Sediment Dynamics in Changing Environments (Proceedings of a symposium held in Christchurch, New Zealand, December 2008). IAHS Publ. 325, 2008.

Reformation of pool-riffle sequences and induced bed armouring in a sand-bed stream following river rehabilitation

A. F. KEENE[1], R. T. BUSH[1], M. D. CHEETHAM[1] & W. D. ERSKINE[2]

1 *Southern Cross Geoscience, School of Environmental Science and Management, Southern Cross University, PO Box 157, Lismore, Australia*
annabelle.keene@scu.edu.au

2 *School of Environmental and Life Sciences, University of Newcastle, PO Box 127, Ourimbah, Australia*

Abstract A series of structures was built along Widden Brook to trap sandy bed load as part of a river rehabilitation project. Stock-proof fencing of the riparian corridor was also carried out. The combination of in-stream structures and riparian revegetation has successfully sequestered large volumes of sand over the last six years, causing a substantial reduction in downstream sand supply. Downstream channel response to sand sequestration has included up to 1 m of bed degradation, channel contraction to less than half of the initial channel width, formation of marginal in-channel benches, reformation of a well-defined, rhythmically-spaced pool-riffle sequence and creation of a partially gravel-armoured bed surface. Sand storage in the study reach has starved the river immediately downstream, inducing bed erosion and the size-selective transport of sand and fine gravel. Residual pool depths now store four times the volume of water that was present before the start of river rehabilitation.

Key words channel response; sand storage; residual pool depth; grain size analysis; longitudinal profile; Widden Brook

INTRODUCTION

Pool-riffle sequences, like meanders, are fundamental morphological characteristics of alluvial river channels (Leopold *et al.*, 1964; Keller, 1972; Richards, 1976b; Keller & Melhorn, 1978; O'Neill & Abrahams, 1984). Pools are topographically low areas of the channel bed produced by scour at high flow, and have very low water-surface gradients at low flow. Riffles are topographically high areas of the channel bed which tend to fill at high flow and scour at low flow, and which have relatively high water-surface gradients at low flow. Runs are intermediate between pools and riffles in terms of depth and water-surface gradient (Leopold *et al.*, 1964; Richards, 1976b; Lisle, 1982).

There are few studies that have devised techniques for objectively defining individual pools and riffles in a sequence. The problem with the identification of pools and riffles has been the reliance on discharge-dependent criteria. Richards (1976b) defines riffles and pools as positive and negative residuals, respectively, from a regression line fitted through the bed profile. O'Neill & Abrahams (1984) devised a more objective technique based on the differences in height between successive points in a bed elevation survey. Lisle (1987) proposed the use of "residual depths" to define the difference in pool depth or bed elevation between a pool and the crest of the downstream riffle. Hence, the depth of the pool is controlled by the elevation of the riffle crest immediately downstream.

The development of alternating pools and riffles in a "pseudo-cyclic" manner is a characteristic of both straight and meandering channels, with pools located at meander bends and riffles at crossovers (Knighton, 1998). Pool-riffle spacing is more or less regular at around 5 to 7 channel widths (Leopold *et al.*, 1964; Keller & Melhorn, 1978). However, as Knighton (1998) identifies, problems of consistent definition and measurement exist due to variations in channel width and pool-to-pool spacing distance. Nevertheless, the concept of rhythmic change in bed topography, particularly for gravel-bed streams, is well established.

Pool-riffle sequences are typically associated with low gradient rivers with mixed load and gravel beds (Clifford & Richards, 1992; Keller & Melhorn, 1978). This characteristic channel bedform has shown little tendency to form in channels that carry uniform sand or silt, although concentrations of surficial coarser materials without changing bed topography have been observed in sandy ephemeral streams (Leopold *et al.*, 1966). Pool and riffle characteristics tend to be correlated with channel gradient, which is controlled by the flow's ability to re-work the channel (Wohl *et al.*, 1993). Pool-riffle sequences have often been associated with spatial patterns in bed

Copyright © 2008 IAHS Press

material size, where riffle sediments are coarser (Leopold *et al.*, 1964; Keller, 1971; Yang, 1971) and also better sorted (Hirsch & Abrahams, 1981; Carling, 1991) than adjacent pool sediments. Importantly, bed topography and particle size characteristics are inter-related. However, Richards (1976b) and Milne (1982) have suggested that while size differences can be identified between pools and riffles, these may be so small as to be statistically insignificant.

