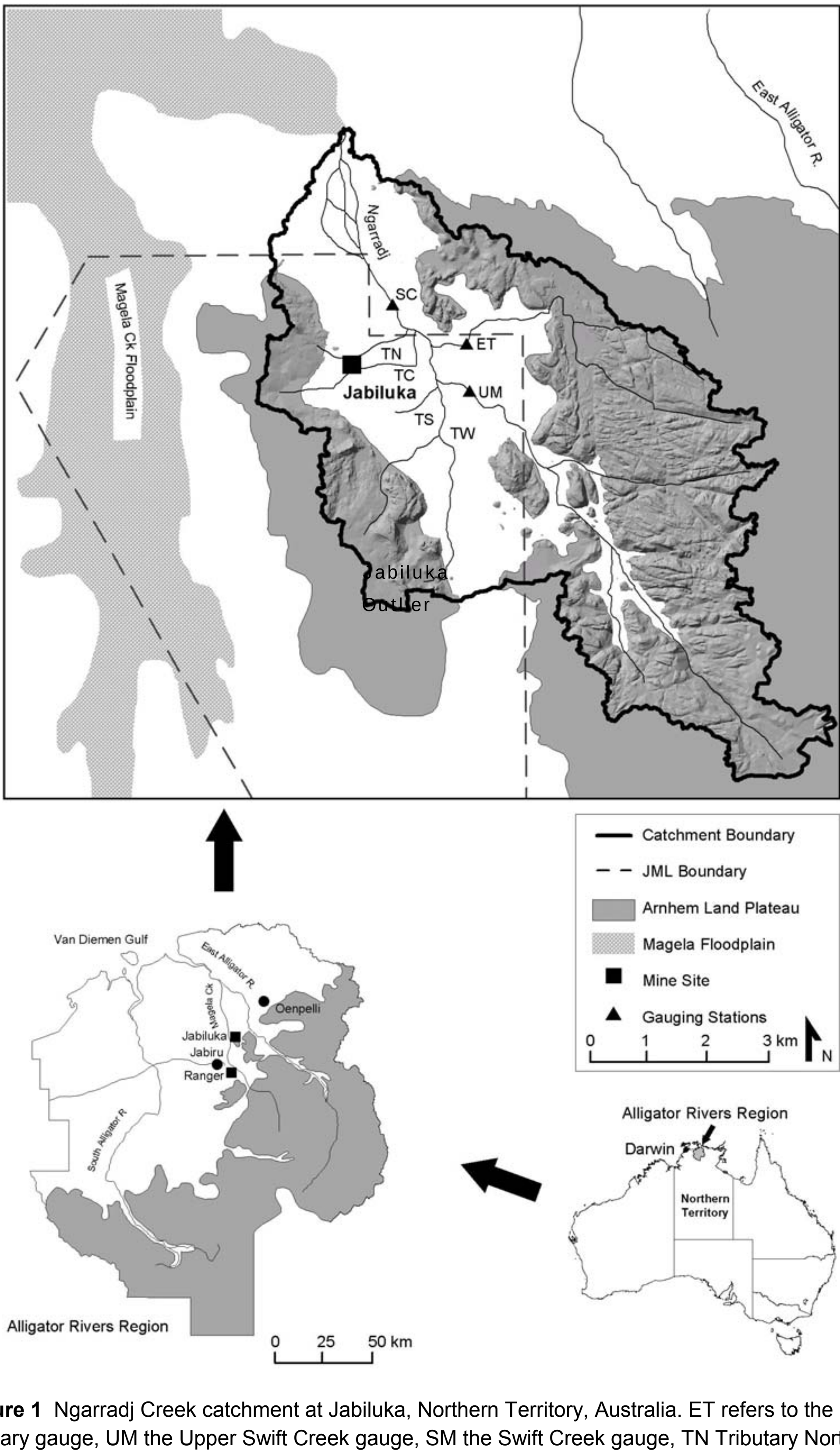


Figure 1 Ngarradj Creek catchment at Jabiluka, Northern Territory, Australia. ET refers to the East Tributary gauge, UM the Upper Swift Creek gauge, SM the Swift Creek gauge, TN Tributary North, TC Tributary Central, TS Tributary South and TW Tributary West. JML refers to the Jabiluka Mineral Lease and the rest of the land to the west of the East Alligator River is Kakadu National Park.

Dry, slightly less humid and warm to hot conditions with little rain occur from April to October (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 (Fig 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).

The aim of this work is to:

1 Measure bedload fluxes in the Ngarradj Creek catchment

2 Establish statistically significant and meaningful relationships between instantaneous bedload flux and discharge or unit stream power

3 Use these relationships to calculate mean annual bedload yields

4 Compare the grain size statistics of bedload and bed material

The methodology is outlined in the next chapter.

2 Methods

2.1 Hydrology

Three river gauging stations were installed by ***eriss*** during the 1998 dry season, two on Ngarradj Creek (Upper Swift Creek and Swift Creek) and one on East Tributary (Figure 1). The respective catchment areas are 18.79, 43.61 and 8.46 km^2. A 0.2 mm tipping bucket rain gauge was installed at each gauging station and the number of tips were recorded at 6 minute intervals. The East Tributary and Upper Swift Creek gauges were discontinued in June 2007, whereas the Swift Creek gauge is still operating. Moliere et al (2002a) outline the methods used to infill gaps in the record and the results for the first three years. We have adopted similar methods to infill gaps for the period after the 2000/2001 water year. Rainfall data were also collected at 10 minute intervals between July 1994 and April 2005 at Jabiluka mine by Energy Resources of Australia using a 0.5 mm tipping bucket rain gauge. We infilled gaps in this record by regression with the nearby Oenpelli record. Due to the cultural significance of the Arnhem Land plateau to the traditional owners, rain gauges were not allowed to be installed in the upper catchment (Moliere et al 2002a). A long rainfall record exists for Oenpelli (1910–2009) which is located 20 km north-east of the Jabiluka mine (Fig 1). The Oenpelli record is used to determine historical trends in annual rainfall. The Bureau of Meteorology (1999) infilled gaps in the Oenpelli record up to that time, and we used regression with Jabiru Airport to infill more recent gaps.

Moliere et al (2002a) determined the total annual rainfall over the Ngarradj catchment upstream of the Swift Creek gauge by the Thiessen Polygon method (Thiessen 1911). Temporal changes in annual rainfall for the water year (September to August) at Oenpelli were assessed by the cumulative sum (CUSUM) technique. To calculate CUSUMs, the mean for the complete period of record, 1910–2008, was used. Then deviations from the mean were calculated and added consecutively. CUSUMs exhibit a positive slope when annual rainfall increases, a negative slope when annual rainfall decreases and zero slope when annual rainfall oscillates about a constant mean. Following Erskine and Townley-Jones (2009), the non-parametric Mann Whitney test in Minitab 15 was used to determine whether periods of increasing and decreasing rainfall had statistically significantly different rainfall distributions.

Stage data were measured at 6 minute intervals by a pressure transducer and optical shaft encoder in a float well at each gauging station. A stable rating curve derived from weekly velocity-area gaugings at the gauging wire was used to convert stage to discharge (Moliere et al 2002a). At 95% confidence limits, the fitted rating curves have errors in bankfull discharge values of ± 14% at Upper Swift Creek, ± 11% at Swift Creek and ± 5% at East Tributary (Moliere et al 2002a). Data gaps were infilled by regression with a neighbouring station.

2.2 Bedload measurements

The slot and conveyor belt system of Leopold and Emmett (1976, 1977, 1997), the electromagnetic device of Reid et al (1984) and the Birkbeck-type slot sampler with a pressure pillow system (Reid et al 1980, Laronne et al 1992) were too expensive, and involved too much channel and floodplain disturbance for use in the world-heritage listed Kakadu National Park. The Birkbeck system has been developed for automatic operation in ephemeral channels (Laronne et al 1992) but could not be emptied between floods in the seasonally wet tropics of northern Australia. Instead, hand-held, pressure difference, Helley-Smith bedload samplers (Helley & Smith 1971, Emmett 1980) were used for all field measurements at the gauging wire at each gauge. The square orifice internal diameter was 76.2 mm and the polyester monofilament bag had a mesh diameter of 0.2 mm (Fig 2). The sampler has an expansion ratio of 3.2 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 (the ratio of the mean flow velocity through the sampler to mean flow velocity at the same point in the absence of the 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. While sediment trap efficiency varies with non-standard designs of the Helley-Smith sampler (Hubbell et al 1985, Pitlick 1988, Ryan & Porth 1999, Kleinhans & Ten Brinke 2001), the standard design (thick wall) was used for this study. For bedload particle sizes less than 0.25 mm, data should be discarded (Emmett 1981). As Emmett's (1981) recommendation referred to a 0.25 mm diameter mesh bag, the relevant grain size for this study is 0.2 mm. Beschta (1981) 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 three gauging stations because of coarse sand and low particulate organic matter loads (see below).

There is considerable temporal variability inherent in 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, but reduced the average spacing between measurement points because the channels under study are small, with bankfull widths varying from 6.0 ± 0.0 m at East Tributary, to 8.9 ± 0.1 m at Upper Swift Creek, to 17.9 ± 0.2 m at Swift Creek. 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; 0.63 m, 2.92 m, 1.17 ± 0.04 m at Upper Swift Creek; and 0.77 m, 1.64 m, 1.05 ± 0.02 m at Swift Creek. As a result, the average number of point measurements per section was 4 at East Tributary, 5 at Upper Swift and 6 at Swift Creek. The spacing between collection points varied for each sample so that zones of visually faster bedload flux were sampled more intensively. Our spacing between point bedload measurements was more detailed and one order of magnitude less (ie closer together) than that adopted by Roberts (1991) and Jansen and Nanson (2004) on the sand-bed, anabranching reach of the neighbouring Magela 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 to 3 m intervals. Emmett (1981) reported that the Helley-Smith sampler has been previously used on channels of less than 4 m width. We did not observe finer bedload being drawn into the sampler during our field measurements. The sample at each measurement point should be collected over 30 to 60 s (Emmett 1981). The 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. The sample time varied between sample points and between the same sample point on different transects depending on the bedload flux. The longer sampling times compensate for the narrow cross section and hence fewer point measurements. Furthermore, 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 that prevented the collection of additional bedload samples.

Figure 2 Helley-Smith BLS 30 pressure difference bedload sampler designed for operation with a winch on a cableway (photo by Tony Walker)

All bedload measurements were made during the 1998/1999, 1999/2000, 2000/2001 and 2001/2002 wet seasons at the cablewire section where all velocity-area gaugings were also taken at each site. This section is located in a straight reach of an otherwise sinuous channel. Bedload gaugings were obtained either by wading or out of a boat. The sampler was always oriented parallel to the flow to avoid the problems listed by Gaudet et al (1994). Low turbidities (Evans et al 2004) ensured that sampler misalignment did not occur and that a reasonable fit between the sampler bottom and river bed was achieved at all times. The problems of blockage of sampler intake by gravels and perching of the sampler intake above the bed on gravels, outlined by Vericat et al (2006) in gravel bed rivers, were not an issue for these sand bed streams.

All bedload samples were bagged and labelled in the field, transported to the laboratory and evaporated in an oven at 105º C for at least 24 hours so that a constant mass was finally obtained. Oven dry masses are used in subsequent calculations, except where immersed mass is stated.

2.3 Bedload yields

Bedload yields were calculated by up to thirty-nine methods at each gauging station (Table 1) to help define the most reliable methods for the Alligator Rivers Region. Bedload ratings were determined for raw and $\log_{10}$-transformed data (see section 3.3) and combined with both the hourly and daily hydrographs for the period 1 September 1998 to 31 August 2005 (Methods 1–6) at each gauging station. All hydraulic terms used in this section are defined in section 3.3. River loads can be underestimated by methods where unmeasured fluxes are estimated from discharge using a least squares regression for the logarithm of load/flux (Ferguson 1986, 1987). Underestimation of true loads by the rating curve method increases with scatter about, and slope of, the rating curve (Ferguson 1986, 1987). While there are three methods of handling bias correction (Cohn & Gilroy 1992), it is usual only for the methods of Ferguson (1986, 1987) and Duan (1983) to be used to correct sediment yields (Walling & Webb 1988, Phillips et al 1999). King et al (2004) only used the Duan (1983) method for bias correction of bedload yields. Ferguson's (1986) and Duan's (1983) corrections for bias were used with all methods based on $\log_{10}$-transformed ratings (Methods 4, 6, 10, 12, 15, 19, 21, 23, 25, 31, 33, 35, 37 in Table 1). Unit bedload flux ratings were also determined for raw and $\log_{10}$-transformed data (see section 3.3) and combined with the hourly and daily hydrographs for the same period (Methods 7–12). The sediment rating-flow duration method, using Piest's (1964) duration classes, was applied to determine the mean annual bedload yield (Methods 13–15) because Walling (1977a) found that Piest's (1964) duration classes produced the most accurate suspended sediment yields when compared with methods using other flow duration class intervals. The flow duration curve based on mean daily discharge for the same time period as the hourly and daily hydrographs was adopted. Bedload ratings combined with the flow duration curve were determined for both raw and $\log_{10}$-transformed data (Methods 13–15). Ratings between bedload immersed weight and unit stream power, excess stream power and their $\log_{10}$-transformed values (Bagnold 1977, 1980, 1986, Leopold & Emmett 1997) were also determined and combined with hourly and daily hydrographs for the same time period (Methods 16–27). Finally, ratings of adjusted immersed weight (Bagnold 1986) and both unit stream power and excess unit stream power, and their $\log_{10}$-transformed values, were also used in combination with hourly and daily hydrographs (Methods 28–39). Significant bedload ratings were defined as those that were not only statistically significant ($\rho \leq 0.05$) but also explained a 'meaningful' amount of the variance in bedload flux. At least 0.60 of the variance in bedload flux had to be explained for a bedload rating to be accepted as reliable.

2.4 Bedload grain size

The samples for each bedload transect were combined, oven-dried and then sieved through a stack of stainless steel sieves at phi (φ) / 2 intervals. The φ scale for sediments is:

$$\Phi = -\log_2 d \qquad (1)$$

where d is the particle diameter in mm.

The phi scale was used to calculate the graphic grain size statistics (Folk & Ward 1957) of each sample, as outlined by Saynor et al (2006). The grain size scale of Wentworth is used throughout this report and is also discussed by Saynor et al (2006). The verbal scale of Folk (1980) will be used to describe the bedload sediments at each gauging station.

2.5 Bed-material grain size

Saynor et al (2006) published the results of the bed-material grain size statistics at the eight cross sections at each gauging station for each year between 1998 and 2003. The upper 0.1 m of bed material was collected with a hand trowel at 6 to 8 equally spaced points across each permanently marked cross section at each gauging station, then bulked, oven-dried and then sieved through a stack of stainless steel sieves at phi (φ) / 2 intervals. Folk and Ward (1957) graphic grain size statistics were calculated from the cumulative frequency distributions. The Saynor et al (2006) data are used here and compared with the bedload grain size statistics. The non-parametric Mann Whitney test in Minitab 15 was used to determine whether there are significant differences in the grain statistics of bedload and bed material at each gauging station.

Table 1 Range of methods used to calculate bedload yields at the East Tributary, Upper Swift Creek and Swift Creek gauging stations in the Ngarradj catchment for the period 1 September 1998 to 31 August 2005. All methods are not used at each site. See Figure 1 for location of sites.

Method number	Bedload rating curve	Streamflow record
1	Regression on raw data	Hourly discharges
2	Regression on raw data	Mean daily discharges
3	Regression on $\log_{10}$-transformed data	Hourly discharges
4	Regression on $\log_{10}$-transformed data with Ferguson (1986) and Duan (1983) bias corrections	Hourly discharges
5	Regression on $\log_{10}$-transformed data	Mean daily discharges
6	Regression on $\log_{10}$-transformed data with Ferguson (1986) and Duan (1983) bias corrections	Mean daily discharges
7	Regression of unit bedload flux on discharge	Hourly discharges
8	Regression of unit bedload flux on discharge	Mean daily discharges
9	Regression of $\log_{10}$-transformed unit bedload flux on $\log_{10}$-transformed discharge	Hourly discharges
10	Regression of $\log_{10}$-transformed unit bedload flux on $\log_{10}$-transformed discharge data with Ferguson (1986) and Duan (1983) bias corrections	Hourly discharges
11	Regression of $\log_{10}$-transformed unit bedload flux on $\log_{10}$-transformed discharge	Mean daily discharges
12	Regression of $\log_{10}$-transformed unit bedload flux on $\log_{10}$-transformed discharge data with Ferguson (1986) and Duan (1983) bias corrections	Mean daily discharges
13	Regression on raw data	Flow duration curve
14	Regression on $\log_{10}$-transformed data	Flow duration curve
15	Regression on $\log_{10}$-transformed data with Ferguson (1986) and Duan (1983) bias corrections	Flow duration curve
16	Regression of immersed weight on unit stream power	Hourly discharges
17	Regression of immersed weight on unit stream power	Mean daily discharges
18	Regression of immersed weight on excess unit stream power	Hourly discharges
19	Regression of immersed weight on excess unit stream power	Mean daily discharges
20	Regression of $\log_{10}$-transformed immersed weight on $\log_{10}$-transformed unit stream power	Hourly discharges

Method number	Bedload rating curve	Streamflow record
21	Regression of $\log_{10}$-transformed immersed weight on $\log_{10}$-transformed unit stream power with Ferguson (1986) and Duan (1983) bias corrections	Hourly discharges
22	Regression of $\log_{10}$-transformed immersed weight on $\log_{10}$-transformed unit stream power	Mean daily discharges
23	Regression of $\log_{10}$-transformed immersed weight on $\log_{10}$-transformed unit stream power with Ferguson (1986) and Duan (1983) bias corrections	Mean daily discharges
24	Regression of $\log_{10}$-transformed immersed weight on $\log_{10}$-transformed excess unit stream power	Hourly discharges
25	Regression of $\log_{10}$-transformed immersed weight on $\log_{10}$-transformed excess unit stream power with Ferguson (1986) and Duan (1983) bias corrections	Hourly discharges
26	Regression of $\log_{10}$-transformed immersed weight on $\log_{10}$-transformed excess unit stream power	Mean daily discharges
27	Regression of $\log_{10}$-transformed immersed weight on $\log_{10}$-transformed excess unit stream power with Ferguson (1986) and Duan (1983) bias corrections	Mean daily discharges
28	Regression of adjusted immersed weight on unit stream power	Hourly discharges
29	Regression of adjusted immersed weight on unit stream power	Mean daily discharges
30	Regression of adjusted immersed weight on excess unit stream power	Hourly discharges
31	Regression of adjusted immersed weight on excess unit stream power	Mean daily discharges
32	Regression of $\log_{10}$-transformed adjusted immersed weight on $\log_{10}$-transformed unit stream power	Hourly discharges
33	Regression of $\log_{10}$-transformed adjusted immersed weight on $\log_{10}$-transformed unit stream power with Ferguson (1986) and Duan (1983) bias corrections	Hourly discharges
34	Regression of $\log_{10}$-transformed adjusted immersed weight on $\log_{10}$-transformed unit stream power	Mean daily discharges
35	Regression of $\log_{10}$-transformed adjusted immersed weight on $\log_{10}$-transformed unit stream power with Ferguson (1986) and Duan (1983) bias corrections	Mean daily discharges
36	Regression of $\log_{10}$-transformed adjusted immersed weight on $\log_{10}$-transformed excess unit stream power	Hourly discharges
37	Regression of $\log_{10}$-transformed adjusted immersed weight on $\log_{10}$-transformed excess unit stream power with Ferguson (1986) and Duan (1983) bias corrections	Hourly discharges
38	Regression of $\log_{10}$-transformed adjusted immersed weight on $\log_{10}$-transformed excess unit stream power	Mean daily discharges
39	Regression of $\log_{10}$-transformed adjusted immersed weight on $\log_{10}$-transformed excess unit stream power with Ferguson (1986) and Duan (1983) bias corrections	Mean daily discharges

3 Results and discussion

3.1 Hydrology

3.1.1 Rainfall

Rainfall is important for generating runoff and temporal trends in rainfall can have profound impacts on bedload transport. Rainfall is strongly seasonal at each station (Fig 3). The water year, September to August, has been used because August has the lowest mean monthly rainfall (Fig 3). Little rainfall is recorded in September but convective thunderstorms develop increasingly during the late afternoon in October and November, resulting in increasing monthly rainfall. Monsoonal and sometimes cyclonic rainfall is usually experienced between December and March when monthly rainfall exceeds 250 mm. There are only minor differences between mean and median monthly rainfall at this time, indicating that the rainfall data are not significantly skewed (Fig 3). Rainfall usually declines abruptly during April although tropical cyclones are sometimes experienced at this time. Little rainfall is recorded between May and August (Fig 3).

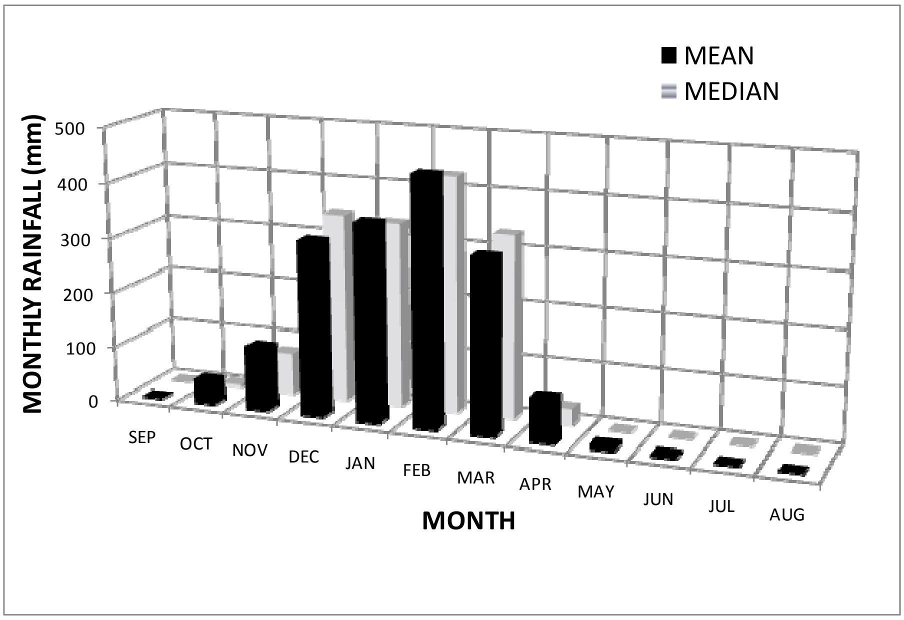


Figure 3 Mean and median monthly rainfall at the Swift Creek gauge for the period 1998–2009. For location of the gauge, see Figure 1.

For the nine years common period of record, 1998–2007, mean annual rainfall varied from 1731 ± 98 mm (SE) at Upper Swift Creek, to 1737 ± 105 mm at Swift Creek, to 1754 ± 116 mm at East Tributary. Mean annual rainfall over the catchment (Thiessen Polygon method) for the same common period of record was 1735 ± 100 mm. Figure 4 shows the total annual rainfall over the Ngarradj catchment for each water year plotted on the Oenpelli annual rainfall distribution (Moliere et al 2002a). Table 2 shows the average recurrence interval for each year of record. Clearly the period 1998–2007 was wet with six of the nine years having average recurrence intervals much greater than the mean annual rainfall which has a recurrence interval of 2 years for the adopted $\log_{10}$-normal distribution (Moliere et al 2002a).

Table 2 Total annual catchment rainfall and its average recurrence interval for each year of record for the Ngarradj catchment. Catchment rainfall determined by the Thiessen (1911) polygon method using the data for the East Tributary, Upper Swift Creek, Swift Creek and Jabiluka gauges.

Water Year	Total annual catchment rainfall (mm)	Average Recurrence Interval (years)
1998/1999	1826	1:13
1999/2000	2047	1:71
2000/2001	1897	1:21
2001/2002	1380	1:1.8
2002/2003	1769	1:9
2003/2004	1330	1:1.6
2004/2005	1357	1:1.7
2005/2006	1936	1:29
2006/2007	2072	1:80

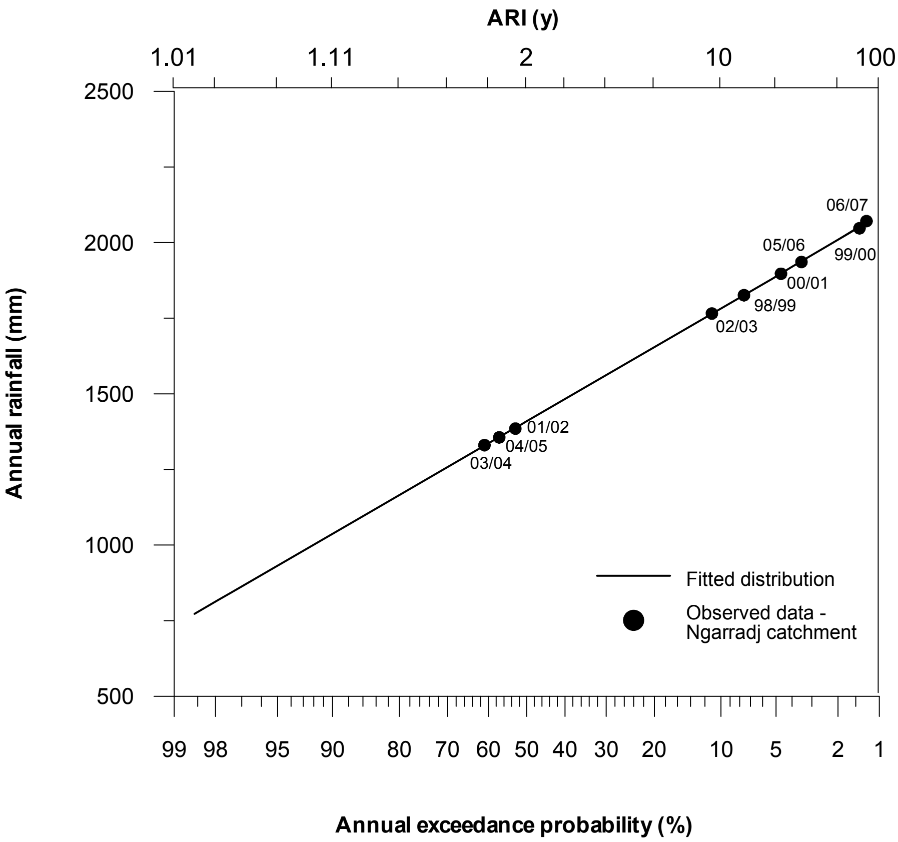


Figure 4 Annual rainfall frequency curve for Oenpelli (from Moliere et al 2002a) showing the total annual Ngarradj catchment rainfall for the nine years of record, 1998–2007. ARI = average recurrence interval. See Fig 1 for location of Oenpelli and the Ngarradj catchment.

Figure 5 shows changes in annual rainfall at Oenpelli by a CUSUM plot. CUSUMs at Oenpelli exhibit a largely positive slope from 1910 to 1918 and a negative slope from 1919 to 1954 (Fig 5). CUSUMs then remained essentially constant until 1972 when they increased until 1984. There was then a short period of decreasing CUSUMs until 1993 when they increased again until 2010 (Fig 5). The means and standard errors for each of the above time periods are listed in Table 3. The wet periods have a mean annual rainfall between 1537 and

1648 mm whereas the dry periods have a mean between 1267 and 1287 mm. Rainfall oscillates between these two different states with one exception, 1955–1972, when rainfall was essentially constant at an intermediate value of 1436 mm.

In relation to rainfall across the ARR, Carter (1990) concluded that:

> …from about 1920 to 1960 the rainfall throughout the Region was below the long-term average and that from 1960 to the present (say 1985) all sites have had rainfall above the long-term average. It appears that there may now be a change to a lower average.

He went on to suggest that there were short-term cycles of about 6 years and possibly, long-term cycles of 15 to 20 years. Furthermore, he concluded that the annual rainfall pattern is bi-modal with alternating periods of low and high rainfall and that all the low periods had roughly the same average and all the high periods also had a common mean. Erskine and Townley-Jones (2009) recently concluded that annual rainfall on the Central Coast of NSW exhibited multi-decadal periods of alternating high and low rainfall which they called alternating flood- and drought-dominated regimes following the earlier work of Warner (1987a, 1987b, 1994) and Erskine and Warner (1988, 1998, 1999). However, the wet and dry rainfall periods at Oenpelli, Darwin, Katherine and Pine Creek are usually shorter and out of phase with those in NSW.

Table 3 Alternating wet and dry annual rainfall periods at Oenpelli defined by CUSUMS. For location of Oenpelli, see Fig 1. This is the closest long-term rainfall station to the Ngarradj Creek catchment.

Time Period	1910–1918	1919–1954	1955–1972	1973–1984	1985–1993	1994–2010
Mean ± Standard Error (mm)	1537 ± 101	1267 ± 38	1436 ± 63	1640 ± 72	1287 ± 87	1648 ± 78
Rainfall Period	Wet	Dry	Constant/ Intermediate	Wet	Dry	Wet

The first period (1910–1918) was significantly wetter ($\rho = 0.0036$) than the second period (1919–1954) and the second period was significantly drier ($\rho = 0.0356$) than the third period (1955–1972). The third period was non-significantly drier ($\rho = 0.0541$) than the fourth period (1973–1984) but the fourth period was significantly wetter ($\rho = 0.0173$) than the fifth period (1985–1993). Finally, the fifth period was significantly drier ($\rho = 0.005$) than the sixth period (1994–2010). The Mann Whitney test was also used to compare annual rainfall distributions between non-contiguous periods. All three wet periods were not significantly different ($\rho > 0.4996$) and both dry periods were not significantly different ($\rho = 0.9434$). All wet periods were also significantly different to all dry periods ($\rho < 0.0423$). The intermediate period was usually but not always significantly different to wet and dry periods. Therefore, with the exception of the 1955–1972 intermediate period, annual rainfall at Oenpelli alternates between significantly different wet and dry states. Clearly our results for a longer record at Oenpelli confirm the earlier conclusions of Carter (1990). We have also found similar historical rainfall trends at other stations in the Top End (Erskine et al 2011) and are seeking to find climatic drivers for these changes in mean annual rainfall. These rainfall trends have important implications for bedload transport because the alternating wet and dry periods are likely to have different bedload fluxes and sediment supply rates which will impact on river channel dynamics (Erskine et al 2011).

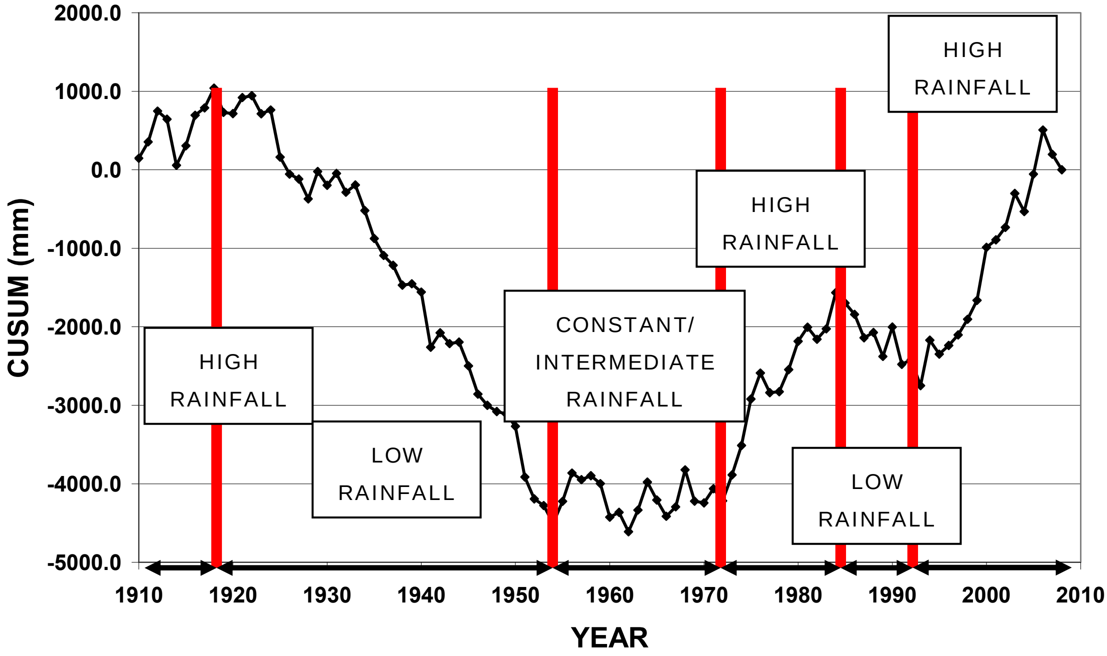


Figure 5 CUSUMs of annual rainfall (September to August) at Oenpelli between 1910 and 2010 showing alternating flood- (high rainfall) and drought-dominated regimes (low rainfall). See Fig 1 for location of Oenpelli.

3.1.2 Runoff

Streams in the Ngarradj catchment only flow seasonally, as shown in Figure 6 for the East Tributary gauge. Between 190 and 440 mm of rainfall (mean of 312 ± 14 mm for all three stations) is required before streamflow starts at the beginning of the wet season. Runoff usually commences in December (five of nine years). November was the earliest month in which runoff commenced (two of nine years) and January was the latest (two of nine years). Flow persists to at least April (one of nine years) but can continue until August (one of nine years) during wet years. Mean annual runoff for the common period, 1998–2007, varied with catchment area from 7299 ± 745 ML at East Tributary to 15405 ± 1845 ML at Upper Swift Creek to 30493 ± 3782 ML at Swift Creek. As a percentage of annual rainfall, mean annual runoff decreased with catchment area and ranged from 48 ± 8% at East Tributary to 46 ± 11% at Upper Swift Creek to 39 ± 9% at Swift Creek.

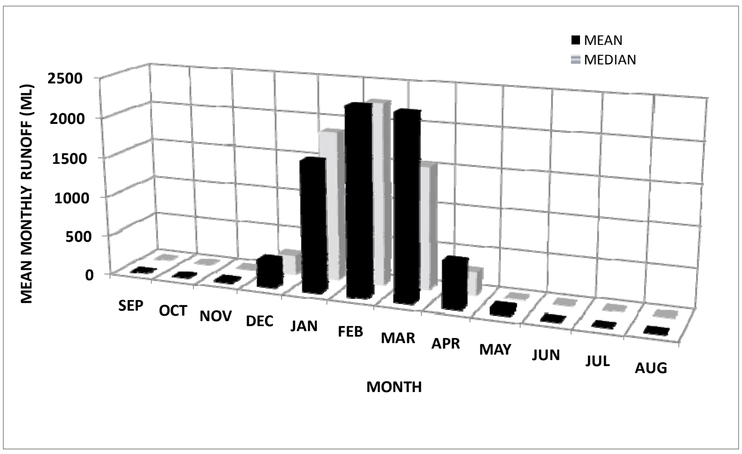


Figure 6 Mean monthly runoff at the East Tributary gauge for the common period of record, 1998–2007. See Figure 1 for location of the site.

Interestingly, the mean percentage runoff and standard error at Swift Creek are exactly the same for the Swift Creek rainfall as well as for the weighted catchment rainfall using Thiessen Polygons with all four rainfall stations. Clearly the spatial variation in rainfall is minor throughout the Ngarradj catchment upstream of the Swift Creek gauge. This is hardly surprising given that the stations are located either on the lowlands (three ***eriss*** gauges) or on the Jabiluka outlier (ERA gauge).

Bankfull discharge was determined morphologically as the point at which overbank flow first commenced at each gauging station (Moliere et al 2002a). It was approached or exceeded during each year between 1998/1999 and 2006/2007. The largest flood for the common period of record, 1998–2007, occurred in February/March 2007 after bedload gaugings had ceased. Flood peak discharge for the February/March 2007 event ranged from 2.3 times greater than bankfull discharge at East Tributary to 2.6 times greater at Upper Swift Creek to 5.1 times greater at Swift Creek. However, the flood peak was not recorded at Swift Creek because the datalogger was inundated and, consequently, has been estimated by correlation with neighbouring stations. During the period that bedload gaugings were undertaken (1998–2002), the largest flood occurred in 1998/1999 and exceeded bankfull discharge at Swift Creek and Upper Swift Creek but only approached bankfull at East Tributary (8.5 m^3/s peak discharge compared to a bankfull discharge of 9.0 m^3/s). Clearly where rainfall generated events are being gauged and wet season access is solely dependent on helicopters, as in the Ngarradj Creek catchment, it is more difficult to sample large events than where predictable snow-melt floods are involved (Leopold & Emmett 1976, 1977, 1997, Ryan & Emmett 2002, King et al 2004).

3.2 Bedload measurements

Following the recommendation of Leopold and Emmett (1997) to publish important research results, especially in relation to bedload, this report contains the bedload fluxes and associated hydraulic and sedimentologic data for the Ngarradj Creek bedload study (see Tables 4, 5 and 6 for the East Tributary, Upper Swift Creek and Swift Creek data respectively). Such data are very limited and complement the work of Leopold and Emmett (1976, 1977, 1997) and Ryan and Emmett (2002). A total of 404 point bedload measurements was obtained for 52 double traverses at East Tributary, 576 point bedload measurements for 57 double traverses at Upper Swift Creek and 654 point bedload measurements for 60 double traverses at Swift Creek over the four wet seasons (1998/1999, 1999/2000, 2000/2001, 2001/2002). The sampled mean discharges varied from 0.0315 to 2.842 m^3/s at East Tributary, 0.0135 to 5.057 m^3/s at Upper Swift Creek and 0.103 to 11.65 m^3/s at Swift Creek. The corresponding bankfull discharges are 9.0, 12.28 and 17.36 m^3/s (Moliere et al 2002a) and therefore maximum measured discharges varied from 31.6 (East Tributary) to 41.2% (Upper Swift Creek) to 67.1% (Swift Creek) of bankfull discharge. Measured total mean bedload fluxes ranged from 0.030 to 366 g/s or 0.009 to 91.0 g/m.s at East Tributary, 2.23 to 449.0 g/s or 0.489 to 72.66 g/m.s at Upper Swift Creek and 8.070 to 855.2 g/s or 1.56 to 142.5 g/m.s at Swift Creek.

Channel width (W in m), mean flow depth (Y_m in m) and mean flow velocity (V in m/s) for each bedload gauging were determined as follows. The hydraulic geometry equations for each gauge for the period 1998–2003 were derived from the velocity-area gauging data and then each equation was solved for the mean discharge during each bedload gauging at each site.

The hydraulic geometry equations determined by the method of Carlston (1969) are:

$$W = 4.9276\ Q^{0.1075} \quad (2)$$

F ratio = 231.99

$\rho = 3.99296 \times 10^{-23}$

Adjusted $R^2 = 0.778$

Standard Error = 1.07 m

N = 67 (East Tributary)

$$W = 6.616\ Q^{0.1032} \quad (3)$$

F ratio = 130.93

$\rho = 2.06087 \times 10^{-17}$

Adjusted $R^2 = 0.657$

Standard Error = 1.09 m

N = 69 (Upper Swift Creek)

$$W = 7.6472\ Q^{0.2332} \quad (4)$$

F ratio = 231.01

$\rho = 2.59 \times 10^{-24}$

Adjusted $R^2 = 0.757$

Standard Error = 1.15 m

N = 75 (Swift Creek)

$$Y_m = 0.4373\ Q^{0.4335} \quad (5)$$

F ratio = 1068.6

$\rho = 4.5322 \times 10^{-42}$

Adjusted $R^2 = 0.942$

Standard Error = 1.14 m

N = 67 (East Tributary)

$$Y_m = 0.3848\ Q^{0.6503} \quad (6)$$

F ratio = 1171.0

$\rho = 3.68 \times 10^{-44}$

Adjusted $R^2 = 0.945$

Standard Error = 1.19 m

N = 69 (Upper Swift Creek)

$Y_m = 0.3301\ Q^{0.567}$ (7)

F ratio = 812.0

$\rho = 2.72432 \times 10^{-41}$

Adjusted $R^2 = 0.916$

Standard Error = 1.20 m

N = 75 (Swift Creek)

$V = 0.464\ Q^{0.459}$ (8)

F ratio = 823.4

$\rho = 1.2588 \times 10^{-38}$

Adjusted $R^2 = 0.926$

Standard Error = 1.17 m/s

N = 67 (East Tributary)

$V = 0.3928\ Q^{0.2465}$ (9)

F ratio = 251.6

$\rho = 2.24 \times 10^{-24}$

Adjusted $R^2 = 0.787$

Standard Error = 1.16 m/s

N = 69 (Upper Swift Creek)

$V = 0.3962\ Q^{0.1998}$ (10)

F ratio = 200.8

$\rho = 1.20392 \times 10^{-22}$

Adjusted $R^2 = 0.730$

Standard Error = 1.14 m/s

N = 75 (Swift Creek)

All bedload, hydraulic and grain size data are included in Tables 4, 5 and 6 for East Tributary, Upper Swift Creek and Swift Creek gauges respectively. The exponents of the hydraulic geometry equations (b for width, f for mean depth and m for mean velocity) must sum to unity and the product of the constants (a for width, c for mean depth and k for mean velocity) must equal 1 (Leopold & Maddock 1953). All equations at each site satisfy these requirements. Rhodes (1977) used the exponents of the at-a-station hydraulic geometry equations to classify channels on a ternary diagram. At East Tributary m>f>b whereas at Upper Swift Creek f>m>b and at Swift Creek f>b>m. East Tributary is a type 4 river whereas both Upper Swift Creek and Swift Creek are type 10 rivers (Rhodes 1977).

For type 4 rivers, width-depth ratio and velocity-area ratio decrease while Froude Number and slope-roughness ratio increase with increasing discharge (Rhodes 1977). Froude Number (Fr) is:

$$Fr = V / (g.Y)^{0.5} \qquad (11)$$

where g is gravitational acceleration constant.

Slope-roughness ratio (SR) is:

$$SR = S^{0.5} / n \qquad (12)$$

where S is slope and n is Manning's roughness coefficient.

For type 10 rivers, all the above morphologic and hydrodynamic parameters decrease with increasing discharge (Rhodes 1977). This indicates that the East Tributary gauge is characterised by higher stream powers than the other two stations and should exhibit different bedload transport characteristics to the other two gauges.

Water surface slopes at flood stage were determined by Saynor et al (2004a) as 0.0015 m/m at East Tributary and 0.00078 m/m at Upper Swift Creek. The bed slope at Swift Creek was 0.00095 m/m (Saynor et al 2004a). These slope values are used in all subsequent calculations, where relevant.

It is important to emphasise that the channels at all three gauging stations are very low energy streams. The maximum Froude Number for the bedload gaugings was only 0.289 at East Tributary, 0.284 at Upper Swift Creek and 0.267 at Swift Creek. Similarly, the maximum mean flow velocity for the bedload gaugings was 0.75 m/s at East Tributary, 0.59 m/s at Upper Swift Creek and 0.65 m/s at Swift Creek. Bankfull unit stream powers reported by Saynor et al (2004a) at the eight cross sections for each gauge ranged from 8.6 to 24.7 W/m^2 at East Tributary, 0.8 to 1.7 W/m^2 at Upper Swift Creek and 5.8 to 12.0 W/m^2 at Swift Creek. These are low to moderate values (Nanson & Croke 1992, Erskine 1999).

At East Tributary, 33 (63%) of the bedload gaugings were conducted when there was no change in stage, 4 (8%) when stage was rising and 15 (29%) when stage was falling. At Upper Swift Creek, 30 (53%) of the bedload gaugings were conducted when there was no change in stage, 2 (3%) when stage was rising and 25 (44%) when stage was falling. At Swift Creek, 28 (47%) of the bedload gaugings were conducted when there was no change in stage, 3 (5%) when stage was rising and 29 (48%) when stage was falling. Such a high percentage of steady and falling stage samples is expected because Moliere et al (2002b) found that rainfall over the catchment exhibits a strong diurnal cycle with a peak in the late afternoon. At Darwin, a strong peak in rainfall also occurs between about 14:00 and 22:00 h (Soman et al 1995, Li et al 1996). The average peak in runoff at Ngarradj occurs at 23:00 h with a corresponding lag time from peak rainfall to runoff of approximately 5 h (Moliere et al 2002b). Minimum storm runoff occurs at approximately 12:00 h (Moliere et al 2002b). Therefore, bedload gaugings during daylight are most likely to encounter falling stages or steady discharges.

Table 4 Bedload data and hydraulic parameters for the bedload measurements at the East Tributary gauging station. See Fig 1 for location of site. Q is water discharge; V is mean flow velocity; Y_m is mean flow depth; D_{50} is bedload median size; D_m is mean bedload size; Qs is bedload flux or dry mass per unit time; Qsw is specific bedload flux or dry mass per unit width and time; ω is unit stream power; ω_0 is threshold unit stream power from Bagnold (1980); and ω-ω_0 is excess unit stream power. These constitute the 'total data set'. [1] data removed to form 'reliable data set'. [2] data removed to form 'above threshold data set'.