Pool-riffle sequences have distinctive channel and flow geometries. Riffle areas tend to be about 15% wider than pools, on average, reflected in the occurrence of distinct downstream trends in width as a function of bankfull discharge in pool-riffle sequences (Richards, 1976a). The development of a pool-riffle sequence occurs through a combination of scour and deposition of bed material, sorted spatially to give a generally regular spacing between consecutive channel features and capable of maintaining bed topography (Knighton, 1998). Pool-riffle sequences are described as an equilibrium bedform, incorporated as a significant stage in models of channel development from a straight to a meandering pattern (e.g. Keller, 1972).

In response to extensive bed degradation, channel enlargement and loss of pool habitat, rehabilitation schemes aim to reintroduce geomorphic complexity to affected river reaches as a means of increasing channel stability, bed scour and physical and hydraulic diversity. Excessive sediment load and sand slugs in river channels aggrade the river bed and infill pools (Erskine, 1996). In such cases, river rehabilitation aims to induce local scour and pool reformation. Pool-riffle sequences are not only significant channel bedforms in terms of geomorphology, but they also provide important aquatic habitat, particularly for fish and invertebrates (Clifford & Richards, 1992). Adjustments in pool-riffle spacing are an important consideration for riparian management and river rehabilitation (Gregory *et al.*, 1994).

The aim of this paper is to examine the pool characteristics and channel morphology of a recently formed pool-riffle sequence in the sand bed channel of Widden Brook, Australia, following the completion of upstream river rehabilitation works. In addition, we examine the change in bed-material grain size induced by the reformation of the pool-riffle sequence.

Regional setting

Widden Brook is a southern tributary of the Goulburn River in the upper Hunter Valley catchment, New South Wales, Australia. The study reach has a catchment area of 600 km^2 and is 0.8 km in length. Maximum flood-plain width in the study reach is about 230 m.

Catchment geology is dominated by a thick sequence of predominantly sedimentary rocks, such as conglomerate, sandstone and siltstone, which form part of the Permo-Triassic Sydney basin (Beckett, 1988), overlain by Tertiary olivine basalts in the upper catchment (Wellman & McDougall, 1974). Underlying the Triassic conglomerates and sandstones are the interbedded Permian shales, sandstones and coals of the Wollombi and Wittingham Coal Measures (Beckett, 1988). Erosion has exposed the Narrabeen Group to form steep escarpments and higher hills which dominate the valley landscape (Branagan *et al.*, 1976). Most of the upper catchment is forested and within the Wollemi National Park.

Mean annual rainfall varies from a maximum of 915 mm at high elevations to a minimum of less than 640 mm at Denman (Station no. 61016; 108 m). Mean summer and winter temperature maxima, respectively, are 23.1°C and 10.0°C at Nullo Mountain (Station no. 62100; 1130 m) and 31.3°C and 18.3°C at Jerrys Plains (Station no. 61086; 90 m).

METHODS

Within the study reach, 14 channel cross-sections were surveyed with selected sections extending across the flood plain. The elevation of the flood plain was taken as the bankfull elevation and was used to define channel width. Bed width is the width of the bed material between the base of each bank.