Date	Q (m^3/s)	Stage Change	V (m/s)	Y_m (m)	D_{50} (mm)	D_m (mm)	Qs (g/s)	Qsw (g/m.s)	ω (kg/m.s)	ω_0 (kg/m.s)	ω´ (kg/m.s)
5 Jan 1999[1]	0.285	Rising	0.26	0.26	0.59	0.66	9.682	2.848	0.4275	0.0125	0.4150
12 Jan 1999[1]	1.547	Rising	0.56	0.53	0.43	0.50	159.2	37.02	2.3200	0.0087	2.3110
19 Jan 1999	0.317	Steady	0.27	0.27	0.46	0.45	9.034	2.259	0.4755	0.0097	0.4658
2 Feb 1999	0.728	Steady	0.40	0.38	0.51	0.56	165.3	34.44	1.0913	0.0128	1.0784
9 Feb 1999	1.081	Falling	0.48	0.46	0.75	0.77	163.9	32.77	1.6208	0.0212	1.6000
16 Feb 1999	0.340	Steady	0.28	0.28	0.65	0.62	21.75	5.958	0.5100	0.0167	0.4933
23 Feb 1999	0.266	Steady	0.25	0.25	0.75	0.66	7.087	2.025	0.3990	0.0197	0.3793
2 Mar 1999[2]	0.196	Steady	0.22	0.22	0.54	0.52	8.635	2.617	0.2940	0.0136	0.2804
9 Mar 1999	0.365	Steady	0.29	0.29	0.59	0.59	24.56	7.017	0.5475	0.0124	0.5351
17 Mar 1999	2.842	Steady	0.74	0.69	0.62	0.76	365.9	91.03	4.2623	0.0185	4.2437
23 Mar 1999	0.573	Falling	0.36	0.35	0.49	0.47	11.73	3.046	0.8588	0.0100	0.8488
30 Mar 1999	0.407	Steady	0.30	0.30	0.51	0.45	15.06	4.016	0.6098	0.0100	0.5997
6 Apr 1999	0.384	Falling	0.30	0.29	0.54	0.52	17.53	4.804	0.5753	0.0140	0.5612
13 Apr 1999[2]	0.196	Steady	0.22	0.22	0.55	0.54	6.860	1.933	0.2933	0.0130	0.2802
20 Apr 1999[2]	0.036	Steady	0.10	0.11	No data	No data	0.177	0.0561	0.0540	0.0119	0.0421
27 Apr 1999[2]	0.0315	Steady	0.09	0.10	No data	No data	0.128	0.0414	0.0473	0.0118	0.0354
3 Dec 1999	0.296	Falling	0.26	0.26	0.49	0.51	12.26	3.716	0.4433	0.0097	0.4336
4 Jan 2000[1]	0.247	Falling	0.24	0.24	0.47	0.47	6.467	1.931	0.3705	0.0122	0.3583
11 Jan 2000	0.487	Steady	0.33	0.32	0.65	0.68	15.46	4.122	0.7305	0.0160	0.7145
18 Jan 2000	0.769	Falling	0.41	0.39	0.56	0.60	69.92	17.75	1.1535	0.0164	1.1371
25 Jan 2000	0.694	Falling	0.38	0.36	0.75	0.83	19.44	4.884	0.9593	0.0162	0.9430
1 Feb 2000[2]	0.159	Steady	0.20	0.20	0.48	0.49	1.254	0.402	0.2378	0.0094	0.2284

Date	Q (m^3/s)	Stage Change	V (m/s)	Y_m (m)	D_{50} (mm)	D_m (mm)	Qs (g/s)	Qsw (g/m.s)	ω (kg/m.s)	$ω_0$ (kg/m.s)	ω´ (kg/m.s)
8 Feb 2000	0.378	Falling	0.29	0.29	0.65	0.67	9.956	2.928	0.5663	0.0124	0.5538
15 Feb 2000	0.909	Steady	0.44	0.42	0.50	0.50	94.95	20.12	1.3635	0.0130	1.3505
22 Feb 2000	0.416	Steady	0.31	0.30	0.41	0.41	3.550	1.109	0.6240	0.0098	0.6142
29 Feb 2000	0.370	Falling	0.29	0.29	0.57	0.57	82.82	28.56	0.5543	0.0158	0.5385
7 Mar 2000	0.968	Steady	0.45	0.43	0.47	0.48	29.43	7.704	1.4520	0.0102	1.4418
14 Mar 2000	0.493	Falling	0.33	0.33	0.52	0.54	131.5	39.56	0.7395	0.0126	0.7269
21 Mar 2000	1.193	Steady	0.50	0.48	0.49	0.41	16.02	5.169	1.7895	0.0103	1.7792
28 Mar 2000	0.250	Steady	0.24	0.24	0.35	0.37	2.808	1.003	0.3750	0.0059	0.3691
6 Apr 2000[2]	0.120	Steady	0.17	0.18	No data	No data	0.0512	0.019	0.1800	0.0092	0.1708
11 Apr 2000	0.556	Steady	0.35	0.34	0.40	0.40	18.41	6.348	0.8333	0.0100	0.8233
20 Apr 2000[2]	0.229	Steady	0.23	0.23	0.48	0.47	3.486	1.268	0.3428	0.0154	0.3273
4 Dec 2000	0.584	Falling	0.36	0.35	0.50	0.54	13.75	3.726	0.8760	0.0127	0.8633
9 Jan 2001[1]	1.763	Rising	0.60	0.56	0.44	0.48	83.49	27.83	2.6438	0.0105	2.6332
23 Jan 2001	0.425	Steady	0.31	0.31	0.55	0.55	10.66	3.552	0.6375	0.0159	0.6216
30 Jan 2001	0.661	Steady	0.38	0.37	0.52	0.52	42.82	11.27	0.9915	0.0163	0.9752
6 Feb 2001	0.402	Steady	0.30	0.30	0.54	0.54	11.95	3.677	0.6030	0.0159	0.5871
13 Feb 2001[1]	1.395	Rising	0.54	0.51	0.53	0.54	154.2	51.40	2.0925	0.0169	2.0757
27 Feb 2001	0.474	Steady	0.33	0.32	0.46	0.46	9.35	2.397	0.7110	0.0126	0.6984
6 Mar 2001	0.261	Steady	0.25	0.25	0.52	0.52	4.400	1.467	0.3915	0.01553	0.3760
13 Mar 2001[2]	0.228	Steady	0.23	0.23	0.48	0.49	4.040	1.616	0.3420	0.0095	0.3325
20 Mar 2001	0.487	Falling	0.33	0.32	0.46	0.46	10.55	3.102	0.7305	0.0099	0.7206
27 Mar 2001	0.349	Falling	0.28	0.28	0.49	0.49	4.615	1.709	0.5228	0.0124	0.5104
3 Apr 2001	0.577	Steady	0.36	0.35	0.54	0.55	3.705	1.278	0.8655	0.0162	0.8493
10 Apr 2001[2]	0.138	Steady	0.19	0.19	0.49	0.49	0.755	0.581	0.2070	0.0118	0.1952
12 Feb 2002	1.915	Falling	0.62	0.58	0.56	0.56	278.6	75.30	2.8725	0.0171	2.8554

Date	Q (m^3/s)	Stage Change	V (m/s)	Y_m (m)	D_{50} (mm)	D_m (mm)	Qs (g/s)	Qsw (g/m.s)	ω (kg/m.s)	$ω_0$ (kg/m.s)	ω´ (kg/m.s)
19 Feb 2002	0.828	Steady	0.42	0.41	0.58	0.58	35.60	8.990	1.2420	0.0164	1.2256
26 Feb 2002	0.456	Falling	0.32	0.31	0.51	0.51	8.045	1.893	0.6833	0.0160	0.6673
4 Mar 2002	0.792	Steady	0.41	0.40	0.48	0.48	30.55	7.793	1.1880	0.0129	1.1751
12 Mar 2002[1,2]	0.228	Steady	0.23	0.23	0.43	0.43	1.900	0.534	0.3420	0.0095	0.3325
19 Mar 2002[2]	0.0984	Steady	0.16	0.16	No data	No data	0.030	0.0094	0.1476	0.0092	0.1385

Table 5 Bedload data and hydraulic parameters for the bedload measurements at the Upper Swift Creek gauging station. See fig 1 for location of site. Q is water discharge; V is mean flow velocity; Y_m is mean flow depth; D_{50} is bedload median size; D_m is mean bedload size; Qs is bedload flux or dry mass per unit time; Qsw is specific bedload flux or dry mass per unit width and time; ω is unit stream power; $ω_0$ is threshold unit stream power from Bagnold (1980); and $ω-ω_0$ is excess unit stream power. These constitute the 'total data set'. [1] data removed to form 'reliable data set'. [2] data removed to form 'censored data set'.

Date	Q (m^3/s)	Stage Change	V (m/s)	Y_m (m)	D_{50} (mm)	D_m (mm)	Qs (g/s)	Qsw (g/m.s)	ω (kg/m.s)	$ω_0$ (kg/m.s)	ω´ (kg/m.s)
23 Dec 1998	1.115	Falling	0.40	0.41	0.49	0.50	21.89	5.613	0.1230	0.0122	0.1177
5 Jan 1999	0.620	Falling	0.35	0.28	0.44	0.46	14.16	3.539	0.0767	0.0094	0.0673
12 Jan 1999	0.666	Steady	0.36	0.30	0.43	0.44	23.26	4.845	0.0819	0.0082	0.0737
20 Jan 1999	0.512	Falling	0.33	0.25	0.31	0.33	5.230	1.046	0.0646	0.0060	0.0586
2 Feb 1999	0.728	Steady	0.44	0.52	0.27	0.38	1.564	0.592	0.1760	0.0045	0.1715
9 Feb 1999[1]	2.349	Falling	0.48	0.67	0.45	0.47	121.2	19.87	0.2536	0.0114	0.2422
16 Feb 1999	0.656	Steady	0.35	0.29	0.31	0.34	11.66	2.620	0.0807	0.0061	0.0746
23 Feb 1999[2]	0.579	Steady	0.34	0.27	0.51	0.51	196.1	33.24	0.0722	0.0127	0.0595
3 Mar 1999	0.354	Steady	0.30	0.20	0.45	0.46	64.17	10.70	0.0465	0.0116	0.0349
9 Mar 1999	1.307	Falling	0.42	0.46	0.46	0.47	32.20	6.075	0.1498	0.0113	0.1385
17 Mar 1999[1]	5.057	Falling	0.59	1.10	0.42	0.44	359.3	65.33	0.5044	0.0112	0.4931
23 Mar 1999[2]	1.514	Falling	0.44	0.50	0.51	0.51	202.8	31.68	0.1710	0.0155	0.1555
30 Mar 1999[1,2]	1.376	Falling	0.43	0.47	0.48	0.48	53.53	7.873	0.1570	0.0121	0.1449
31 Mar 1999[1,2]	1.774	Falling	0.45	0.56	0.50	0.52	271.8	43.14	0.1971	0.0141	0.1830

Date	Q (m^3/s)	Stage Change	V (m/s)	Y_m (m)	D_{50} (mm)	D_m (mm)	Qs (g/s)	Qsw (g/m.s)	ω (kg/m.s)	$ω_0$ (kg/m.s)	ω´ (kg/m.s)
6 Apr 1999	0.920	Falling	0.39	0.37	0.51	0.51	143.8	23.19	0.1094	0.0142	0.0952
13 Apr 1999	0.429	Falling	0.32	0.22	0.56	0.53	57.62	9.220	0.0551	0.0148	0.0403
20 Apr 1999	0.157	Steady	0.25	0.12	0.49	0.49	14.36	2.374	0.0224	0.0115	0.0109
4 May 1999	0.0285	Steady	0.16	0.04	0.48	0.52	2.296	0.489	0.0049	0.0048	0.0001
3 Dec 1999	0.0135	Falling	0.14	0.02	0.55	0.55	32.06	5.130	0.0025	0.0022	0.0003
4 Jan 2000	0.733	Falling	0.36	0.31	0.42	0.42	4.334	0.711	0.0892	0.0062	0.0830
11 Jan 2000	0.937	Falling	0.39	0.37	0.49	0.49	33.71	5.714	0.1112	0.0100	0.1012
18 Jan 2000	3.14	Falling	0.52	0.81	0.49	0.49	133.3	20.83	0.3290	0.0139	0.3151
25 Jan 2000	1.228	Steady	0.41	0.44	0.48	0.49	138.2	22.66	0.1417	0.0130	0.1287
1 Feb 2000	0.616	Steady	0.35	0.28	0.44	0.45	62.10	10.69	0.0763	0.0097	0.0666
8 Feb 2000	0.700	Steady	0.36	0.31	0.48	0.49	86.92	14.02	0.0856	0.0098	0.0758
15 Feb 2000	1.773	Steady	0.45	0.56	0.52	0.54	123.0	19.84	0.1970	0.0173	0.1797
22 Feb 2000	0.842	Steady	0.38	0.34	0.38	0.39	4.324	0.994	0.1010	0.0062	0.0948
29 Feb 2000	2.116	Rising	0.47	0.63	0.52	0.54	109.9	17.87	0.2309	0.0175	0.2134
7 Mar 2000	1.220	Falling	0.41	0.44	0.29	0.30	7.279	1.754	0.1409	0.0064	0.1345
14 Mar 2000[1]	2.277	Falling	0.48	0.66	0.43	0.41	124.9	20.48	0.2465	0.0083	0.2383
21 Mar 2000[2]	1.045	Falling	0.40	0.40	0.50	0.52	167.4	28.87	0.1226	0.0101	0.1125
28 Mar 2000	0.742	Steady	0.37	0.32	0.35	0.40	69.12	11.43	0.0902	0.0062	0.0840
6 Apr 2000	0.485	Steady	0.33	0.24	0.48	0.49	55.17	9.679	0.0616	0.0096	0.0520
11 Apr 2000	1.746	Rising	0.45	0.55	0.45	0.48	79.86	14.01	0.1943	0.0065	0.1878
20 Apr 2000[2]	0.479	Steady	0.33	0.24	0.41	0.42	105.5	18.76	0.0609	0.0074	0.0534
2 May 2000	0.220	Steady	0.27	0.14	0.47	0.47	25.07	4.249	0.0303	0.0090	0.0213
16 May 2000	0.099	Steady	0.22	0.09	0.47	0.48	6.684	1.146	0.0148	0.0085	0.0064
4 Dec 2000	0.902	Steady	0.38	0.36	0.55	0.58	31.04	5.088	0.1075	0.0164	0.0910
9 Jan 2001	1.990	Falling	0.47	0.60	0.44	0.46	67.47	11.25	0.2185	0.0066	0.2119

Date	Q (m^3/s)	Stage Change	V (m/s)	Y_m (m)	D_{50} (mm)	D_m (mm)	Qs (g/s)	Qsw (g/m.s)	ω (kg/m.s)	$ω_0$ (kg/m.s)	ω´ (kg/m.s)
23 Jan 2001[2]	1.041	Steady	0.40	0.40	0.46	0.47	163.4	27.70	0.1222	0.0063	0.1159
30 Jan 2001	1.68	Falling	0.45	0.54	0.49	0.51	25.11	3.747	0.1877	0.0105	0.1773
6 Feb 2001[2]	1.41	Steady	0.43	0.48	0.53	0.52	90.87	14.54	0.1604	0.0170	0.1435
13 Feb 2001	2.17	Steady	0.48	0.64	0.46	0.47	137.1	22.48	0.2362	0.0106	0.2255
27 Feb 2001[1]	1.23	Steady	0.41	0.44	0.40	0.42	61.36	10.14	0.1420	0.0102	0.1317
6 Mar 2001	0.839	Steady	0.38	0.34	0.53	0.54	81.35	13.79	0.1007	0.0164	0.0844
13 Mar 2001	0.728	Falling	0.36	0.31	0.47	0.49	78.49	15.70	0.0887	0.0126	0.0761
20 Mar 2001	1.208	Falling	0.41	0.44	0.54	0.55	93.35	15.56	0.1396	0.0168	0.1229
27 Mar 2001	0.634	Steady	0.35	0.29	0.47	0.47	54.49	10.09	0.0783	0.0098	0.0686
3 Apr 2001	1.635	Falling	0.44	0.53	0.55	0.57	91.58	15.01	0.1832	0.0172	0.1661
10 Apr 2001	0.416	Steady	0.32	0.22	0.51	0.51	16.88	3.592	0.0536	0.0155	0.0381
17 Apr 2001	0.228	Steady	0.27	0.15	0.52	0.54	12.54	2.85	0.0313	0.0148	0.0165
23 Jan 2002	0.228	Steady	0.29	0.17	0.51	0.52	23.78	3.836	0.0381	0.0117	0.0264
19 Feb 2002	1.65	Steady	0.44	0.53	0.31	0.34	30.71	5.783	0.1847	0.0065	0.1782
26 Feb 2002[2]	0.998	Falling	0.39	0.38	0.56	0.57	304.7	51.38	0.1177	0.0166	0.1011
4 Mar 2002[2]	1.503	Falling	0.43	0.50	0.52	0.52	449.0	72.66	0.1699	0.0171	0.1528
12 Mar 2002	0.588	Steady	0.34	0.27	0.48	0.47	105.1	18.14	0.0732	0.0124	0.0609
19 Mar 2002	0.178	Steady	0.26	0.13	0.56	0.56	24.24	4.260	0.0251	0.0145	0.0106

Table 6 Bedload data and hydraulic parameters for the bedload measurements at the Swift Creek gauging station. See fig 1 for location of site. Q is water discharge; V is mean flow velocity; Y_m is mean flow depth; D_{50} is bedload median size; D_m is mean bedload size; Qs is bedload flux or dry mass per unit time; Qsw is specific bedload flux or dry mass per unit width and time; ω is unit stream power; ω_0 is threshold unit stream power from Bagnold (1980); and $\omega - \omega_0$ is excess unit stream power. These constitute the 'total data set'. [1] data removed to form 'reliable data set'. [2] data removed to form 'censored data set'.

Date	Q (m^3/s)	Stage Change	V (m/s)	Y_m (m)	D_{50} (mm)	D_m (mm)	Qs (g/s)	Qsw (g/m.s)	ω (kg/m.s)	ω_0 (kg/m.s)	ω´ (kg/m.s)
15 Dec 1998[1]	1.250	Falling	0.41	0.38	0.46	0.50	26.04	5.426	0.1474	0.0121	0.1353
6 Jan 1999	1.081	Steady	0.40	0.34	0.40	0.42	48.44	8.074	0.1318	0.0096	0.1222
20 Jan 1999	1.306	Steady	0.42	0.38	0.43	0.46	211.5	35.25	0.1524	0.0101	0.1423
3 Feb 1999[1,2]	6.279	Falling	0.57	0.94	0.58	0.63	327.1	56.89	0.5082	0.0165	0.4917
10 Feb 1999	11.65	Falling	0.65	1.33	0.48	0.56	625.5	104.3	0.8165	0.0146	0.8019
17 Feb 1999[2]	1.732	Falling	0.44	0.45	0.60	0.72	316.7	49.88	0.1893	0.0157	0.1736
23 Feb 1999[2]	1.201	Falling	0.41	0.37	0.53	0.53	292.7	46.83	0.1430	0.0150	0.1280
2 Mar 1999	0.820	Steady	0.38	0.30	0.55	0.59	123.4	19.43	0.1067	0.0146	0.0921
9 Mar 1999	2.374	Steady	0.47	0.54	0.56	0.57	34.46	6.323	0.2410	0.0164	0.2246
18 Mar 1999[1]	4.351	Falling	0.53	0.76	0.64	0.65	161.8	31.11	0.3836	0.0191	0.3645
23 Mar 1999[1,2]	2.802	Falling	0.49	0.59	0.63	0.70	426.1	67.64	0.2737	0.0158	0.2579
30 Mar 1999	2.121	Falling	0.46	0.52	0.40	0.43	175.8	28.36	0.2267	0.0122	0.2145
6 Apr 1999[2]	1.770	Steady	0.44	0.46	0.51	0.53	507.1	78.01	0.1924	0.0150	0.1774
12 Apr 1999	1.067	Steady	0.40	0.34	0.53	0.56	81.42	12.43	0.1306	0.0131	0.1175
20 Apr 1999	0.347	Steady	0.32	0.18	0.56	0.59	71.48	11.17	0.0551	0.0138	0.0413
27 Apr 1999	0.510	Steady	0.35	0.23	0.53	0.57	112.9	17.36	0.0741	0.0124	0.0616
4 May 1999	0.103	Steady	0.25	0.09	0.54	0.52	12.22	1.852	0.0217	0.0126	0.0090
3 Dec 1999	0.699	Falling	0.37	0.27	0.56	0.59	44.29	7.382	0.0944	0.0159	0.0785
21 Dec 1999[1]	2.317	Falling	0.47	0.53	0.49	0.50	45.08	7.909	0.2366	0.0133	0.2233
4 Jan 2000	1.130	Falling	0.41	0.35	0.54	0.58	77.84	13.08	0.1364	0.0127	0.1237
11 Jan 2000	1.616	Falling	0.44	0.43	0.48	0.50	35.36	5.892	0.1795	0.0102	0.1693
18 Jan 2000[1]	4.653	Falling	0.54	0.79	0.49	0.52	98.86	18.31	0.4039	0.0109	0.3930

Date	Q (m^3/s)	Stage Change	V (m/s)	Y_m (m)	D_{50} (mm)	D_m (mm)	Qs (g/s)	Qsw (g/m.s)	ω (kg/m.s)	$ω_0$ (kg/m.s)	ω´ (kg/m.s)
25 Jan 2000	2.223	Falling	0.47	0.52	0.53	0.53	218.5	35.81	0.2292	0.0171	0.2121
1 Feb 2000	0.942	Steady	0.39	0.32	0.52	0.52	189.8	30.51	0.1186	0.0162	0.1024
8 Feb 2000	1.467	Falling	0.43	0.41	0.45	0.47	61.54	10.09	0.1667	0.0102	0.1565
15 Feb 2000	4.121	Falling	0.53	0.74	0.43	0.45	120.9	28.13	0.3680	0.0067	0.3612
22 Feb 2000[2]	1.583	Falling	0.43	0.43	0.58	0.60	381.6	59.62	0.1766	0.0168	0.1599
29 Feb 2000	4.176	Steady	0.53	0.74	0.49	0.51	154.5	33.58	0.3717	0.0108	0.3609
7 Mar 2000[2]	2.504	Falling	0.48	0.56	0.62	0.64	855.2	142.5	0.2511	0.0172	0.2338
14 Mar 2000[1]	6.106	Falling	0.57	0.92	0.56	0.57	222.7	43.66	0.4974	0.0182	0.4793
21 Mar 2000	2.053	Falling	0.46	0.50	0.52	0.53	56.43	11.76	0.2156	0.0170	0.1986
28 Mar 2000[2]	1.528	Steady	0.43	0.42	0.57	0.58	241.4	36.85	0.1719	0.0167	0.1552
6 Apr 2000	0.765	Falling	0.38	0.28	0.54	0.54	194.8	29.97	0.1012	0.0160	0.0852
11 Apr 2000	3.395	Falling	0.51	0.66	0.45	0.45	76.62	18.24	0.3171	0.0107	0.3065
20 Apr 2000[2]	1.268	Steady	0.42	0.38	0.56	0.57	279.0	43.93	0.1490	0.0165	0.1325
2 May 2000	0.631	Steady	0.36	0.25	0.54	0.54	129.5	20.55	0.0873	0.0158	0.0715
16 May 2000	0.276	Steady	0.31	0.16	0.45	0.46	12.62	1.975	0.0462	0.0091	0.0371
4 Dec 2000	0.552	Falling	0.35	0.24	0.53	0.56	8.070	2.002	0.0787	0.0157	0.0631
9 Jan 2001[1]	3.220	Rising	0.50	0.64	0.48	0.66	10.54	1.728	0.3045	0.0082	0.2963
17 Jan 2001[1,2]	8.370	Falling	0.61	1.10	0.53	0.55	62.54	12.51	0.6335	0.0185	0.6150
23 Jan 2001[1,2]	1.818	Falling	0.45	0.46	0.61	0.63	201.8	33.08	0.1964	0.0169	0.1795
30 Jan 2001[2]	3.470	Steady	0.51	0.67	0.42	0.44	16.94	4.578	0.3225	0.0067	0.3158
6 Feb 2001[2]	1.905	Rising	0.45	0.48	0.56	0.57	359.7	71.93	0.2036	0.0170	0.1867
13 Feb 2001[1,2]	10.72	Rising	0.64	1.27	0.53	0.55	233.5	51.89	0.7656	0.0188	0.7469
20 Feb 2001	3.070	Steady	0.50	0.62	0.53	0.52	204.6	32.47	0.2936	0.0175	0.2761
27 Feb 2001	2.150	Steady	0.46	0.51	0.42	0.43	80.02	19.05	0.2234	0.0081	0.2154
6 Mar 2001	1.370	Steady	0.42	0.40	0.50	0.48	73.70	12.28	0.1582	0.0166	0.1415

Date	Q (m^3/s)	Stage Change	V (m/s)	Y_m (m)	D_{50} (mm)	D_m (mm)	Qs (g/s)	Qsw (g/m.s)	ω (kg/m.s)	$ω_0$ (kg/m.s)	ω´ (kg/m.s)
13 Mar 2001	1.230	Steady	0.41	0.37	0.43	0.44	79.60	18.51	0.1456	0.0101	0.1356
20 Mar 2001	1.930	Steady	0.45	0.48	0.48	0.49	180.1	26.87	0.2057	0.0103	0.1954
27 Mar 2001	1.485	Falling	0.43	0.41	0.62	0.66	190.8	29.81	0.1682	0.0167	0.1515
4 Apr 2001	3.870	Steady	0.52	0.71	0.53	0.54	76.70	13.22	0.3507	0.0177	0.3330
10 Apr 2001[2]	0.770	Steady	0.38	0.29	0.52	0.52	583.5	106.1	0.1017	0.0124	0.0892
17 Apr 2001	0.410	Steady	0.33	0.20	0.59	0.63	64.19	10.52	0.0627	0.0153	0.0474
23 Jan 2002	0.203	Steady	0.29	0.13	0.57	0.58	8.600	1.564	0.0366	0.0146	0.0220
12 Feb 2002	6.585	Falling	0.58	0.96	0.55	0.56	169.0	32.50	0.5271	0.0183	0.5089
19 Feb 2002[2]	3.590	Steady	0.51	0.68	0.60	0.62	187.1	41.58	0.3310	0.0176	0.3134
26 Feb 2002[2]	1.780	Steady	0.45	0.46	0.60	0.64	540.8	90.74	0.1933	0.0169	0.1764
4 Mar 2002[1]	4.245	Falling	0.53	0.75	0.58	0.61	170.0	28.34	0.3764	0.0178	0.3586
12 Mar 2002[2]	7.298	Falling	0.59	1.02	0.45	0.46	85.82	22.29	0.5703	0.0111	0.5592
19 Mar 2002	0.138	Steady	0.27	0.11	0.51	0.53	24.16	4.860	0.0272	0.0142	0.0130

3.3 Bedload flux

3.3.1 Discharge-based relationships

The mean bedload flux (Qs) for all double traverses at each gauging station was regressed against the corresponding mean discharge (Q) and the following least squares linear equations were derived:

$$Qs = 119.38\ Q - 26.604 \quad (13)$$

F ratio = 137.11

$\rho = 6.11757 \times 10^{-16}$

Adjusted $R^2 = 0.727$

Standard Error = 38.33 g/s

N = 52 (East Tributary)

$$Qs = 55.876\ Q + 24.692 \quad (14)$$

F ratio = 21.276

$\rho = 2.41781 \times 10^{-5}$

Adjusted $R^2 = 0.266$

Standard Error = 77.64 g/s

N = 57 (Upper Swift Creek)

$$Qs = 15.372\ Q + 138.14 \qquad (15)$$

F ratio = 2.913

$\rho = 0.0932$

Adjusted $R^2 = 0.0314$

Standard Error = 169.4 g/s

N = 60 (Swift Creek)

These relationships are shown in Figure 7. While Equations 13 and 14 are highly significant ($\rho < 0.00001$), discharge only adequately explains the variance in bedload flux (Adjusted R^2 = 0.727) for Equation 13. Furthermore, residuals are uniformly distributed about the regression line for only Equations 13 and 14 (Fig 8). Equation 15 clearly has a non-uniform distribution of residuals (Fig 8C) and a very large standard error. Linear regressions are commonly applied in bedload studies and the use of mean channel parameters (as opposed to point values) yields fewer and less significant relationships (Blizzard & Wohl 1998). We only use mean channel parameters because we seek to explain bedload transport at gauging stations not at individual points within a cross section.

The test of Chayes (1970) showed that a second order polynomial regression did not significantly increase the explained variance over the first order polynomial at all three sites. We believe that a statistically significant relationship must also explain at least 0.60 of the variance in bedload flux to be reliable for yield calculations. We acknowledge that this is a stringent criterion, especially as Blizzard and Wohl (1998) found R^2 values no higher than 0.654 for bedload transport in a cobble-bed stream in the Rocky Mountains, USA. The accuracy of computed bedload yields partly depends on the accuracy of the bedload rating as well as on the method of computation. Therefore, all bedload relationships used for yield calculations (see section 3.4) have a $\rho \leq 0.05$ and an adjusted $R^2 > 0.60$.

In an attempt to improve the regressions, the bedload data were interrogated for reliability. It is usual for bedload flux to vary greatly over space and time. Variations in rate of up to 4 times have been reported (Carey 1985, Gomez 1991) and so all transects where the paired values differed by more than 4 times were deleted from the database. In addition, all bedload gaugings where the gauge height change during the paired transects was $\geq$ 0.02 m were deleted. These bedload gaugings comprise the 'reliable data set' as opposed to the 'total data set' used above and contained in Tables 4, 5 and 6. The values deleted from the total data set to yield the reliable data set are flagged in Tables 4, 5 and 6. However, because few data points were found to be unreliable, improved ratings for the raw reliable data set over the raw total data set were only found for East Tributary:

$$Qs = 129.79\ Q - 30.491 \qquad (16)$$

F ratio = 128.44

$\rho = 1.22 \times 10^{-14}$

Adjusted $R^2 = 0.7391$

Standard Error = 37.5 g/s

N = 46 (East Tributary)

A logarithmic transformation is commonly applied in bedload studies because transport rates and discharge typically span many orders of magnitude and the raw data may be skewed towards small transport rates and low discharges (Barry et al 2004, King et al 2004). Therefore, the total data sets were also $\log_{10}$-transformed and the following least squares linear equations were derived:

$$\mathrm{Log}_{10}Qs = 1.994 \log_{10}Q + 1.8119 \qquad (17)$$

F ratio = 154.30

$\rho = 6.7 \times 10^{-17}$

Adjusted $R^2 = 0.7504$

Standard Error = 2.73 g/s

N = 52 (East Tributary)

$$\mathrm{Log}_{10}Qs = 0.592 \log_{10}Q + 1.7475 \qquad (18)$$

F ratio = 18.190

$\rho = 7.9247781 \times 10^{-5}$

Adjusted $R^2 = 0.2349$

Standard Error = 2.95 g/s

N = 57 (Upper Swift Creek)

$$\mathrm{Log}_{10}Qs = 0.4817 \log_{10}Q + 1.926 \qquad (19)$$

F ratio = 13.497

$\rho = 0.000523$

Adjusted $R^2 = 0.1748$

Standard Error = 2.75 g/s

N = 60 (Swift Creek)

These relationships are all highly significant and are shown in Figure 9. The regressions on $\log_{10}$-transformed data for East Tributary and Swift Creek explained a higher percentage variance than for the raw data. However, only the East Tributary $\log_{10}$-transformed bedload rating explained more than 0.60 of the variance in bedload flux. Again the test of Chayes (1970) showed that a second order polynomial regression did not significantly increase the explained variance over the first order polynomial for all three stations. The regression on the $\log_{10}$-transformed 'reliable data set' did improve the coefficient of determination at Swift Creek over the total data set but the adjusted R^2 was < 0.233. At Upper Swift Creek, the regression on $\log_{10}$-transformed reliable data was less significant than for the total data set.

There is no well-defined threshold of motion at any gauge for the $\log_{10}$-transformed rating curves (Fig 9). Our field observations indicate that ripples and dunes and ripples superimposed on dunes and transverse bars are the dominant bedforms at all three gauging stations and, therefore, a threshold condition should exist based on Simons et al's (1965) results. According to Equation 13, threshold of motion should occur at a discharge greater than 0.223 m^3/s at East Tributary. Eleven bedload gaugings were obtained at discharges lower than the estimated threshold of motion and the mean bedload flux for these gaugings was only 2.483 ± 0.895 g/s. This zone of initial displacement is clearly shown as a clustering of points around zero flux (Fig 7A). Therefore, these eleven values were deleted from the East Tributary data set to form the 'above threshold data set' (Table 4) and regressions were recalculated on raw and $\log_{10}$-transformed data:

$$Qs = 126.29\ Q - 35.382 \qquad (20)$$

F ratio = 112.07

$\rho = 4.9738 \times 10^{-13}$

Adjusted $R^2 = 0.7352$

Standard Error = 40.49 g/s

N = 41 (East Tributary)

$$\text{Log}_{10}Qs = 1.6572\ \text{Log}_{10}Q + 1.7618 \qquad (21)$$

F ratio = 62.455

$\rho = 1.2764 \times 10^{-9}$

Adjusted $R^2 = 0.6057$

Standard Error = 2.23 g/s

N = 41 (East Tributary)

These relationships are shown in Figure 10. Equation 20 has a marginally greater coefficient of determination than Equation 13 but Equation 21 has a lower coefficient of determination than Equation 17. The bedload ratings on raw data for Upper Swift Creek and Swift Creek gauges (Fig 7B and 7C) apparently exhibit a threshold of motion at 0 m^3/s. However, recent research has questioned the existence of a true threshold condition because measured bedload fluxes usually occur at much lower discharges than the predicted threshold value (Barry et al 2004). However, Reid and Frostick (1986) found that the mean unit stream power at the finish of bedload transport for a gravel-bed stream near London may be only 20% of that prevailing at threshold of motion. Therefore, we have not further investigated threshold conditions at our three gauging stations.

Specific bedload flux is defined as dry mass per unit width and time (for example, see Barry et al 2004) and is the usual form of expression for bedload flux equations. As the active width of bedload transport (bed width) is not necessarily constant as discharge varies at a site due to scour and fill, specific or unit width bedload fluxes were also calculated. The mean bedload flux per unit bed width and unit time (Qsw) for all double traverses at each gauging station was regressed against the corresponding mean discharge (Q) and the following least squares linear equations were derived for the total data set:

$$Qsw = 30.723\ Q - 6.523 \qquad (22)$$

F ratio = 138.2

$\rho = 5.29 \times 10^{-16}$

Adjusted $R^2 = 0.729$

Standard Error = 9.83 g/m.s

N = 52 (East Tributary)

$$Qsw = 9.5066\ Q + 4.0677 \quad (23)$$

F ratio = 22.7156

$\rho = 1.42 \times 10^{-5}$

Adjusted $R^2 = 0.2794$

Standard Error = 12.78 g/m.s

N = 57 (Upper Swift Creek)

$$Qsw = 3.2968\ Q + 22.322 \quad (24)$$

F ratio = 4.9514

$\rho = 0.02997$

Adjusted $R^2 = 0.0627$

Standard Error = 27.87 g/m.s

N = 60 (Swift Creek)

These relationships are shown in Figure 11. The results for mean bedload flux per unit bed width and time have essentially the same explained variance as for the bedload rating curves (Equations 13, 14 & 15) indicating that the width of bedload transport varies proportionally with discharge. The test of Chayes (1970) showed that a second order polynomial regression did not significantly increase the explained variance over the first order polynomial for mean bedload flux per unit width and time. Similarly, improved coefficients of determination were not obtained for the 'reliable data set' at East Tributary and Upper Swift Creek. Only a minor increase in the coefficient of determination was found for Upper Swift Creek which did not exceed 0.60. The above threshold data set at East Tributary did not yield a unit bedload flux rating with a higher coefficient of determination than for the whole data set. The maximum measured unit bedload flux in the Ngarradj catchment was less than 0.15 kg/m.s at Swift Creek gauge (see Fig 11C) which compares with the peak bedload flux rate ever recorded in the world of 10 kg/m.s for the semi-arid Nahal Yatir in Israel (Laronne et al 1992). The specific or unit bedload flux data sets were also $\log_{10}$-transformed and the following least squares linear equations were derived:

$$Log_{10}\ Qsw = 1.8909\ Log_{10}\ Q + 1.2418 \quad (25)$$

F ratio = 148.0

$\rho = 1.47 \times 10^{-16}$

Adjusted $R^2 = 0.7425$

Standard Error = 2.65 g/m.s

N = 52 (East Tributary)

$$Log_{10}\ Qsw = 0.569\ Log_{10}\ Q + 0.991 \quad (26)$$

F ratio = 18.76

$\rho = 6.35 \times 10^{-5}$

Adjusted $R^2 = 0.2407$

Standard Error = 2.79 g/m.s

N = 57 (Upper Swift Creek)

$Log_{10} Qsw = 0.5353 Log_{10} Q – 1.834$ (27)

F ratio = 19.01

$\rho = 5.39 \times 10^{-5}$

Adjusted $R^2 = 0.2339$

Standard Error = 2.58 g/m.s

N = 60 (Swift Creek)

Again, although all relationships are statistically significant, only the regression for East Tributary explains more than 0.60 of the variance. The regressions on log_{10}-transformed specific or unit bedload flux and discharge for the reliable data set either did not yield significantly improved results over the total data set or, if the adjusted R^2 was higher than for the total data set, it still did not exceed 0.60. Similarly, the above threshold data set at East Tributary did not produce a higher explained variance for log_{10}-transformed unit bedload flux and discharge over that for the whole data set.

The mean bedload flux data were also sorted by gauge height changes during each gauging at each station. Figure 12A shows the bedload ratings for raw data for rising stage, falling stage and steady discharge gaugings and Figure 12B, for the log_{10}-transformed data at East Tributary. All regressions are highly significant ($\rho<0.0033$). Bedload fluxes are highest for falling stages at discharges >0.6 m^3/s for raw data but the falling stage bedload rating passes below the rising stage rating at a discharge of 1.4 m^3/s for log_{10}-transformed data. Nevertheless, the range in discharge for rising stage and steady discharge gaugings is very small because of the timing of storm rainfall and runoff, discussed above (Moliere et al 2002b).

Figure 13A shows the bedload ratings for raw data for falling stage and steady discharge gaugings and Figure 13B, for the log_{10}-transformed data at Upper Swift Creek. There are only two rising stage gaugings and hence the data are excluded from Fig 13. Three of the four regressions are significant ($\rho<0.0209$) but the coefficients of determination are too small (Adjusted $R^2 <0.2716$) to be reliable. Figure 14A shows the bedload ratings for raw data for falling stage, rising stage and steady discharge gaugings and Figure 14B, for the log_{10}-transformed data at Swift Creek. There are only three rising stage gaugings and the maximum steady discharge gauging is only at a discharge of 4.176 m^3/s. Furthermore, the ratings for raw data are not significant at $\rho < 0.05$ and, while the ratings on log_{10}-transformed data are statistically significant, the adjusted R^2 values never exceed 0.2311. Therefore, the stage change ratings cannot be used for reliable load calculations, except at East Tributary, because, except for falling stage gaugings, they do not cover an adequate discharge range and because discharge does not explain a meaningful amount of the variance in bedload flux.

To redress the predominance of falling stage samples would entail undertaking night bedload gaugings where access is solely dependent on helicopter. Clearly this is impossible for safety and cost reasons. Therefore, separate ratings for falling and rising stages and steady discharges were not determined for the reliable data set at all stations and for the above threshold data set at East Tributary because of the reduction in sample size.

Thus far, reliable bedload ratings have only been established for East Tributary (Equations 13, 16, 17, 20, 21, 22 & 25). Although some of the other ratings are statistically significant, the amount of explained variance in bedload flux is too small to be meaningful. Therefore, the influence of unit stream power on bedload transport (Bagnold 1973, 1977, 1979, 1980, 1986) was investigated to determine if more reliable ratings could be established for hydraulic parameters instead of discharge. Stream power equations in general and Bagnold's (1980) formula in particular best matched measured bedload fluxes (Gomez & Church 1989). Unit stream power (ω in kg/m.s) was determined, as outlined below.

3.3.2 Stream power-based relationships

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:

$$\Omega = \rho.Q.S \qquad (28)$$

where ρ is fluid density and S is slope of the energy grade line.

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:

$$\omega = \Omega/w = \tau.V \qquad (29)$$

where w is channel width and τ is bed shear stress.

Unit stream power is often closely correlated with bedload transport (Bagnold 1973, 1977, 1980, 1986, Leopold & Emmett 1976, Reid & Frostick 1986, Laronne & Reid 1993, Blizzard & 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 stream 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 (ω′) is defined as:

$$\omega' = \omega - \omega_0 \qquad (30)$$

where ω_0 is threshold unit stream power for first displacement of bedload.

Bagnold (1980) proposed that ω_0 can be approximately defined as:

$$\omega_0 = 290\ D^{1.5} \log_{10}(12Y/D) \qquad (31)$$

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

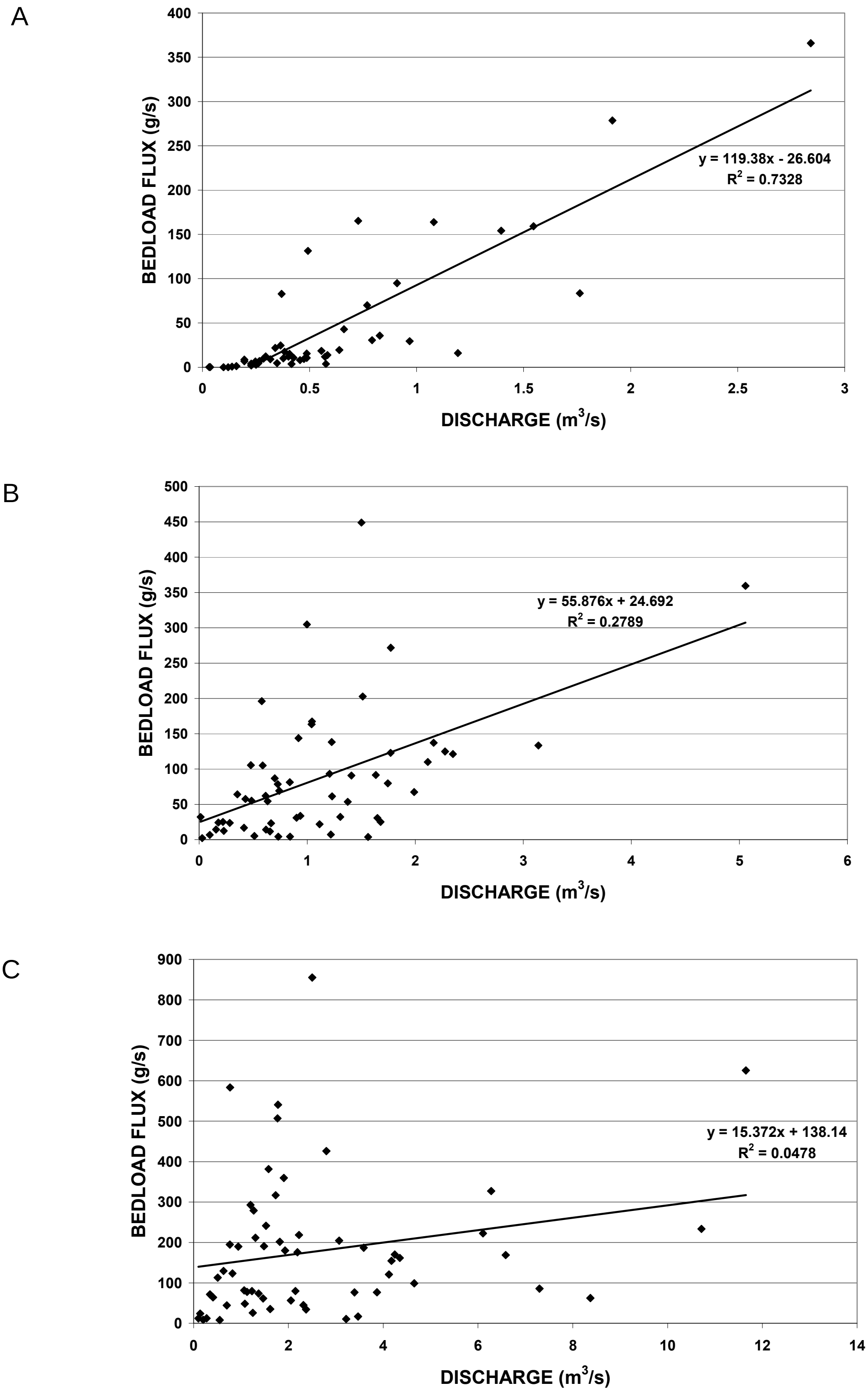


Figure 7 Bedload rating curves on raw data at (A) East Tributary gauge, (B) Upper Swift Creek gauge and (C) Swift Creek gauge

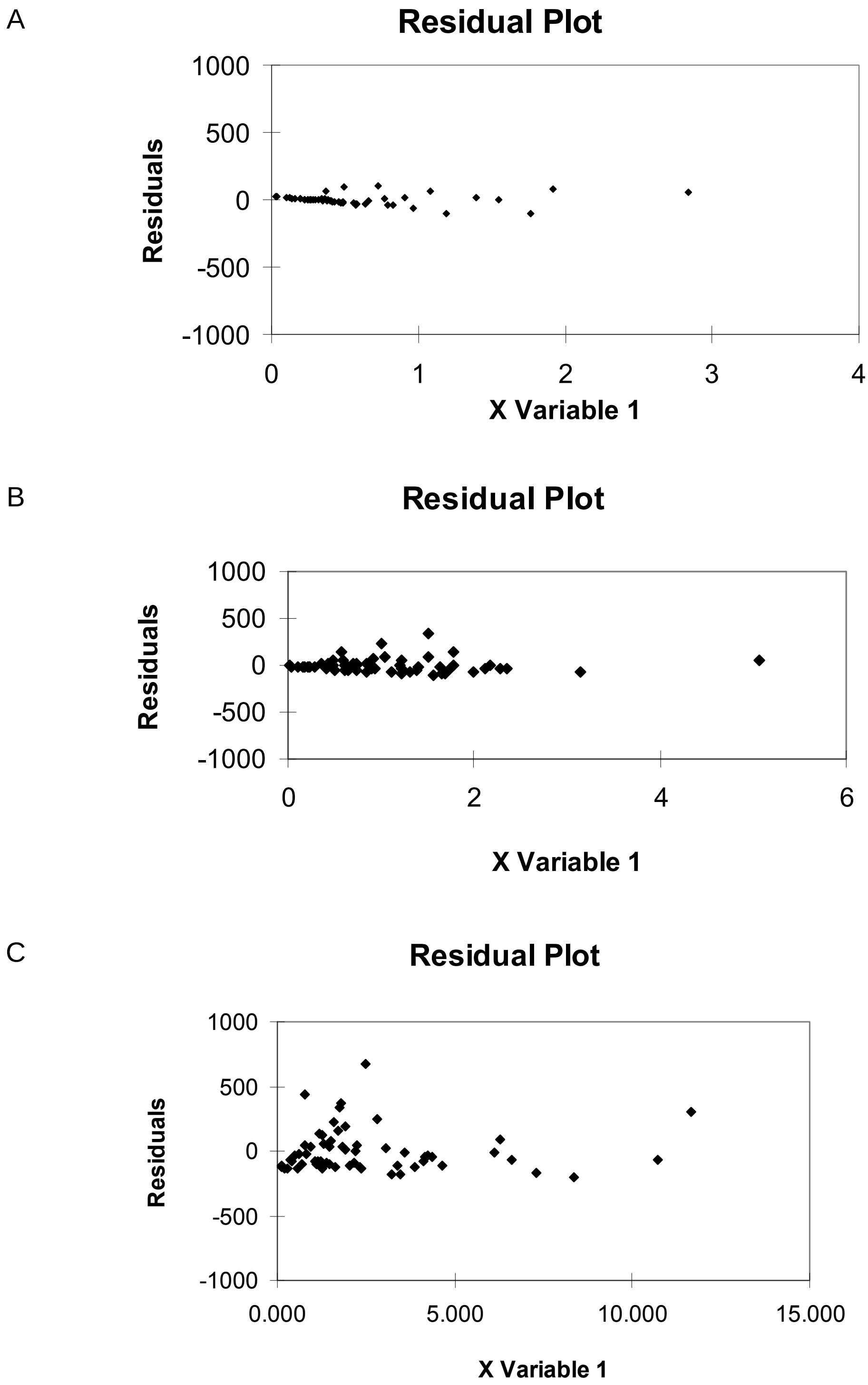


Figure 8 Distribution of residuals about the raw data bedload rating for (A) East Tributary gauge, (B) Upper Swift Creek gauge and (C) Swift Creek gauge