Detailed longitudinal water-surface and bed profiles following the thalweg (line of maximum flow depth) were surveyed using a total station under low-flow conditions in 2004 and 2007 to determine the channel gradient. The approximate depth to underlying bedrock or coarse substrate was determined by driving a metal probe into the bed until refusal. The occurrence of pools, riffles and runs were recorded, and pool depth and spacing (maximum depth *d*, length *l* and spacing in channel and bed width *w*) were measured. Residual pool depths were determined as the maximum pool depth below the downstream riffle crest (Lisle, 1987). Residual pool depth is used here as an indication of the degree of development of the pool-riffle sequence. Pool spacing was determined by measuring the distance on the longitudinal profile between successive pools and dividing this distance by channel width. Thus the pool-to-pool spacing or pool-riffle spacing is reported in channel widths, which allows comparison of streams of different sizes.

Grain size analysis

Bulk sediment samples were collected from the bed, bars and benches within the study reach. Samples were air dried at 60°C and sieved according to the method of Folk (1980) with around 500 g of sediment sieved at 1 φ intervals for 15 min. Folk's (1980) sediment textural classification was applied to the grain size results. Gravel refers to sediment >2 mm in diameter, sand to sediment with diameters between 2 and 0.063 mm, and mud to sediment finer than 0.063 mm. Where the bed was armoured on riffles, Wolman (1954) grid-by-number gravel counts of the surface population were conducted and the *b*-axis diameter of at least 100 gravel clasts was measured. The suggested modifications of the Wolman (1954) method by Leopold (1970) and Kellerhals & Bray (1971) were adopted. Where more than 5% of the sample was finer than 8 mm, a bulk sample of the finer sediment was collected. The bulk sample was dried, sieved and the less than 8 mm fraction was combined with the grid-by-number data using a weighting factor equivalent to the surface exposure of the less than 8 mm fraction. Frequency-by-weight data (bulk samples) are directly comparable to frequency-by-number data (gravel counts) (Kellerhals & Bray, 1971; Diplas & Sutherland, 1987).

Particle size distributions were described by specific percentiles, such as the *D*50, *D*16 and *D*84 (Folk & Ward, 1957). The *D*50 is the median particle diameter corresponding to the 50th percentile. Graphic grain size statistics (graphic mean *Mz*, inclusive graphic standard deviation σ_I, inclusive graphic skewness Sk_I, graphic kurtosis K_G and transformed kurtosis K'_G) were calculated from the cumulative grain size distributions and only use, at most, 90% of the grain size distribution between the 5th and 95th percentiles (Folk, 1980). Nevertheless, such graphic measures are preferred to the method of moments, which weights all grain size fractions equally.

Channel geometry and discharge analysis

The channel surveys provided information on channel width (w), cross-sectional area (A) and hydraulic radius (R_h). Channel capacity was determined using a modified mean section method (Simpson's Rule) for bankfull levels. Hydraulic roughness was estimated by means of the Cowan (1956) summation method. Manning's "*n*" was assessed at 0.07 for the present channel in the study reach. Stream velocity (v) and discharge (Q) corresponding to the channel edge of the benches and flood plains were calculated with Manning's equation (Leopold *et al.*, 1964). Specific stream power (ω) was calculated using the equation:

$$\omega = \gamma Q s w^{-1} \tag{1}$$

where γ (= ρg) is the specific weight of water and s is the water surface slope.

Statistical analysis

Linear regression analysis was undertaken for all bed elevations of the longitudinal profile to estimate the coefficients and determine the residuals of the regression equation, according to the method of Richards (1976b). The slope of the regression equation provides a measure of the gradient of the bed profile. Pools correspond to areas of negative residuals and riffles to areas of positive residuals from the regression equation. All statistical analyses were conducted with SPSS version 14.

RESULTS AND DISCUSSION

River rehabilitation

A total of 12 low to benchfull weirs were built upstream of the study reach in 2001. While some of the weirs failed during subsequent floods, a substantial amount of sand was stored in the backwater areas. Furthermore, stock-proof fencing was also constructed along the lower six weir pools to promote riparian revegetation. Much sand was also stored in the channel margins among the colonising riparian vegetation. While the amount of stored sand has not been quantified, a sand deficit certainly existed in the study reach because the channel started to degrade and contract within two years of the construction of upstream weirs and stock-proof fencing.