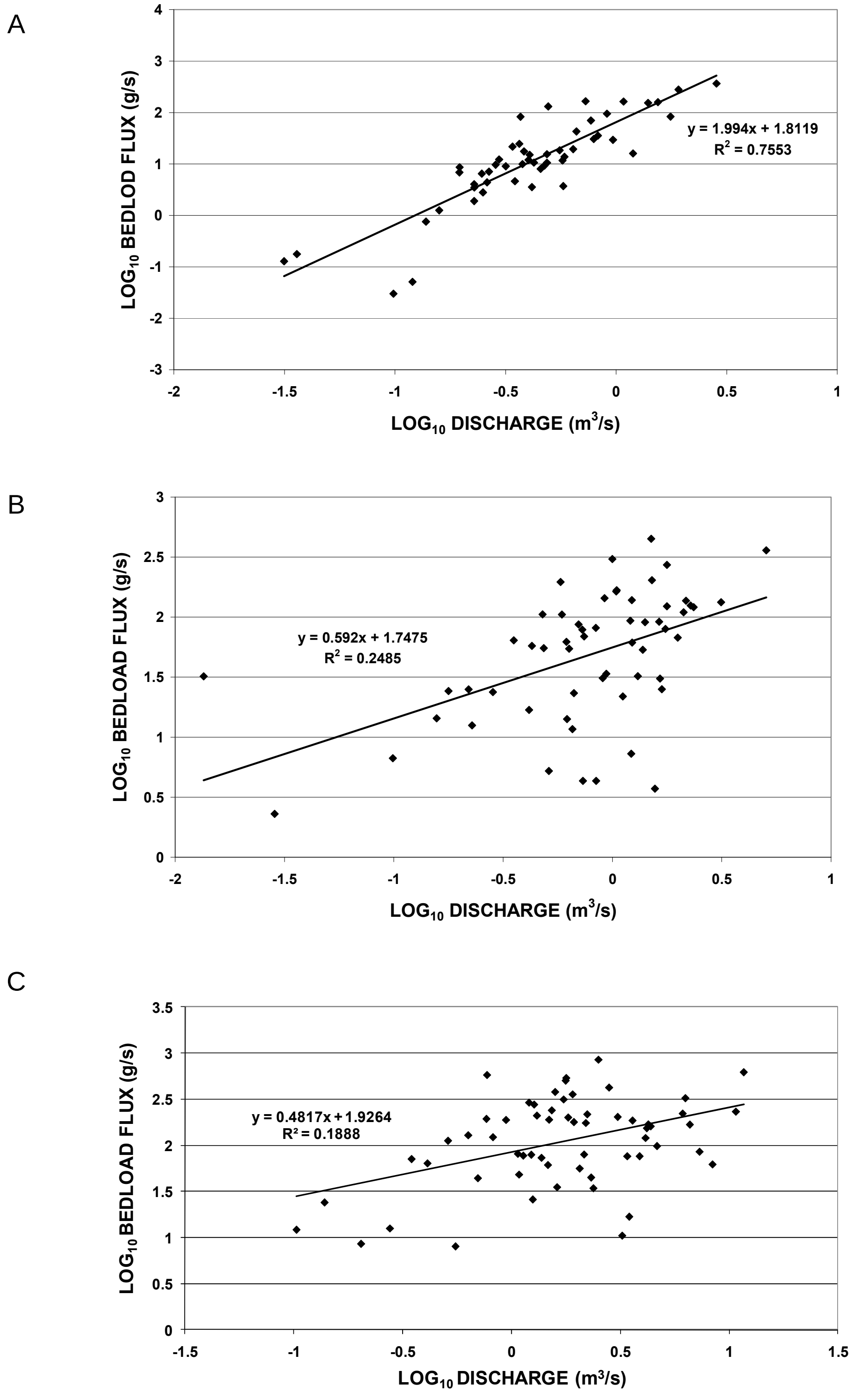


Figure 9 Bedload rating curves on $\log_{10}$ data at (A) East Tributary gauge, (B) Upper Swift Creek gauge and (C) Swift Creek gauge

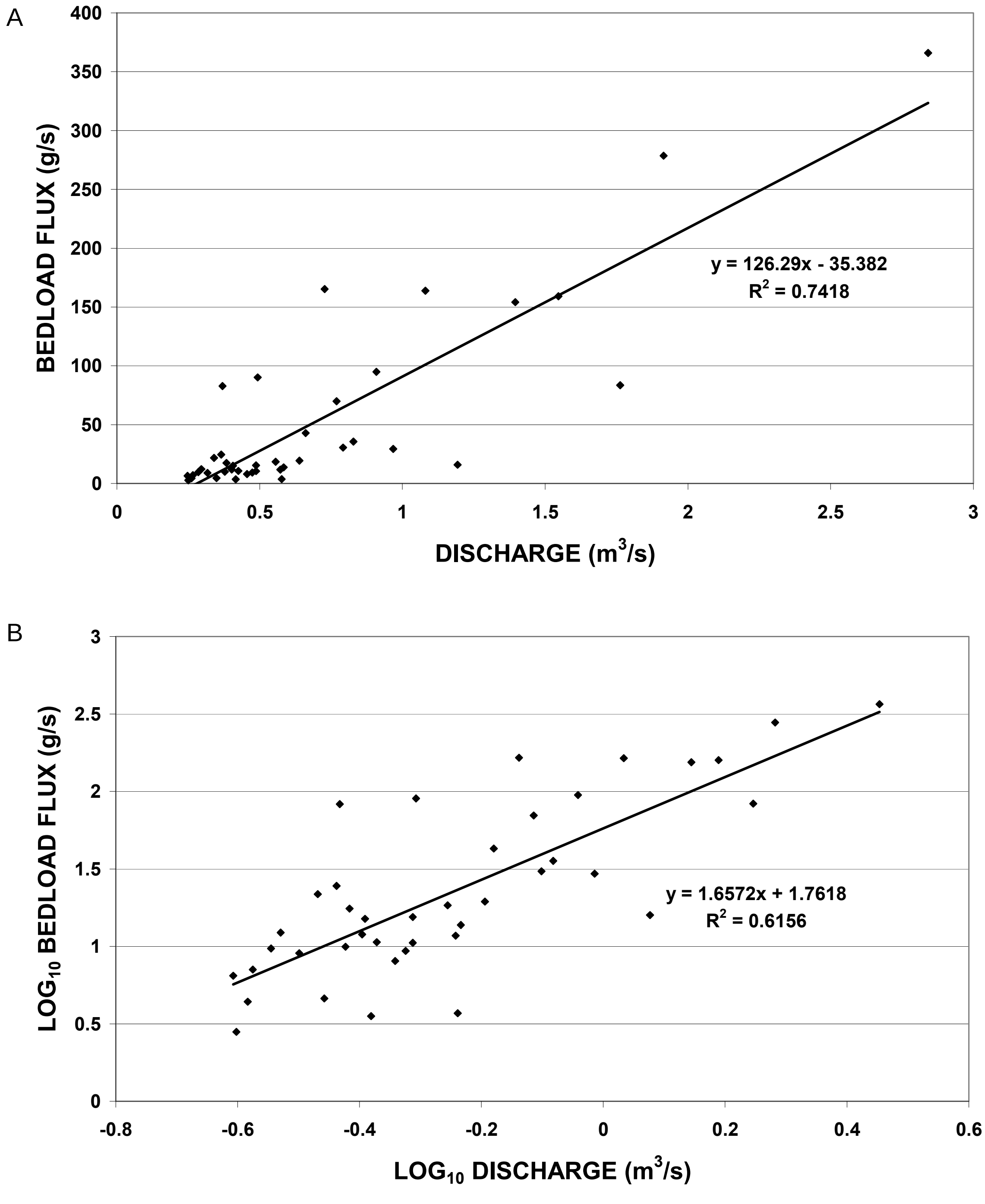


Figure 10 Bedload ratings on (A) raw data and (B) $\log_{10}$-transformed data with values deleted below a discharge of 0.223 m^3/s at East Tributary

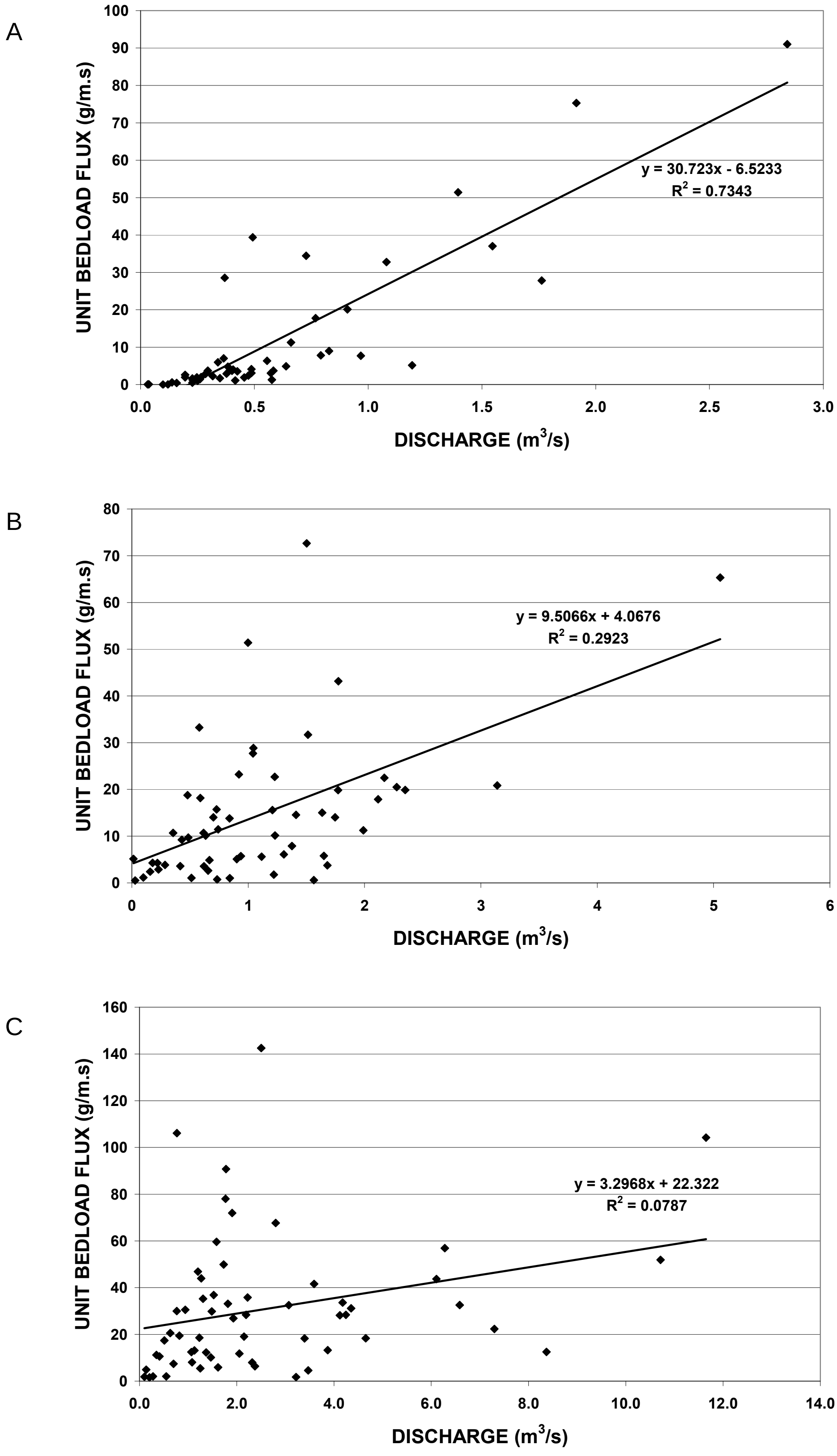


Figure 11 Rating curves of bedload flux per unit bed width and unit time versus discharge at (A) East Tributary gauge, (B) Upper Swift Creek gauge and (C) Swift Creek gauge

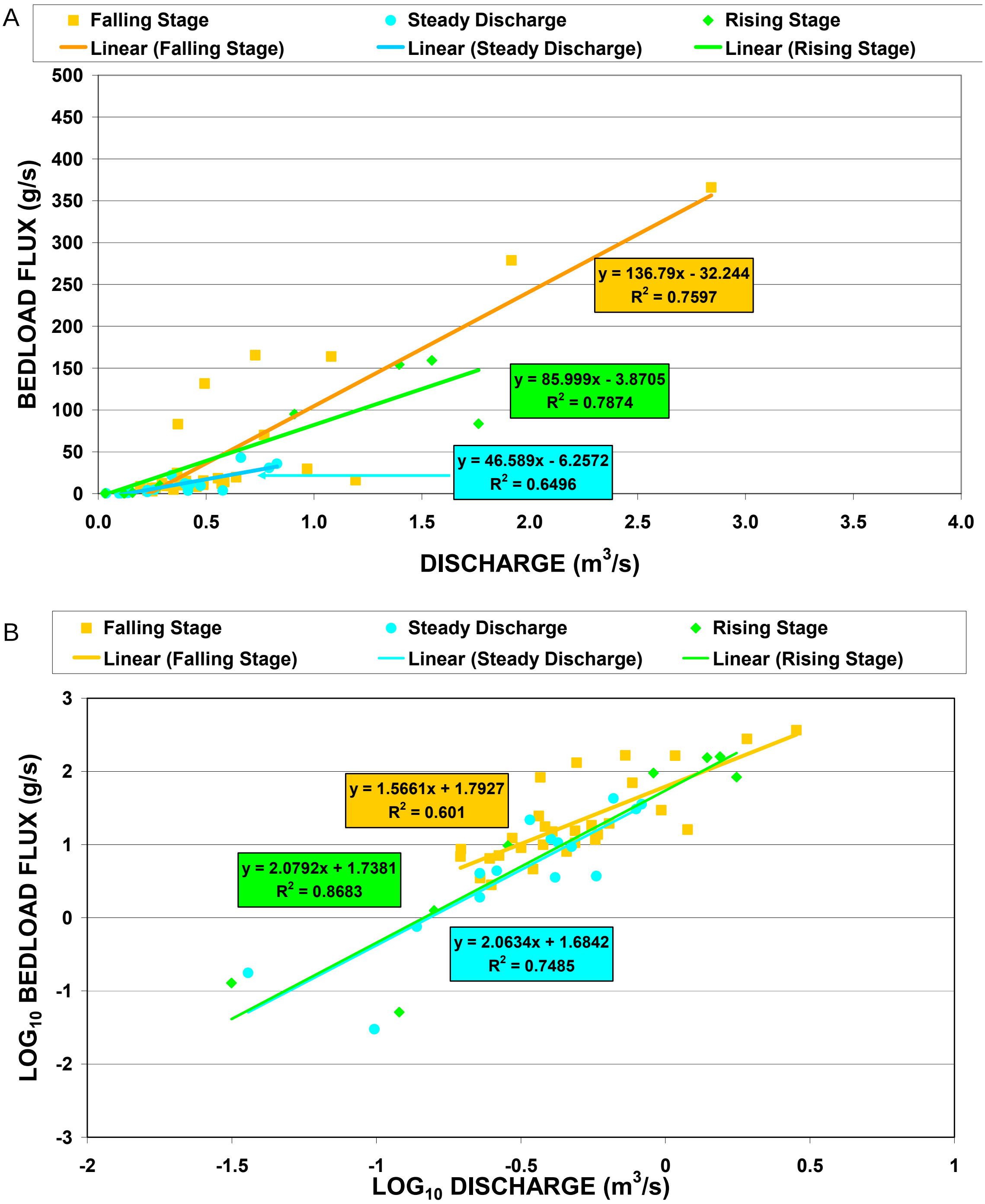


Figure 12 Bedload ratings for (A) raw and (B) $\log_{10}$-transformed data for falling stage, steady discharge and rising stage at East Tributary

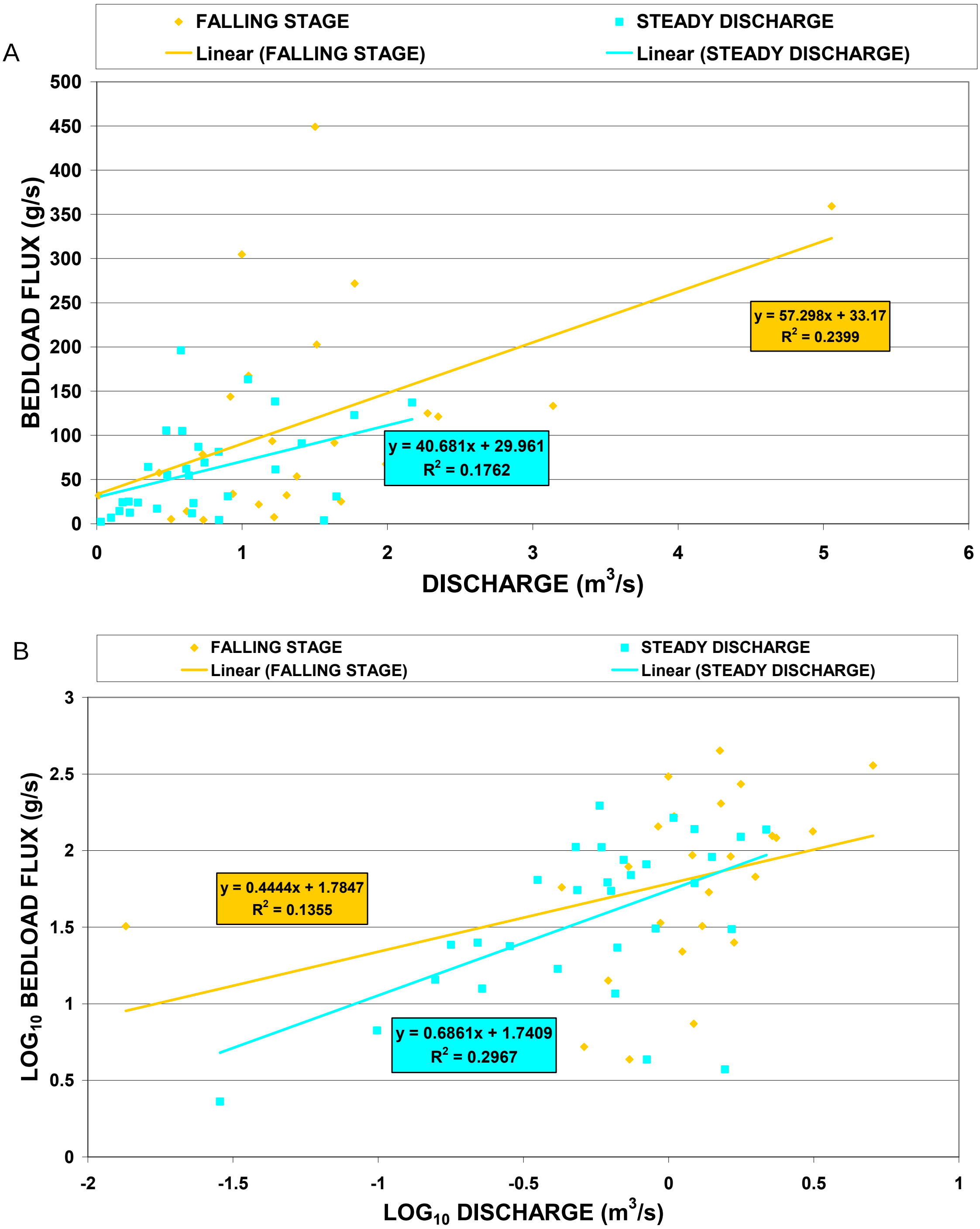


Figure 13 Bedload ratings for (A) raw and (B) log_{10}-transformed data for falling stage and steady discharge at Upper Swift Creek

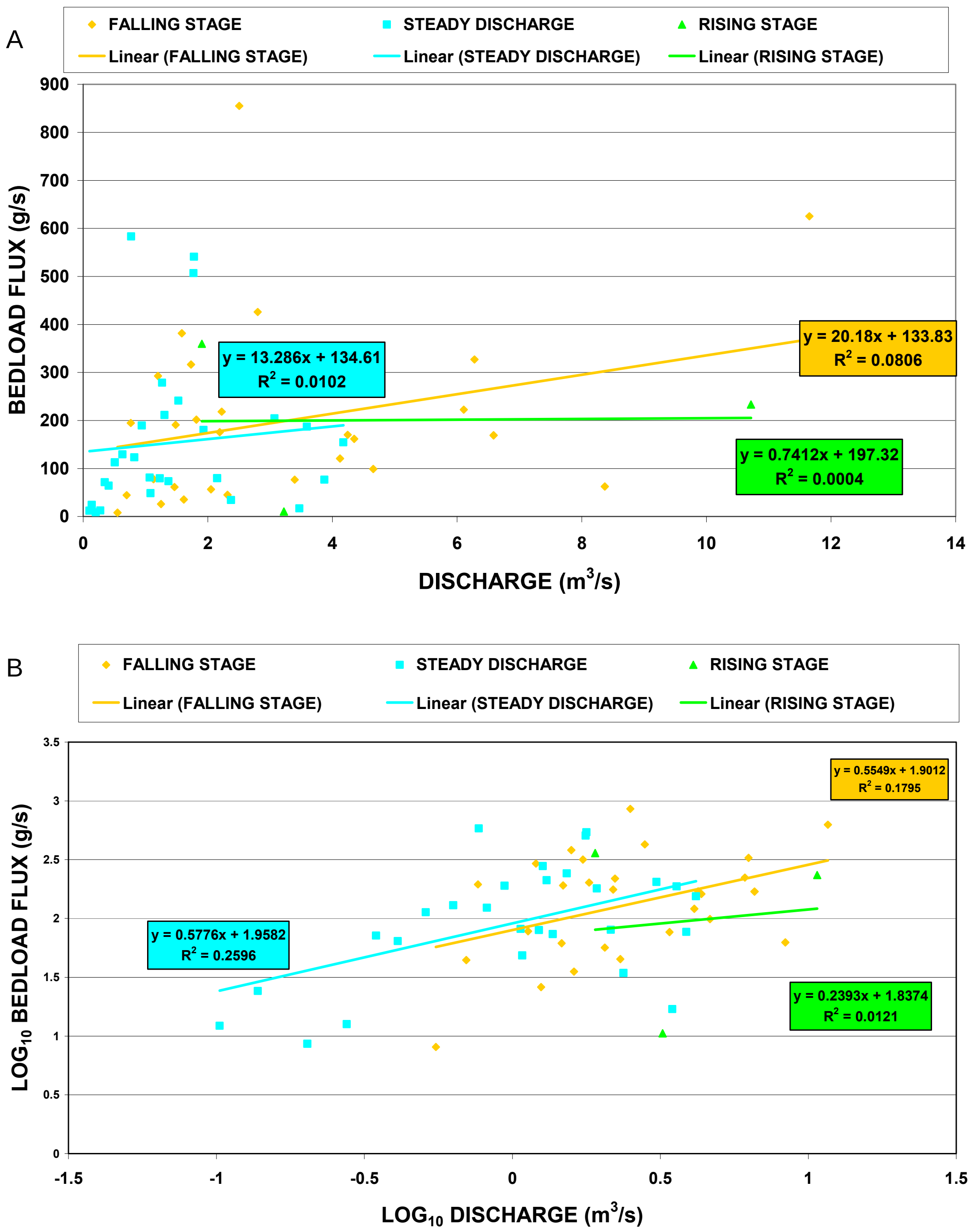


Figure 14 Bedload ratings for (A) raw and (B) $\log_{10}$-transformed data for falling stage, steady discharge and rising stage at Swift Creek

While other formulations for threshold unit stream power have been published (Leopold & Emmett 1997), they produce values similar to Equation 31. 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:

$$ib' = ib\,(Y/Y_r)^{0.66}\,(D/D_r)^{0.5} \qquad (32)$$

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 γ_s is specific gravity of sediment and γ is specific gravity of the fluid. Martin and Church (2000) found that Equation 32 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:

$$ib' = 0.28\,\omega'^{1.5} \qquad (33)$$

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

$$ib = \omega\, e_b / \tan\alpha \qquad (34)$$

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

Efficiency 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 & Emmett 1985). The remainder of the stream power is used in transporting water and suspended sediment over the varying boundary roughness (Mantz & Emmett 1985). These relationships are now explored for the Ngarradj Creek bedload data set (Tables 4, 5 and 6).

For the whole data sets at all three stations, the only significant relationships 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 (plots not shown) and the following least squares equations were obtained:

$$ib = 0.0127\,\omega - 0.0041 \qquad (35)$$

F ratio = 138.2

$\rho = 5.29 \times 10^{-16}$

Adjusted R^2 = 0.729

Standard Error = 0.0061 kg/m.s

N = 52 (East Tributary)

$Log_{10}ib = 1.8909\ Log_{10}\ \omega - 2.2979$ (36)

F ratio = 148.0

$\rho = 1.47 \times 10^{-16}$

Adjusted $R^2 = 0.7425$

Standard Error = 2.65 kg/m.s

N = 52 (East Tributary)

These equations have the same adjusted R^2 as Equations 22 and 25 respectively. This means that the terms to convert Qsw and Q to ib and ω respectively are constants for these data sets. 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:

$ib = 0.0127\ \omega' - 0.0039$ (37)

F ratio = 137.6

$\rho = 5.75 \times 10^{-16}$

Adjusted $R^2 = 0.7281$

Standard Error = 0.0061 kg/m.s

N = 52 (East Tributary)

$Log_{10}ib = 1.8056\ Log_{10}\ \omega' - 2.29$ (38)

F ratio = 144.48

$\rho = 2.31 \times 10^{-16}$

Adjusted $R^2 = 0.7378$

Standard Error = 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 15 and 16. The following least squares equations were derived:

$ib' = 0.1431\ \omega - 0.0724$ (39)

F ratio = 157.7

$\rho = 4.40409 \times 10^{-17}$

Adjusted $R^2 = 0.7545$

Standard Error = 0.0643 kg/m.s

N = 52 (East Tributary)

$ib' = 0.1432\ \omega' - 0.0706$ (40)

F ratio = 157.1

$\rho = 4.78 \times 10^{-17}$

Adjusted $R^2 = 0.7537$

Standard Error = 0.0644 kg/m.s

N = 52 (East Tributary)

$ib' = 0.0474\ \omega^2 - 0.0212\ \omega - 0.0057$ (41)

F ratio = 70.16

$\rho < 0.0001$

Adjusted $R^2 = 0.897$

Standard Error = 0.0416 kg/m.s

N = 52 (East Tributary)

$ib' = 0.0475\ \omega'^2 - 0.0203\ \omega' - 0.0056$ (42)

F ratio = 69.31

$\rho < 0.0001$

Adjusted $R^2 = 0.896$

Standard Error = 0.418 kg/m.s

N = 52 (East Tributary)

$Log_{10} ib' = 2.5539\ Log_{10}\ \omega - 1.6177$ (43)

F ratio = 252.71

$\rho = 3.4396 \times 10^{-21}$

Adjusted $R^2 = 0.8315$

Standard Error = 0.4367 kg/m.s

N = 52 (East Tributary)

$Log_{10} ib' = 2.5366\ Log_{10}\ \omega' - 1.0549$ (44)

F ratio = 246.3

$\rho = 5.86243 \times 10^{-21}$

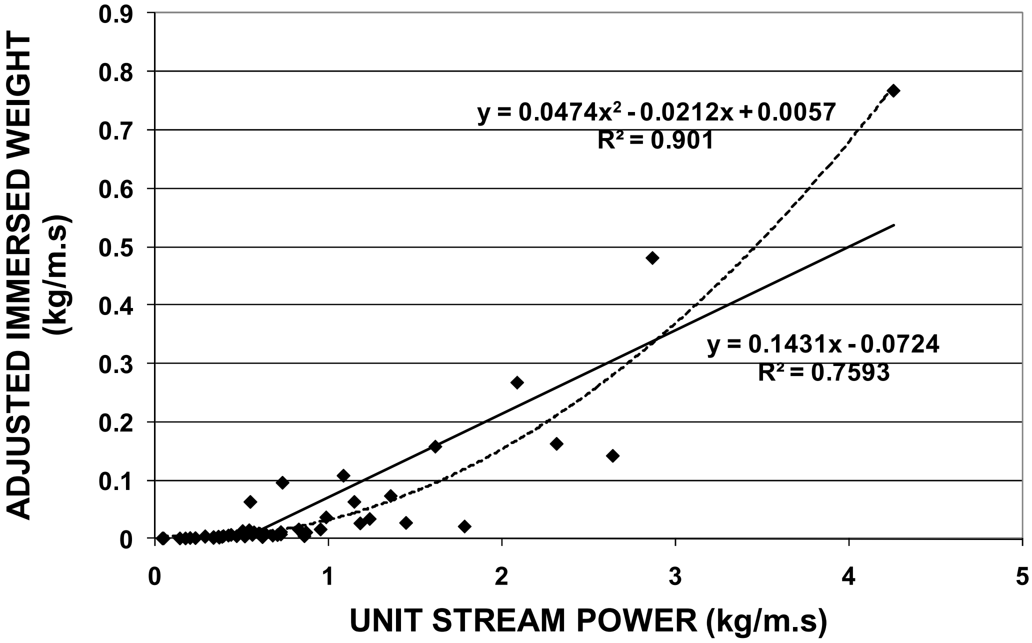
Adjusted $R^2 = 0.8279$

Standard Error = 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 41 & 42) significantly increased the explained variance over the first order polynomial for adjusted bedload immersed weight (Equations 39 & 40). This is shown in Figure 15. However, there is little difference between Equations 41 and 42, indicating the close similarity in values between ω and ω′.

A



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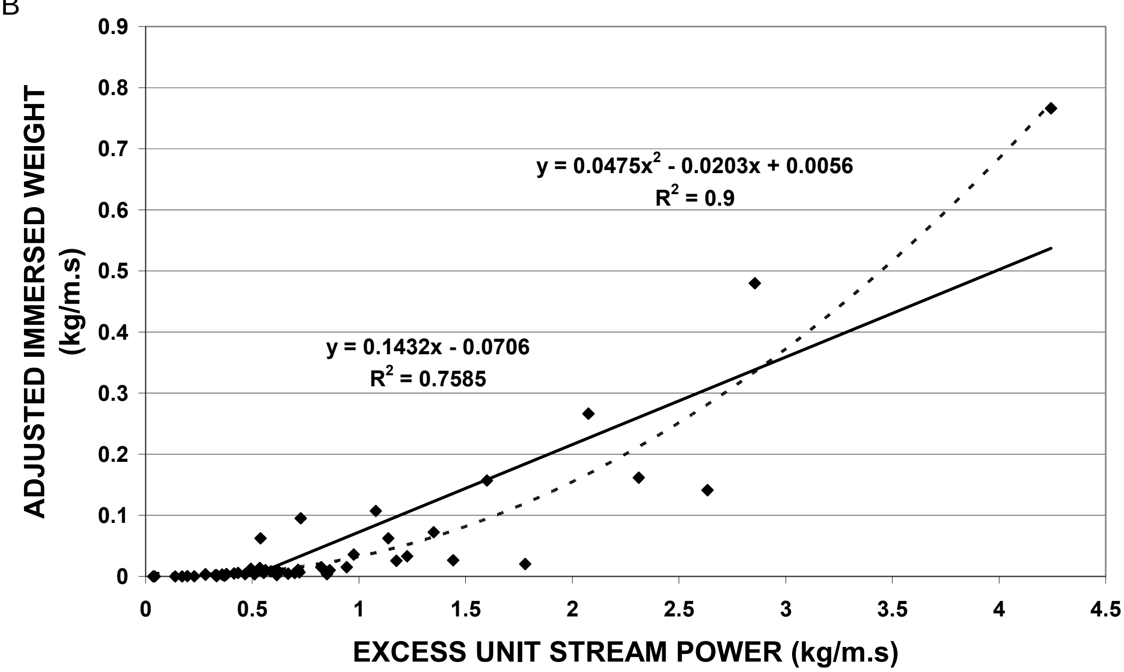


Figure 15 Relationships between adjusted immersed weight and (A) unit stream power, and (B) excess unit stream power for the East Tributary gauge

Equation 34 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 16. Most stream kinetic energy is clearly taken up overcoming 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 16). Such a result has been commonly reported (Bagnold 1973, Leopold & Emmett 1976, Reid & Frostick 1986, Laronne & Reid 1993).

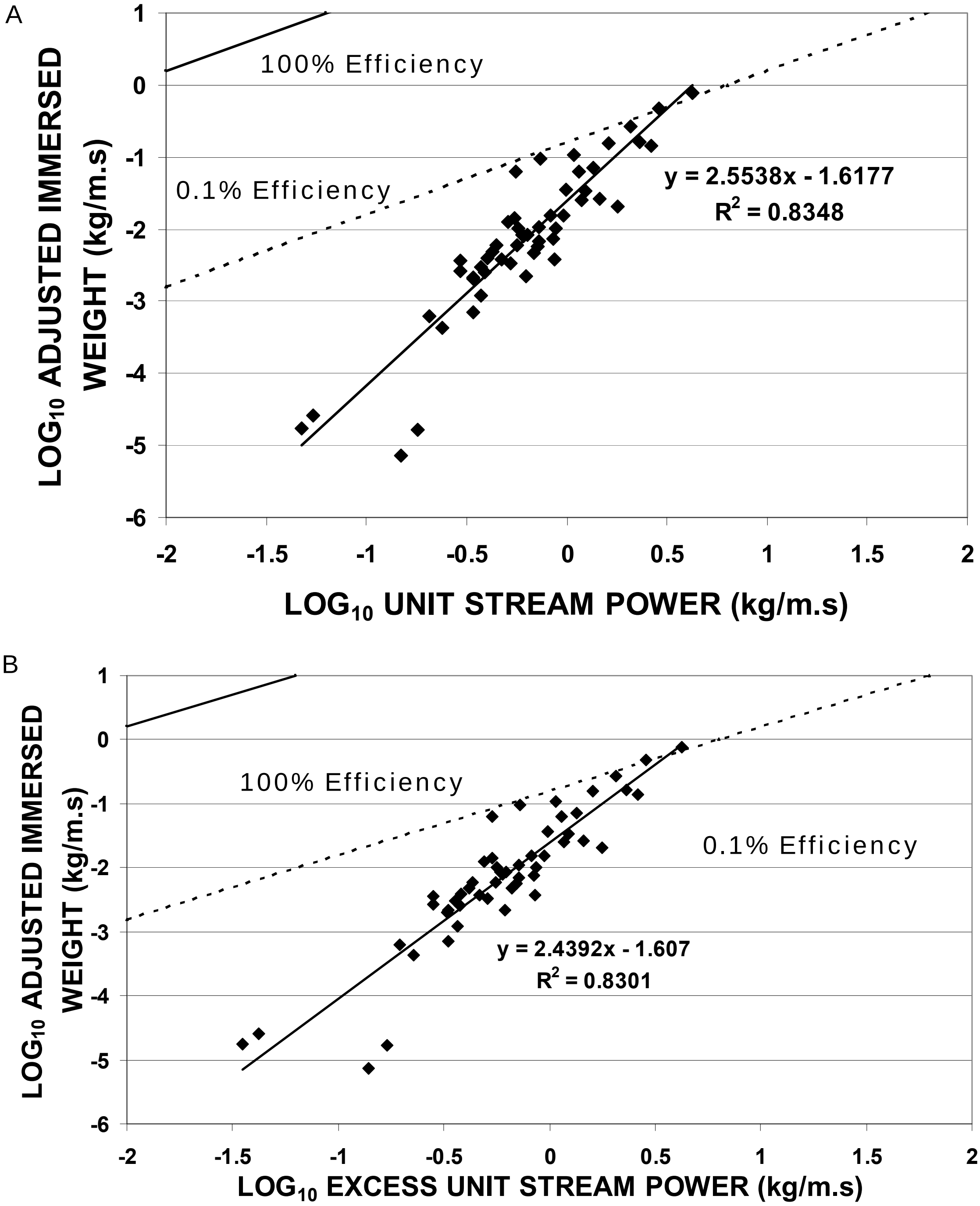


Figure 16 Relationships between log_{10} adjusted immersed weight and (A) log_{10} unit stream power, and (B) log_{10} excess unit stream power for the East Tributary gauge

The power function between adjusted immersed weight and excess unit stream power at East Tributary is simply derived by rearranging Equation 44 and taking the antilog of the y intercept (see Carlston 1969):

$$ib' = 0.0247\ \omega'^{2.5366} \qquad (45)$$

Equation 45 is very different to Equation 27 of Leopold and Emmett (1997) for the East Fork River.

Because of the high correlation between bedload flux and discharge, and their $\log_{10}$-transformed values for East Tributary, all the relationships tested above are also highly significant. The reliable and above threshold data sets for East Tributary were also tested for relationships between bedload immersed weight and adjusted immersed weight and the various measures of unit stream power. All relationships were statistically significant and adjusted R^2 always exceeded 0.60, except for two regressions for the 'above threshold data set' in Table 4. However, none of the regressions for the reliable and above threshold data sets exceeded the adjusted R^2 for the corresponding regression for the whole data set. Therefore, the results are not presented here.

Next, the reliable data sets for Upper Swift Creek and Swift Creek gauges were 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 adjusted $R^2 > 0.60$. Therefore, in the next section, the Upper Swift Creek and Swift Creek data were subjected to greater scrutiny in an attempt to find a significant bedload rating.

3.3.3 Bedload relationships for censored data sets

The bedload data at Upper Swift Creek and Swift Creek gauges 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 completed the bedload gaugings, such conditions were believed to reflect very low and very high sand supply respectively. Very low and very high sand supply did not occur at consistent times through the wet season but bed scour was related to the occurrence of larger floods approaching and exceeding bankfull stage. Very low and very high sand supply 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= 10 at Upper Swift Creek; n = 18 at Swift Creek) were deleted from the total data set and the rating curves recalculated. These data were called the 'censored data sets' for differentiation from the 'above threshold data set', 'reliable data sets' and 'total data sets' analysed above. The data deleted from the total data set to produce the censored data set at Upper Swift Creek and Swift Creek gauges are clearly tagged in Tables 5 and 6 respectively. For the censored data sets, four regressions were significant at Upper Swift Creek and three regressions were significant at Swift Creek. At Upper Swift Creek, the mean bedload flux was significantly related to mean discharge and the following least squares curvilinear equation was derived:

$$Qs = 10.19\ Q^2 + 12.044\ Q + 28.218 \qquad (46)$$

F ratio = 9.86

$\rho = 0.003$

Adjusted $R^2 = 0.665$

Standard Error = 36.05 g/s

N = 47 (Upper Swift Creek)

The test of Chayes (1970) showed that the second order polynomial regression significantly increased the explained variance over the first order polynomial which did not have an adjusted $R^2 > 0.60$. For the censored data set at Upper Swift Creek, bedload immersed weight was significantly related to excess unit stream power and the following least squares curvilinear equation was derived:

$$ib = 0.146\ \omega'^{2} - 0.001\ \omega' + 0.0036 \qquad (47)$$

F ratio = 17.65

$\rho < 0.0001$

Adjusted $R^2 = 0.682$

Standard Error = 0.0038 g/s

N = 47 (Upper Swift Creek)

The test of Chayes (1970) again showed that the second order polynomial regression significantly increased the explained variance over the first order polynomial which did not have an adjusted $R^2 > 0.60$.

Adjusted bedload immersed weight was significantly related to both unit stream power and excess unit stream power, and the following least squares linear equations were derived:

$$ib' = 0.1709\ \omega - 0.0087 \qquad (48)$$

F ratio = 100.4

$\rho = 4.86 \times 10^{-13}$

Adjusted $R^2 = 0.6837$

Standard Error = 0.0108 kg/m.s

N = 47 (Upper Swift Creek)

$$ib' = 0.1713\ \omega' - 0.0069 \qquad (49)$$

F ratio = 96.99

$\rho = 8.37 \times 10^{-13}$

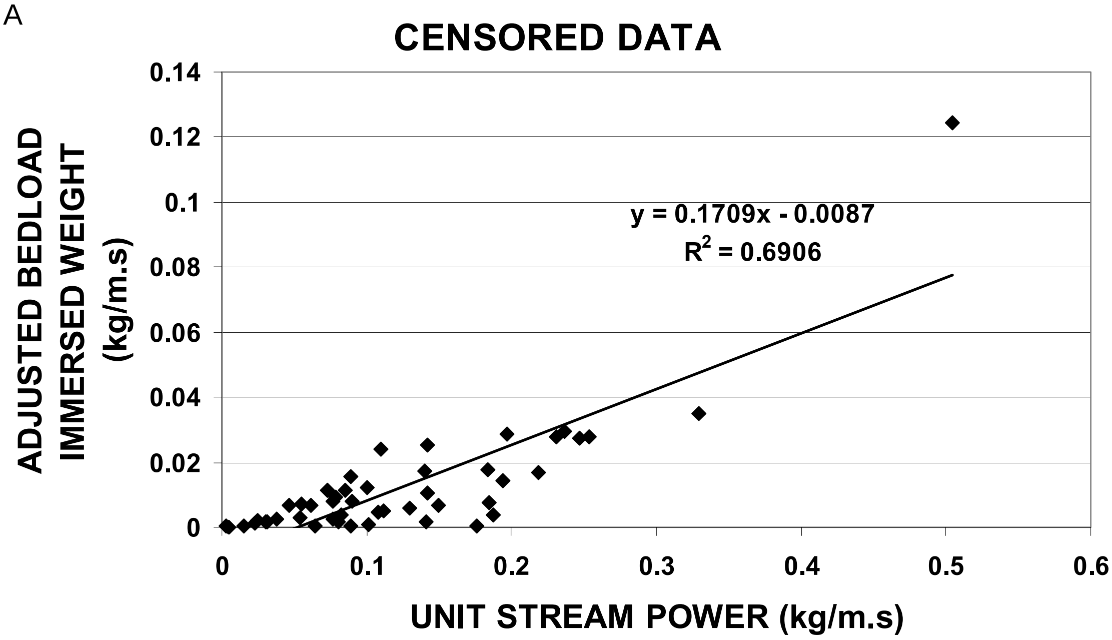
Adjusted $R^2 = 0.6760$

Standard Error = 0.0110 kg/m.s

N = 47 (Upper Swift Creek)

The two above relationships are similar and are shown in Figure 17.

A



B

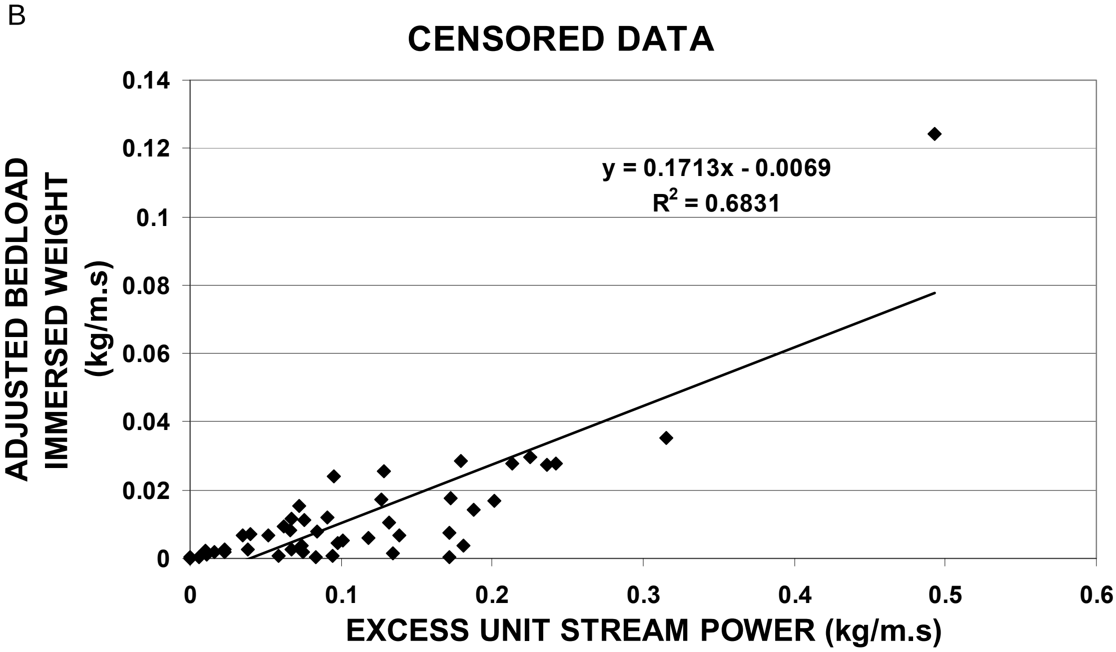


Figure 17 Adjusted bedload immersed weight versus (A) unit stream power and (B) excess unit stream power for the censored data set at Upper Swift Creek gauge

For the censored data at Swift Creek, the mean bedload flux was significantly related to mean discharge and the following least squares curvilinear equation was derived:

$$Qs = 4.1606\ Q^2 - 3.9265\ Q + 81.586 \qquad (50)$$

F ratio = 13.65

$\rho = 0.001$

Adjusted $R^2 = 0.625$

Standard Error = 64.44 kg/m.s

N = 42 (Swift Creek)

The test of Chayes (1970) again showed that the second order polynomial regression significantly increased the explained variance over the first order polynomial which did not have an adjusted $R^2 > 0.60$ (Fig 18A).

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 18B & 18C):

$$\mathrm{Log}_{10} i_b' = 1.2347\ \mathrm{Log}_{10}\omega - 0.3656 \qquad (51)$$

F ratio = 64.38

$\rho = 7.34 \times 10^{-10}$

Adjusted $R^2 = 0.6072$

Standard Error = 2.23 kg/m.s

N = 42 (Swift Creek)

$$\mathrm{Log}_{10} i_b' = 1.0337\ \mathrm{Log}_{10}\omega' - 0.4616 \qquad (52)$$

F ratio = 63.0

$\rho = 9.61 \times 10^{-10}$

Adjusted $R^2 = 0.6020$

Standard Error = 2.24 kg/m.s

N = 42 (Swift Creek)

Unlike the relationships for East Tributary (Fig 16), 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 18B and 18C 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.

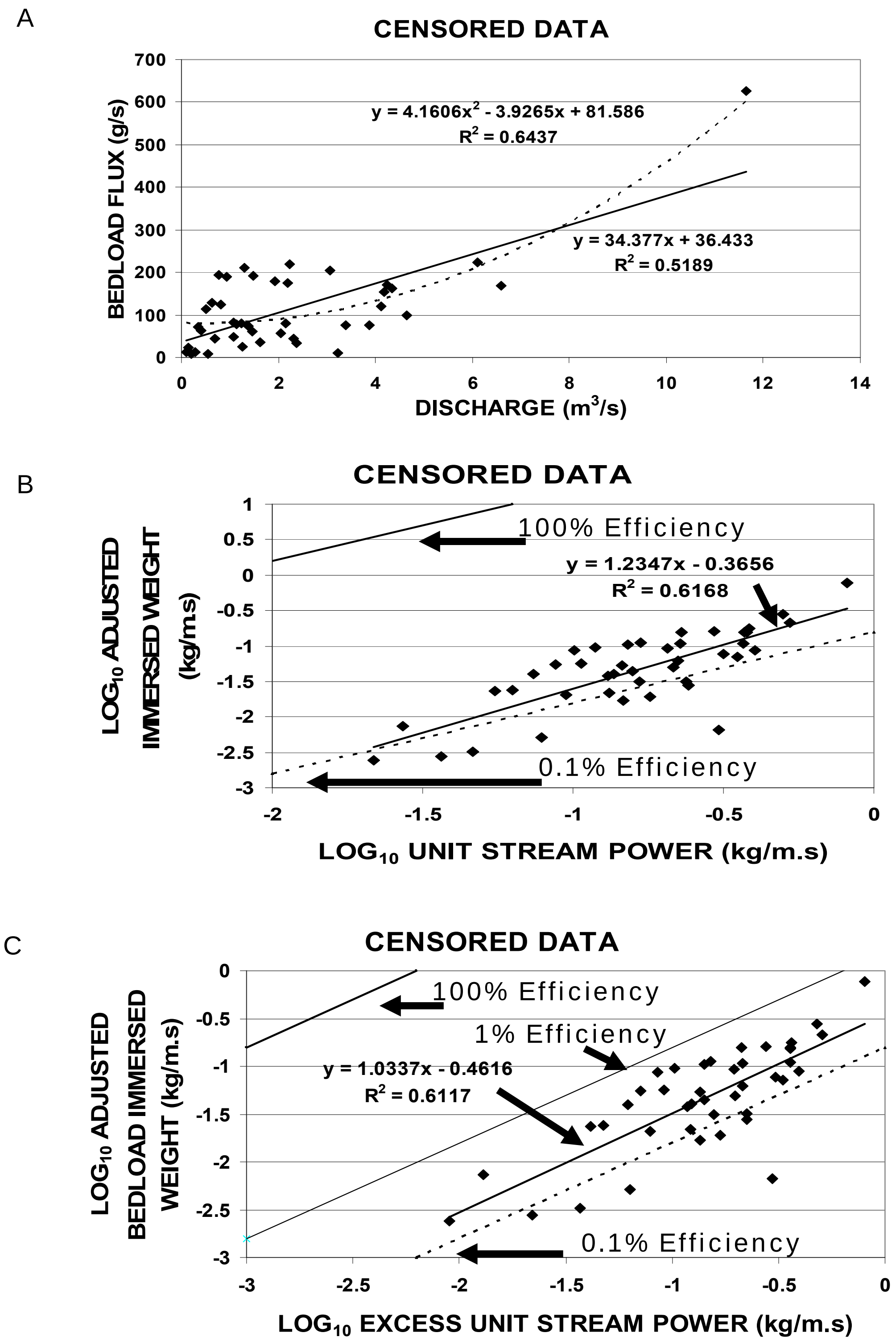


Figure 18 Significant regressions on censored bedload data for Swift Creek gauge with an adjusted R^2 > 0.60. (A) Bedload flux versus discharge, (B) Log_{10}-transformed adjusted bedload immersed weight and unit stream power and (C) Log_{10}-transformed adjusted bedload immersed weight and excess unit stream power.