Channel morphology

Widden Brook is a straight, low sinuosity stream (Fig. 1; Table 1). Mean bankfull discharge is 34.6 m^3/s and mean specific stream power is 28.7 W/m^2 for the study reach. On a bivariate plot of bankfull discharge per unit channel width *vs* channel slope, the study reach plots in the field where no channel changes have been recorded for engineered channels in England and Wales due to the low specific stream power (Brookes, 1987). Nevertheless, significant channel contraction is currently occurring in the study reach by bed degradation into a narrow part of the pre-river rehabilitation bed which strands the remainder of the former bed as a bench next to the current contracted channel. Figure 1 shows this contracted channel and the channel margin which has been colonised by riparian vegetation. Sand storage in the marginal benches and vegetation colonisation of the sand have been responsible for the majority of the recent channel contraction.

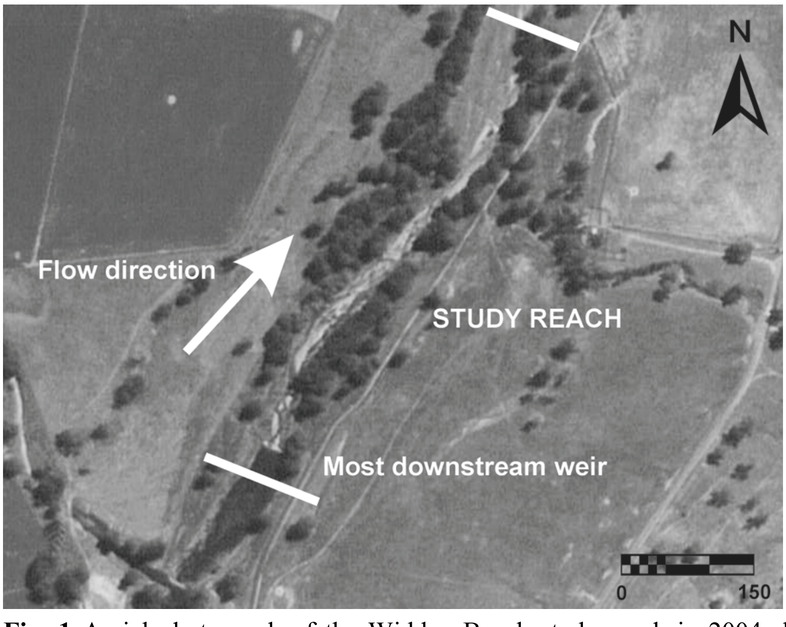

Fig. 1 Aerial photograph of the Widden Brook study reach in 2004 showing the present contracted channel, vegetated channel margins and continuous flood plain.

Table 1 Summary channel morphology and pool-riffle characteristics of the study reach on Widden Brook.

s (m/km)	*P* (km/km)	Mean *w* (m)	*n*	Maximum residual *d* (m)	Mean residual *d* (m)	Mean *l* (m)	Mean pool spacing (channel *w*)	Mean pool spacing (bed *w*)
3.04	1.29	42.8	11	1.27	0.65	11.3	0.94	1.64

s, channel slope; *P*, sinuosity; *w*, channel width; *n*, number of pool-riffle sequences; *d*, pool depth; *l*, pool length.

Pool-riffle morphology

Channel morphology and pool-riffle characteristics are summarised in Table 1. According to Wohl *et al.* (1993), with decreasing channel gradient the longitudinal bed profile is likely to show an increasing relative pool depth and pool spacing, due to a greater available flow energy for channel bed scour and the formation of pools in less resistant channels. However, from Table 1, residual pool depths have increased and pool spacing decreased with a relatively steep channel-bed gradient in the study reach. Residual pool depths at cease-to-flow in 2007 were considerably greater than in 2004 and hence prior to the commencement of river rehabilitation. These pools now store four times the volume of water than in 2004. This represents greater geomorphic complexity and a substantial increase in aquatic habitat.