The above analyses have produced 23 bedload ratings that are both statistically significant ($\rho < 0.05$) and have an adjusted $R^2 > 0.60$. Therefore, 16 equations were used to calculate bedload yields for East Tributary (Equations 13, 16, 17, 20, 21, 22, 25, 35, 36, 37, 38, 41, 42, 43, 44), four equations for Upper Swift Creek (Equations 46, 47, 48, 49) and three equations for Swift Creek (Equations 50, 51 & 52), as described below.

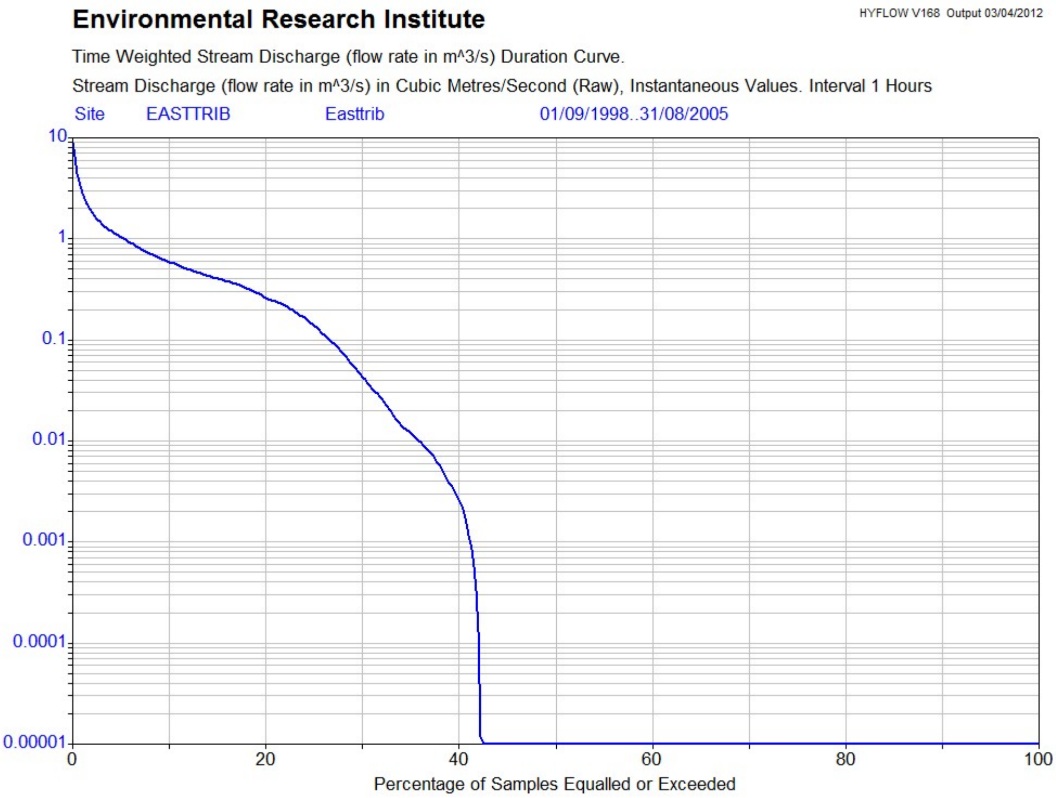
3.4 Bedload yields

The flow duration curves for the period 1 September 1998 to 31 August 2005 for the three gauging stations are shown in Figure 19. As recommended by Searcy (1959), a $\log_{10}$ scale is used for discharge. Assuming cease-to-flow coincides with a discharge of 0.00001 m^3/s, a reasonable assumption, mean daily discharge ranged over six orders of magnitude at East Tributary, seven orders of magnitude at Upper Swift Creek and eight orders of magnitude at Swift Creek. Of course, the number of orders of magnitude of mean daily discharge will depend on the adopted cease-to-flow discharge. Median daily flow (50% duration) increased with catchment area and varied from 0 m^3/s at East Tributary, to 0.28 m^3/s at Upper Swift Creek to 0.40 m^3/s at Swift Creek. All flow duration curves show a rapid reduction in mean daily discharge when flow reached a low but variable discharge. This threshold discharge was 0.002 m^3/s at East Tributary, 0.008 m^3/s at Upper Swift Creek and 0.009 m^3/s at Swift Creek. In these seasonal streams, cease-to-flow conditions occurred for about 58% of the time at East Tributary, about 17% of the time at Upper Swift Creek and about 24% of the time at Swift Creek (Figure 19). Figure 20 is looking upstream past Swift Creek gauging station showing flow at an instantaneous discharge of 1.33 m^3s^{-1}.

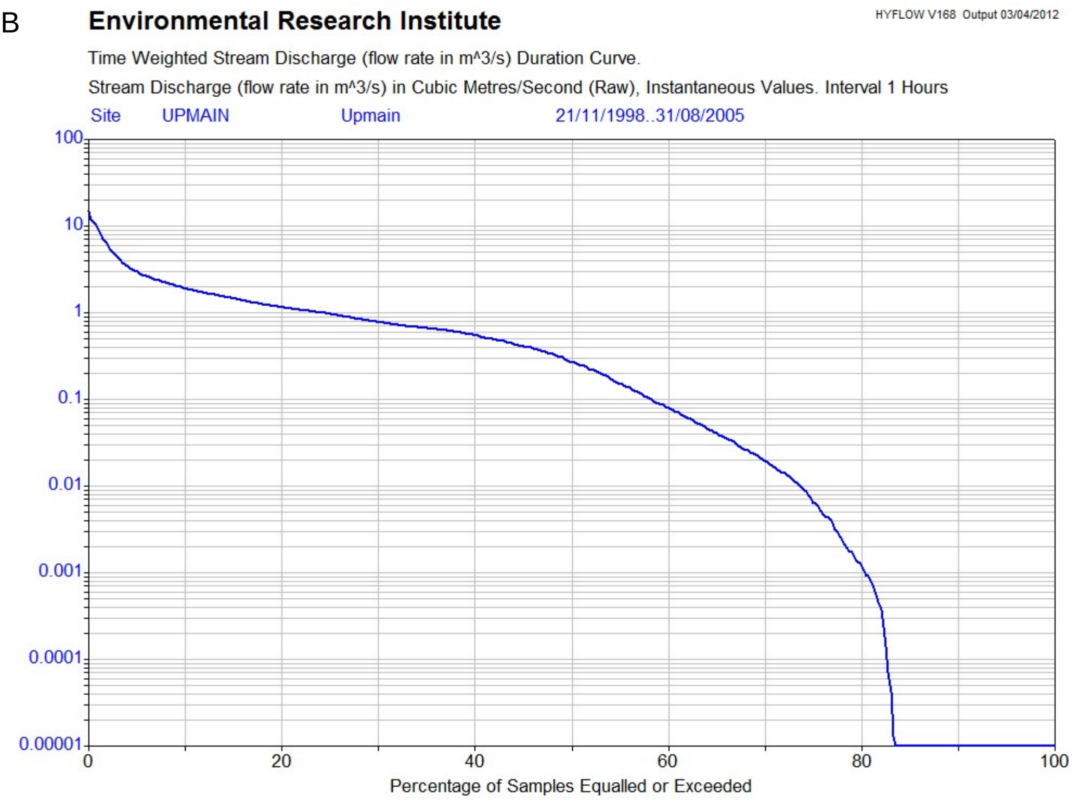
For calculation of bedload yields, rating curves for bedload immersed weights (Equations 35, 36, 37, 38, 41, 42, 43, 44, 45, 47, 48, 49, 51, 52) were converted to dry weights by multiplying the bedload flux by $\gamma_s/(\gamma_s-\gamma)$ (Gomez & Church 1989, Martin & Church 2000). Furthermore, unit flux was multiplied by bed width to obtain total flux for the section. For East Tributary, Methods 1 to 39 inclusive (Table 1) were used to calculate bedload yields; for Upper Swift Creek, Methods 1, 2, 13, 18, 19, 28, 29, 30, 31; and for Swift Creek, Methods 1, 2, 13, 32, 33, 34, 35, 36, 37, 38, 39. The results are shown in Tables 7, 8 and 9 for East Tributary, Upper Swift Creek and Swift Creek respectively. For East Tributary, the bedload yields for Equation 16 on the reliable and Equations 20 and 21 for the above threshold data sets were also calculated. The results are included in Table 10.

Bedload yields range over three orders of magnitude for East Tributary (Tables 7 & 10) and two orders of magnitude for both Upper Swift Creek and Swift Creek (Tables 8 & 9). With the sole exception of Methods 18 and 19 at Upper Swift Creek (Table 8), bedload yields calculated with hourly discharges exceeded yields calculated with daily discharges (Tables 7, 8, 9 & 10). Walling and Webb (1981) found a similar result for suspended sediment yields. This is due to the hourly discharges usually including larger discharges with higher bedload fluxes than the daily discharges. The daily average of the hourly fluxes usually slightly exceeds the daily flux, despite the mean of the hourly discharges equalling the mean daily discharge. Hourly discharge hydrographs should be used for all load calculations in the Ngarradj Creek catchment.

A


Environmental Research Institute
HYFLOW V168 Output 03/04/2012
Time Weighted Stream Discharge (flow rate in m^3/s) Duration Curve.
Stream Discharge (flow rate in m^3/s) in Cubic Metres/Second (Raw), Instantaneous Values. Interval 1 Hours
Site EASTTRIB Easttrib 01/09/1998..31/08/2005
10
1
0.1
0.01
0.001
0.0001
0.00001
0
20
40
60
80
100
Percentage of Samples Equalled or Exceeded

B


Environmental Research Institute
HYFLOW V168 Output 03/04/2012
Time Weighted Stream Discharge (flow rate in m^3/s) Duration Curve.
Stream Discharge (flow rate in m^3/s) in Cubic Metres/Second (Raw), Instantaneous Values. Interval 1 Hours
Site UPMAIN Upmain 21/11/1998..31/08/2005
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0
20
40
60
80
100
Percentage of Samples Equalled or Exceeded

C

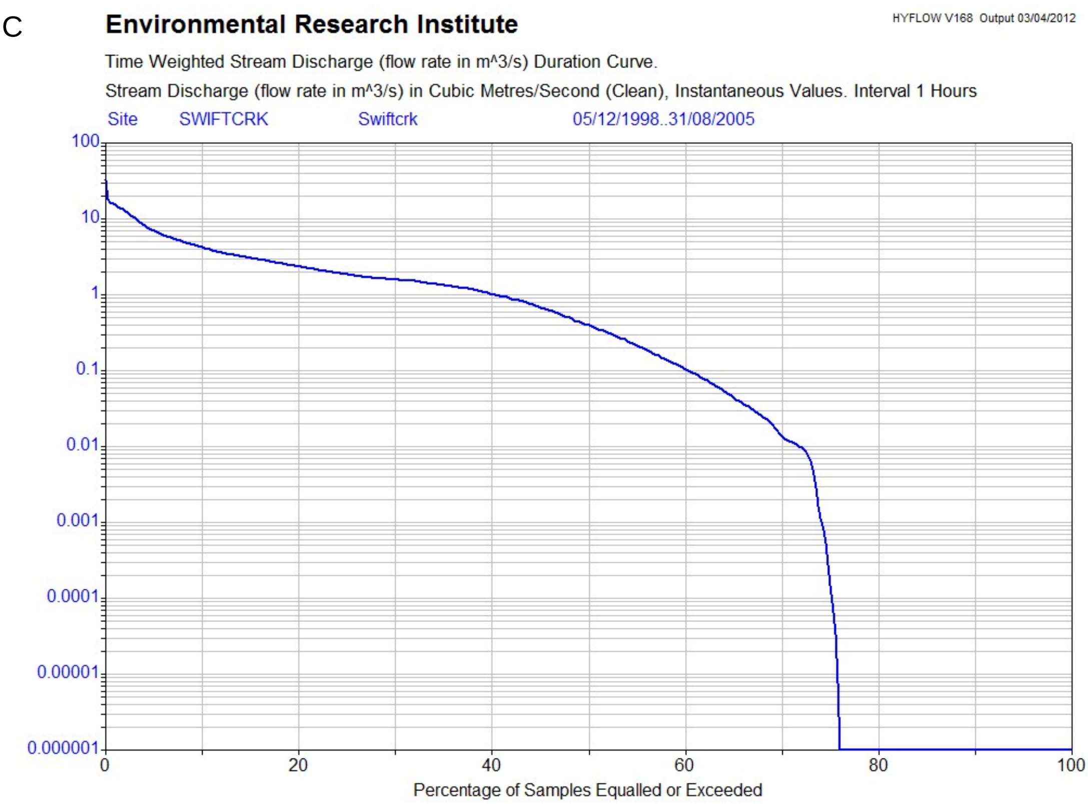


Figure 19 Flow duration curves for the period 1 September 1998 to 31 August 2005 at (A) East Tributary, (B) Upper Swift Creek and (C) Swift Creek

Figure 20 Upstream at Swift Creek gauging station at 12:40 on 4/2/03 (stream discharge of 1.33 m^3s^{-1})

Table 7 Annual bedload yield in tonnes for East Tributary gauge calculated by the specified methods which are detailed in Table 1 for the whole data set. See Figure 1 for location of site.

Water Year	Method 1 Equation 13	Method 2 Equation 13	Methods 3 & 4 Equation 17	Methods 5 & 6 Equation 17	Method 7 Equation 22	Method 8 Equation 22	Methods 9 & 10 Equation 25	Methods 11 & 12 Equation 25	Method 13 Equation 13	Methods 14 & 15 Equation 17
1998/99	639	634	926	612	868	762	1235	813	N/A	N/A
1999/00	689	679	1025	701	938	776	1365	933	N/A	N/A
2000/01	731	727	1098	770	1000	867	1463	1023	N/A	N/A
2001/02	355	351	618	432	494	361	825	575	N/A	N/A
2002/03	663	661	1165	815	924	834	1555	1085	N/A	N/A
2003/04	443	438	546	390	592	507	728	519	N/A	N/A
2004/05	381	371	779	569	537	420	1040	758	N/A	N/A
Mean	557	551	880	613	765	647	1173	815	696	1573
Standard Error	60	60	90	61	81	80	120	81	N/A	N/A
Ferguson (1986) Bias Correction	N/A	N/A	(1.653)[1] 1455	(1.653)[1] 1013	N/A	N/A	(1.600)[1] 1877	(1.600)[1] 1304	N/A	(1.653)[1] 2600
Duan (1983) Bias Correction	N/A	N/A	(1.540)[1] 1355	(1.540)[1] 944	N/A	N/A	(1.519)[1] 1782	(1.519)[1] 1238	N/A	(1.540)[1] 2422

N/A – Not Applicable

[1] – Bias Correction Factor

Table 7 (continued)

Water Year	Method 16 Equation 35	Method 17 Equation 35	Methods 18 Equation 37	Method 19 Equation 37	Methods 20 & 21 Equation 36	Methods 22 & 23 Equation 36	Methods 24 & 25 Equation 38	Methods 26 & 27 Equation 38	Method 28 Equation 41	Method 29 Equation 41
1998/99	55	38	55	39	49	37	49	37	150	29
1999/00	62	45	62	46	54	41	54	42	169	44
2000/01	69	51	69	51	58	45	58	46	182	35
2001/02	37	34	38	35	32	24	31	25	115	31
2002/03	73	60	74	61	59	46	59	46	225	75
2003/04	30	22	30	22	30	24	30	24	75	16
2004/05	45	38	45	39	38	30	37	30	176	94
Mean	53	41	53	42	46	35	45	36	156	46
Standard Error	6	5	6	5	5	4	5	4	18	11
Ferguson (1986) Bias Correction	N/A	N/A	N/A	N/A	(1.103)[1] 51	(1.103)[1] 39	(1.115)[1] 50	(1.115)[1] 40	N/A	N/A
Duan (1983) Bias Correction	N/A	N/A	N/A	N/A	(1.100)[1] 51	(1.100)[1] 39	(1.110)[1] 50	(1.110)[1] 40	N/A	N/A

N/A – Not Applicable

[1] – Bias Correction Factor

Table 7 (continued)

Water Year	Method 30 Equation 42	Method 31 Equation 42	Methods 32 & 33 Equation 43	Methods 34 & 35 Equation 43	Methods 36 & 37 Equation 44	Methods 38 & 39 Equation 44
1998/99	150	29	215	107	752	365
1999/00	169	45	237	128	828	438
2000/01	183	36	255	140	891	480
2001/02	115	31	152	84	532	291
2002/03	225	75	288	161	1010	560
2003/04	75	16	117	65	407	222
2004/05	176	94	207	127	726	442
Mean	156	47	210	116	735	400
Standard Error	18	11	22	13	78	44
Ferguson (1986) Bias Correction	N/A	N/A	(1.653)[1] 347	(1.653)[1] 192	(1.677)[1] 1233	(1.677)[1] 671
Duan (1983) Bias Correction	N/A	N/A	(1.557)[1] 327	(1.557)[1] 181	(1.561)[1] 1147	(1.561)[1] 624

N/A – Not Applicable

[1] – Bias Correction Factor

Table 8 Annual bedload yield in tonnes for Upper Swift Creek gauge calculated by the specified methods which are detailed in Table 1. See Figure 1 for location of site. All bedload rating equations are based on raw data for the censored data set in Table 5 and hence no bias corrections for reformations from log_{10}-transformation are needed.

Water Year	Method 1 Equation 46	Method 2 Equation 46	Method 13 Equation 46	Method 18 Equation 47	Method 19 Equation 47	Method 28 Equation 48	Method 29 Equation 48	Method 30 Equation 49	Method 31 Equation 49
1998/99	1157	1033	N/A	977	1211	2371	2285	2383	2366
1999/00	1333	1233	N/A	922	1425	2516	2432	2532	2512
2000/01	1338	1186	N/A	1109	1411	2709	2625	2720	2706
2001/02	641	607	N/A	493	720	1118	1069	1123	1105
2002/03	1391	1253	N/A	1298	1556	2981	2890	2991	2981
2003/04	771	709	N/A	520	818	1509	1452	1520	1515
2004/05	804	724	N/A	681	893	1267	1216	1274	1255
Mean	1062	959	2107	857	1148	2067	1996	2078	2063
Standard Error	119	104	N/A	115	127	284	277	285	285
Ferguson (1986) Bias Correction	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Duan (1983) Bias Correction	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

N/A – Not Applicable

Table 9 Annual bedload yield in tonnes for Swift Creek gauge calculated by the specified methods which are detailed in Table 1. See Figure 1 for location of site. All equations were determined for the censored data set in Table 6.

Water Year	Method 1 Equation 50	Method 2 Equation 50	Method 13 Equation 50	Methods 32 & 33 Equation 51	Methods 34 & 35 Equation 51	Methods 36 & 37 Equation 52	Methods 38 & 39 Equation 52
1998/99	1881	1772	N/A	17848	17570	16354	16306
1999/00	2365	2287	N/A	18102	17853	16755	16710
2000/01	2047	1890	N/A	19126	18823	17060	17014
2001/02	1063	1044	N/A	7964	7853	7017	6994
2002/03	1843	1664	N/A	18926	18545	16524	16466
2003/04	1244	1205	N/A	10164	10027	9637	9611
2004/05	1280	1238	N/A	8879	8735	8031	8004
Mean	1675	1586	3270	14430	14201	13054	13015
Standard Error	183	168	N/A	1941	1906	1732	1728
Ferguson (1986) Bias Correction	N/A	N/A	N/A	(1.372)[1] 19798	(1.372)[1] 19484	(1.370)[1] 17884	(1.370)[1] 17831
Duan (1983) Bias Correction	N/A	N/A	N/A	(1.280)[1] 18470	(1.280)[1] 18177	(1.274)[1] 16631	(1.274)[1] 16581

N/A – Not Applicable

[1] – Bias Correction Factor

Table 10 Annual bedload yield in tonnes for East Tributary gauge calculated by the specified methods which are detailed in Table 1, and the specified equations. See Figure 1 for location of site. Equation 16 was derived for the reliable data set, and Equations 20 and 21, for the above threshold data set. Table 4 contains the data for each data set.

Water Year	Method 1 Equation 16	Method 2 Equation 16	Method 13 Equation 16	Method 1 Equation 20	Method 2 Equation 20	Method 13 Equation 20	Methods 3 & 4 Equation 21	Methods 5 & 6 Equation 21	Methods 14 & 15 Equation 21
1998/99	681	675	N/A	618	608	N/A	596	479	N/A
1999/00	734	722	N/A	661	648	N/A	659	536	N/A
2000/01	781	776	N/A	714	707	N/A	696	577	N/A
2001/02	369	376	N/A	355	350	N/A	370	305	N/A
2002/03	711	708	N/A	658	653	N/A	694	570	N/A
2003/04	470	464	N/A	417	407	N/A	380	319	N/A
2004/05	407	395	N/A	374	359	N/A	440	369	N/A
Mean	593	588	748	542	533	693	548	451	842
Standard Error	65	64	N/A	58	58	N/A	56	45	N/A
Ferguson (1986) Bias Correction	N/A	N/A	N/A	N/A	N/A	N/A	(1.374)[1] 753	(1.374)[1] 620	(1.374)[1] 1157
Duan (1983) Bias Correction	N/A	N/A	N/A	N/A	N/A	N/A	(1.389)[1] 761	(1.389)[1] 626	(1.389)[1] 1170

N/A – Not Applicable

[1] – Bias Correction Factor

Bedload rating-flow duration curve estimates of bedload yield (Methods 13, 14 & 15) overestimate yields (Tables 7, 8, 9 & 10), as also found for suspended sediment by Walling and Webb (1981, 1988) and Webb et al (1997). The bias correction methods of Ferguson (1986, 1987) and Duan (1983) always produce higher bedload yields than the other methods (Tables 7, 9 & 10). Furthermore, the correction factors cited in Tables 7, 9 and 10 are usually much lower than those found by King et al (2004) for bedload transport by gravel-bed rivers in Idaho. Less reliable bedload ratings such as those of King et al (2004) would result in even greater overestimation of bedload yields. Clearly these bedload ratings do not underestimate sediment yields (Ferguson 1986, 1987) and, therefore, the need for bias correction should be questioned (Walling & Webb 1988, Webb et al 1997). Slightly rewording Walling and Webb (1988), this indicates that bias associated with logarithmic transformation is not the prime cause of the inaccuracy of rating curve estimates of bedload yield for the Ngarradj Creek sites. We believe that bias correction by all methods (Cohn & Gilroy 1992) is not necessary for routine use in bedload yield calculations. Walling and Webb (1988) concluded from their assessment of suspended sediment yields that other factors not reflected in the correction factors are clearly important in determining suspended sediment yields. We believe that the same applies to bedload yields. While continuously recording turbidity meters have largely solved the problem of accurate suspended sediment yield determination (Walling 1977a, Walling & Webb 1981, 1985, 1988), an affordable and accurate method for continuously-recording bedload fluxes has still not been developed. Highly efficient bed slots combined with either conveyor belts (Leopold & Emmett 1976, 1977, 1997) or continuously weighing pressure pillow systems (Reid et al 1980, Laronne et al 1992) may provide the answer.

The best estimate of the mean annual bedload yield for East Tributary is about 550–600 ± 65 t/yr. Methods 1 and 2 with Equation 13 in Table 7 and Methods 1 and 2 with Equation 16 in Table 10 produce yields in this range. As noted above, Equation 13 for the whole data set indicates that threshold of motion should occur at a discharge greater than 0.223 m^3/s. Equation 16 for the reliable data set also exhibits a threshold of motion but at a discharge of 0.235 m^3/s. These values are very similar.

Field observations confirm that the first displacement of the bed material does occur between 0.22 and 0.24 m^3/s. Methods 1 and 2 with Equation 20 for the above threshold data set produce a slightly lower bedload yield (Table 10) because the threshold of motion occurs at a slightly higher discharge, namely 0.28 m^3/s. Equation 15 (log_{10}-transformed whole data set) produces a higher bedload yield (Methods 3, 4, 5, 6, 14 & 15 in Table 7) because there is no threshold of motion and hence all discharges transport bedload. Methods 3, 4, 5 and 6 with Equation 21 produce results within the range 451–761 t/yr because the regression was derived for the above threshold data set and hence contains an implicit threshold condition. All rating curve-flow duration estimates (Methods 13, 14 & 15) overpredict whereas the immersed bedload weight/adjusted immersed bedload weight regressions (Methods 16 to 39 inclusive) greatly underpredict bedload yields. The reason that the immersed bedload weight regressions underpredict bedload yields is that they contain an implicit threshold of motion condition. For example, Equation 35 (Methods 16 & 17) predicts no transport at discharges less than 1.06 m^3/s and Equation 37 (Methods 18 & 19), at discharges less than 1.07 m^3/s. Even when excess specific stream power exceeds zero according to Bagnold's (1980) criterion (ie bedload transport should occur), there is no transport until a second higher threshold is exceeded when excess specific stream power is much greater than zero. This suggests that Bagnold's (1980) threshold of motion equation (Equation 31) does not apply to the channels in the Ngarradj Creek catchment.

The best estimate of the mean annual bedload yield for Upper Swift Creek is about 850–1150 ± 120 t/yr. Methods 1 and 2 with Equation 46 and Methods 18 and 19 with Equation 47 in Table 8 produce yields in this range. As bedload rating-flow duration curve estimates (Method 13) overpredict bedload yields in Ngarradj Creek (see above), the estimate of Method 13 is rejected. Therefore, the mean annual bedload yields estimated by Methods 28 to 31 inclusive are also rejected because they are similar to the bedload rating-flow duration estimate (Table 8).

The best estimate of the mean annual bedload yield for Swift Creek is about 1550–1700 ± 180 t/yr. Methods 1 and 2 with Equation 50 in Table 9 are of this magnitude. Again the estimate by Method 13 is rejected as being too high (bedload rating-flow duration curve technique) and, therefore, the mean annual bedload yields estimated by Equation 51 (Methods 32 to 39 inclusive) are also rejected because they are even higher than that by Method 13.

On the basis of the above analyses the mean annual bedload yields for the East Tributary, Upper Swift Creek and Swift Creek gauges are taken to be 575, 1000 and 1625 t/yr respectively. As expected, mean annual bedload yields increase proportionally with catchment area (Fig 21A) and specific mean annual bedload yield decreases with catchment area (Fig 21B) because sediment supply is higher in smaller catchments (Walling 1983). In other words, the sediment delivery ratio or the percentage of the gross erosion rate delivered to streams decreases with increasing catchment area because of increasing sediment storage on hill slopes and in fans and floodplains (Walling 1983). Clearly, additional bedload yields are required for the Alligator Rivers Region (ARR) to determine whether Figure 21 is indicative of a regional relationship.

It is essential that an independent and accurate method of determining bedload yield is applied to the Ngarradj Creek catchment to better evaluate the accuracy of the above methods of calculating bedload yields. Erskine et al (2001) identified a braided floodout and a fan delta reach downstream of the Swift Creek gauge, which is located in their sinuous reach, and upstream of the terminal wetland reach. Annual repeated detailed surveys of the two reaches between the Swift Creek gauge (sinuous reach) and the terminal wetland could provide annual bedload yields for Ngarradj Creek by quantifying the annual addition to storage. These values should be indicative of the annual bedload yield passing the Swift Creek gauge. Such accurate and reliable bedload yields are urgently required for the ARR.

3.5 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 Upper Swift Creek and at Swift Creek, 116 and 118 grain size distributions respectively were evaluated. The coarsest bedload particle had a b-axis diameter of 6 mm at East Tributary and Upper Swift Creek, 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 Upper Swift Creek and 45 mm for Swift Creek, to maintain sediment trap efficiency. This diameter is in fact 76.2 mm (see Section 2.2) and hence the Helley Smith bedload samplers will have performed as designed for all samples at all sites in the Ngarradj Creek catchment. As the grains are rounded, b- and a-axis diameters are similar.

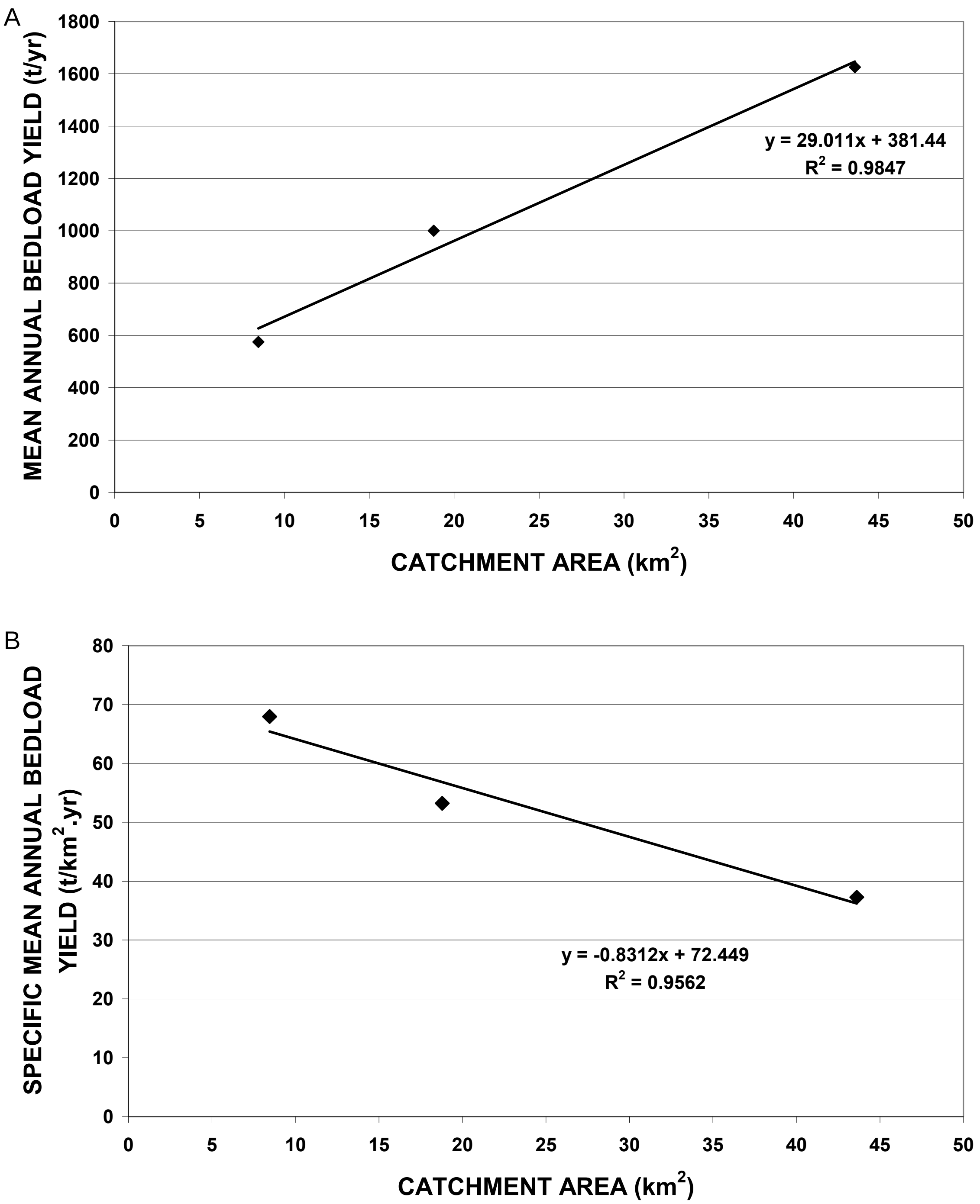


Figure 21 (A) Relationship of mean annual bedload yield with catchment area and (B) relationship between specific mean annual bedload yield and catchment area for the Ngarradj Creek catchment

As noted in Section 2.2, a 0.2 mm diameter mesh 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 116 grain size distributions obtained for Upper Swift Creek, 16 had a 95th percentile just finer than 0.2 mm (mean of 0.189 ± 0.001 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 mesh of the sampler bags was clogged by fine sediment to such a degree as to reduce the sampler trap efficiency.

Folk and Ward's (1957) and Folk's (1980) graphic grain size statistics for the bedload samples at each gauging station are summarised in Table 11. Mean and median bedload size for each double traverse bedload sample were presented in Tables 4, 5 and 6 for East Tributary, Upper Swift Creek and Swift Creek respectively. Saynor et al (2006) should be read in conjunction with this section because they explain all the grain size terms used below. Folk's (1980) verbal scale for grain size is now used to compare and contrast the bedload sediments at each site. At East Tributary, bedload is a moderately sorted, coarse skewed, leptokurtic, coarse sand. At Upper Swift Creek, bedload is a moderately sorted, coarse skewed, mesokurtic, medium sand. At Swift Creek, bedload is a moderately sorted, coarse skewed, leptokurtic, coarse sand. Therefore, bedload sediments are similar at all sites. While there is a slight downstream coarsening in bedload graphic mean size (Table 11), it is non-significant.

Table 11 Mean graphic grain size statistics (after Folk 1980) ± standard error of estimate for bedload samples at the three gauging stations in the Ngarradj Creek catchment. See Fig 1 for location of the gauges.

Gauging Station	Graphic mean size (ø ± SEE; mm)	Inclusive graphic standard deviation (ø ± SEE; mm)	Inclusive graphic skewness (mean ± SEE)	Graphic kurtosis (mean ± SEE)	Transformed kurtosis (mean ± SEE)	Number of samples for complete transects
East Tributary	0.90 ± 0.03 ø; 0.53 mm	0.73 ± 0.01 ø; 0.60 mm	-0.10 ± 0.01	1.16 ± 0.03	0.53 ± 0.004	95
Upper Swift Creek	1.07 ± 0.02 ø; 0.48 mm	0.74 ± 0.01 ø; 0.60 mm	-0.13 ± 0.01	1.10 ± 0.02	0.52 ± 0.003	116
Swift Creek	0.88 ± 0.02 ø; 0.54 mm	0.79 ± 0.01 ø; 0.58 mm	-0.14 ± 0.01	1.15 ± 0.02	0.53 ± 0.003	118

3.6 Bed-material grain size

Saynor et al (2006) discussed, among other things, the changes in bed-material grain size statistics at the three gauging stations in the Ngarradj Creek catchment between 1998 and 2003. Bed material refers to the sediment in the bed of the channel when rivers cease flowing during the dry season. The mean and standard error of the graphic grain size statistics at each gauge for the eight permanently marked cross sections for each year reported by Saynor et al (2006) is contained in Table 12. In this section, the differences in grain size statistics between bedload, which is mobile during the wet season, and bed material, which is stationary during the dry season, are investigated for the same sites for the same time period (1998–2002) using the extensive data sets presented in Section 3.5 and in Saynor et al (2006).

At East Tributary, there is no significant difference in graphic mean size between bedload and bed material for the period 1998–2002 (0.90 ø or 0.53 mm versus 0.89 ø or 0.54 mm). However, there is a significant difference in inclusive graphic standard deviation with bedload being better sorted than the bed material (0.73 ø versus 1.06 ø). While there is also a significant difference in inclusive graphic skewness (-0.11 versus -0.21), both are negatively or coarse skewed. The last two results suggest that bedload consists of a subset of slightly finer sediment of the bed material which is thus better sorted and slightly less coarse skewed. Both graphic and normalised kurtosis of bedload and bed material were significantly different.

Table 12 Summary of bed-material grain size statistics at the eight permanently marked cross sections at the three gauging stations in the Ngarradj Creek catchment between 1998 and 2003 (from Saynor et al 2006). See Figure 1 for location of gauges.

Gauging Station	Year	Graphic mean size (Φ) Mean ± SE	Inclusive graphic standard deviation (Φ) Mean ± SE	Inclusive graphic skewness Mean ± SE	Graphic kurtosis Mean ± SE	Transformed kurtosis Mean ± SE
East Tributary	1998	1.21 ± 0.07	1.15 ± 0.13	-0.14 ± 0.04	1.21 ± 0.06	0.55 ± 0.01
	1999	0.79 ± 0.07	1.11 ± 0.34	-0.29 ± 0.16	1.22 ± 0.16	0.55 ± 0.04
	2000	0.88± 0.05	1.01 ± 0.06	-0.17 ± 0.02	1.16 ± 0.04	0.54 ± 0.01
	2001	0.80± 0.11	1.05 ± 0.12	-0.23 ± 0.06	1.20 ± 0.06	0.54 ± 0.01
	2002	0.83± 0.27	1.01 ± 0.19	-0.24 ± 0.10	1.26 ± 0.30	0.54 ± 0.06
	2003	0.85± 0.07	0.84 ± 0.07	-0.16 ± 0.04	1.22 ± 0.03	0.55 ± 0.01
Upper Swift Creek	1998	0.90± 0.13	1.04 ± 0.17	-0.15 ± 0.08	1.23 ± 0.05	0.55 ± 0.01
	1999	0.77± 0.04	0.89 ± 0.03	-0.11 ± 0.02	1.08 ± 0.02	0.52 ± 0.00
	2000	0.84± 0.07	1.05 ± 0.16	-0.17 ± 0.06	1.17 ± 0.08	0.54 ± 0.01
	2001	0.84± 0.05	0.93 ± 0.04	-0.18 ± 0.02	1.23 ± 0.03	0.55 ± 0.01
	2002	0.95± 0.09	0.78 ± 0.05	-0.13 ± 0.05	1.12 ± 0.06	0.53 ± 0.01
	2003	0.97± 0.08	0.83 ± 0.11	-0.11 ± 0.07	1.21 ± 0.10	0.55 ± 0.02
Swift Creek	1998	1.09± 0.04	0.87 ± 0.04	-0.09 ± 0.02	1.12 ± 0.02	0.53 ± 0.00
	1999	0.84± 0.05	0.87 ± 0.02	-0.11 ± 0.01	1.11 ± 0.03	0.52 ± 0.01
	2000	0.96± 0.08	0.91 ± 0.11	-0.05 ± 0.04	1.23 ± 0.15	0.54 ± 0.02
	2001	0.74± 0.08	0.87 ± 0.04	-0.17 ± 0.02	1.14 ± 0.02	0.53 ± 0.00
	2002	1.00± 0.07	0.90 ± 0.05	-0.15 ± 0.04	1.12 ± 0.04	0.53 ± 0.01
	2003	0.90± 0.07	0.88 ± 0.03	-0.13 ± 0.02	1.16 ± 0.02	0.54 ± 0.00

At Upper Swift Creek, there is a significant difference in graphic mean size between bedload and bed material for the period 1998–2002 (1.07 ø or 0.48 mm versus 0.89 ø or 0.54 mm). Furthermore, there is a significant difference in inclusive graphic standard deviation with bedload being better sorted than the bed material (0.74 ø versus 0.89 ø). The last two results suggest that bedload consists of a subset of slightly finer sediment of the bed material which is thus better sorted. There is no significant difference in inclusive graphic skewness (-0.13 versus -0.12), with both being negatively or coarse skewed. There were no significant differences in graphic and transformed kurtosis.

At Swift Creek, there is no significant difference in graphic mean size between bedload and bed material for the period 1998–2002 (0.88 ø or 0.54 mm versus 0.89 ø or 0.54 mm). However, there is a significant difference in inclusive graphic standard deviation with bedload being better sorted than the bed material (0.79 ø versus 0.89 ø). There is no significant difference in inclusive graphic skewness (-0.14 versus -0.12), with both being negatively or coarse skewed. There were no significant differences in graphic and transformed kurtosis.

There is little difference in grain size statistics between bedload and bed material. Those differences which were significant suggest that most of the bed material is transported as bedload during each wet season. There may be some size selective transport at all three stations with bedload being better sorted at all three stations and with bedload being finer at Upper Swift Creek. At East Tributary, bedload samples are also less coarse skewed. All these differences in grain size statistics indicate that bedload is a slightly finer fraction of the total bed material but the differences are mainly in the extreme coarse fraction (pebble gravel) which may be mobile only under extreme events.

4 Summary, conclusions and implications

Bedload transport in the Ngarradj Creek catchment is irregular and was only closely associated with discharge at one of the three gauging stations. Disequilibrium conditions where either substantial erosion or deposition occurred in the measurement reach prevented the establishment of significant relationships between bedload flux and discharge. Censoring the bedload transport data set at two gauging stations by removing data for disequilibrium conditions produced significant bedload ratings. Discharge was a more accurate predictor of bedload flux than unit stream power or excess unit stream power. Measurement of the annual bedload contribution to sedimentation in the braided floodout and fan delta reaches of lower Ngarradj Creek would provide an important data base on bedload yield against which to assess the accuracy of the bedload yields calculated for the Swift Creek gauge using derived bedload ratings and the discharge record.

Kuhnle (1992) found that mean bedload transport rates were greater during rising stages than during falling stages at higher flow strengths on two small gravel-bed rivers in northern Mississippi, USA. However, as stage declined, one stream exhibited greater transport rates for low flows. Hysteretic relationships (rising v falling stages) for bedload transport could not be determined for the Ngarradj Creek catchment by the above manual program because of the preferential occurrence of rising stages at night (Moliere et al 2002b) in response to the diurnal variation in rainfall intensity (Soman et al 1995, Li et al 1996, Moliere et al 2002b). To sample the full hydrograph requires a new program involving either automatic sampling with a conveyor belt in a slot (Leopold & Emmett 1976, 1977, 1997), the electromagnetic device of Reid et al (1984) or the Birkbeck-type slot sampler with a continuously weighing pressure pillow system (Reid et al 1980, Laronne et al 1992), or manual sampling at night from a safe working platform which crosses the entire channel (Bunte et al 2007). Bedload dynamics require further investigation in the Alligator Rivers Region by the adoption of a revised programme that is capable of sampling rising stages, falling stages and steady discharges throughout the wet season.

At least hourly discharge hydrographs should be used for all sediment load calculations in the Ngarradj Creek catchment in order to achieve the most precise result. A similar result has been reported for suspended sediment load estimation (Walling & Webb 1981, 1988). Furthermore, the flow duration-sediment rating curve method is not recommended for use in the ARR because it tends to overestimate loads (Walling & Webb 1981, 1988, Webb et al 1997). Therefore, the various bias correction procedures proposed for retransformations (Duan 1983, Ferguson 1986, 1987, Cohn & Gilroy 1992) used with this technique, which further inflate sediment yields, are not recommended for routine use.

Threshold unit stream power for first entrainment of bedload has been estimated by Bagnold (1980) and Leopold and Emmett (1997). When these criteria were used at the three gauging stations in the Ngarradj Creek catchment, it was found that bedload fluxes exhibited a second higher threshold and therefore bedload transport did not commence until excess unit stream power was much greater than zero. This new threshold condition was about four times greater than that predicted by Bagnold (1980) and Leopold and Emmett (1997). This indicates that the Bagnold (1980) and Leopold and Emmett (1997) threshold criteria do not fit the Ngarradj Creek bedload data. Either further research is required to define the threshold unit stream power for first displacement of sand or the concept of threshold of motion for sand requires reappraisal as suggested by Barry et al (2004) for gravel-bed rivers. In particular, the differentiation between first displacement and last transport must be made. If Reid and Frostick's (1986) measurement of the mean unit stream power at the finish of bedload transport may be only 20% of that prevailing at threshold of motion is generally applicable, then it is necessary to discriminate between settling and entraining grains. This may be extremely difficult.

Several potential sources of error may occur when estimating sediment yields from sediment rating curves (Walling 1977b). Extrapolation of the stage-discharge curve to overbank flows is problematic (Powell et al 1996) because large errors may occur. Furthermore, the validity of the estimate of unit stream power as momentum is transferred between high velocity channel flow and lower velocity overbank flow can be questioned (Powell et al 1996). In addition, the importance of medium- and long-term temporal fluctuations in transport rate that may occur independently of discharge (Schick & Lekach 1983) cannot be assessed as yet for the Ngarradj Creek catchment. However, this is essentially the reason that the ‘censored data set’ was created for the Upper Swift Creek and Swift Creek gauges.

Hean and Nanson (1987) found that for rivers with an abundant supply of bed material available for transport, a relatively small percentage change in rainfall can result in potentially major shifts in annual bedload yields. Their increases in mean annual rainfall in south eastern Australia were 10–20% and produced 60–100% increases in annual bedload yields. The changes in mean annual rainfall between the alternating wet and dry time periods outlined in Table 3 at Oenpelli range from -21.5 to 29.6%. The last two rainfall changes (1973–1984 v 1985–1993 and 1985–1993 v 1994–2010) have the maximum percentage changes in mean annual rainfall which exceed the range for the drainage basins investigated by Hean and Nanson (1987). Clearly the increase in rainfall for the most recent wet period in the Ngarradj Creek catchment is greatly above the range reported for south eastern Australia. All our measurements were undertaken during the last wet period (1994–2010) when mean annual rainfall at Oenpelli was the highest on record. This severely limits the extrapolation of our results to other time periods, both wet and dry, and both in the past and in the future. This indicates that longer-term bedload measurements are required for the Alligator Rivers Region.

Bedload transport efficiencies differed greatly between the two gauges (East Tributary and Swift Creek) for which they could be determined (Figures16A & B and 18B & C). At East Tributary, bedload transport efficiency was variable for both unit stream power and excess unit stream power. Nevertheless, efficiency peaked at about 0.1% at the highest stream powers. At Swift Creek, bedload transport efficiency was essentially constant with both unit and excess unit stream power at a value slightly in excess of 0.1%. The differences in hydraulic geometry between these sites (Type 4 versus Type 10 channel according to Rhodes’s (1977) classification scheme) are reflected in differences in bedload transport efficiency.

We suspect that sediment delivery ratios are very low in the Ngarradj Creek catchment on the Koolpinyah or lowland surface because of low angles and long, often gravel-armoured slopes (Duggan 1994, Erskine & Saynor 2000). Windthrow probably reduces sediment delivery even further because it creates fully enclosed depressions similar to microbasins (Riley et al 1997) and because it also protects the soil surface from the effects of raindrop splash by supplying copious amounts of large wood. Furthermore, because the proportion of lowland increases with catchment area, sediment delivery ratios should decrease even faster than for agricultural catchments (Walling 1983). Unless gullying or channel incision occurs, slopes are decoupled from channels.

Emmett (1980, 1981) found that median particle size of bedload on East Fork River, Wyoming, USA, was 1.13 mm compared with 1.25 mm for bed material. While he concluded that they were sensibly the same, he noted that the bed material consisted of some larger particles that are rarely transported. A similar situation occurs on Ngarradj Creek. Grain size distributions of bedload for each transect should be determined along with dry season bed-material grain size distributions (as was undertaken herein) to permit comparison of bedload with bed-material size in the Alligator Rivers Region. Bedload is certainly better sorted than bed material and this improved sorting is most likely a consequence of size selective transport.

The bedload yields reported here serve as important baseline data for the subsequent determination of the impact of the Jabiluka mine, if mining is approved. There are now important solute, suspended sediment and bedload yields available for the pre-mining period that can be compared to post-mining data to measure the impact of mining. Similar information should be acquired for new mining sites in the Alligator Rivers Region.

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