Pool spacings of 0.94 and 1.64 in terms of bankfull width and bed width, respectively, are significantly smaller than the oft-quoted 5–7 times the channel width (Leopold *et al.*, 1964; Keller & Melhorn, 1978). However, we have determined that significant channel contraction is currently occurring, as outlined above. This contraction is also evident up- and downstream of the study reach, where it is due to a combination of different biogeomorphic processes, such as oblique accretion in straight reaches, bench formation and subsequent tree colonisation in slightly sinuous reaches and active point bar formation (i.e. point bar accretion greatly exceeds cut bank erosion) in more sinuous reaches. As the channel is currently adjusting its geometry, the above pool-riffle spacing is probably representative of a smaller channel. We have identified alternating multi-decadal periods of high and low rainfall in the Denman record which conform to the flood- and drought-dominated regimes (FDRs and DDRs, respectively) of Erskine & Warner (1999) elsewhere in the Hunter Valley. They found that channels contract during DDRs and widen during FDRs. A change from a FDR to a DDR started in about 2000 and the current river rehabilitation works were timed to reinforce a natural phase of channel adjustment to a climatically-driven shift in flood regime. However, the river rehabilitation works were constructed without being aware of the shift in flood regime.

The longitudinal bed profiles shown in Fig. 2 depict the channel gradient of the study reach. Channel gradient is dependent on the combined effect of grain size and discharge, as found by

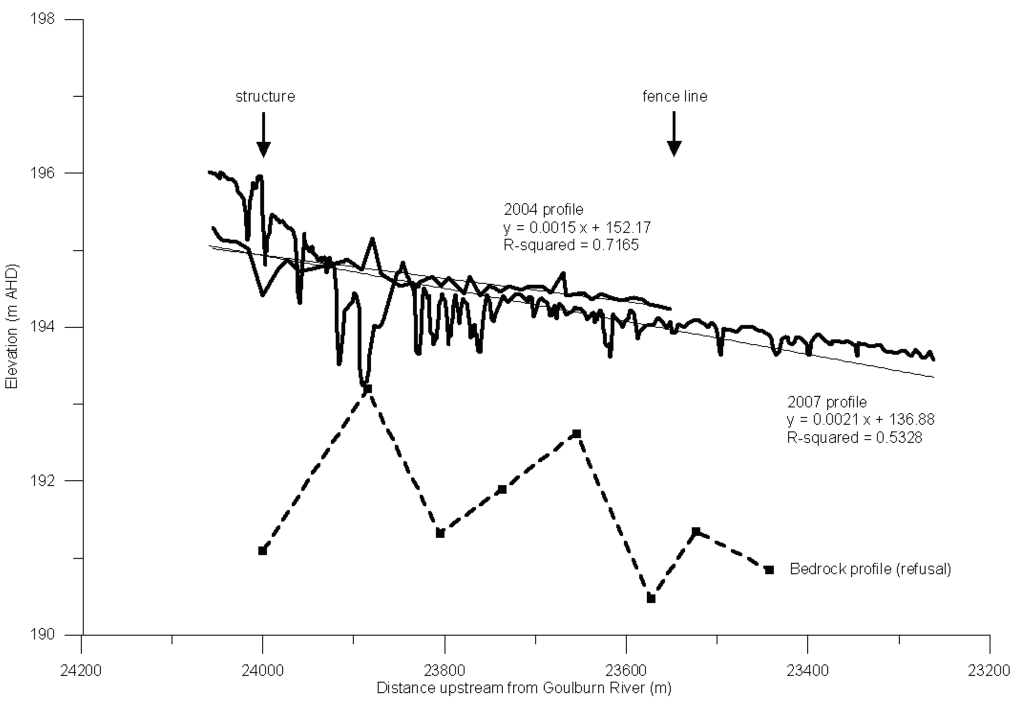

Fig. 2 Longitudinal bed profiles of Widden Brook in the study reach in 2004 and 2007 showing the thalweg regression lines and bedrock (depth to refusal).

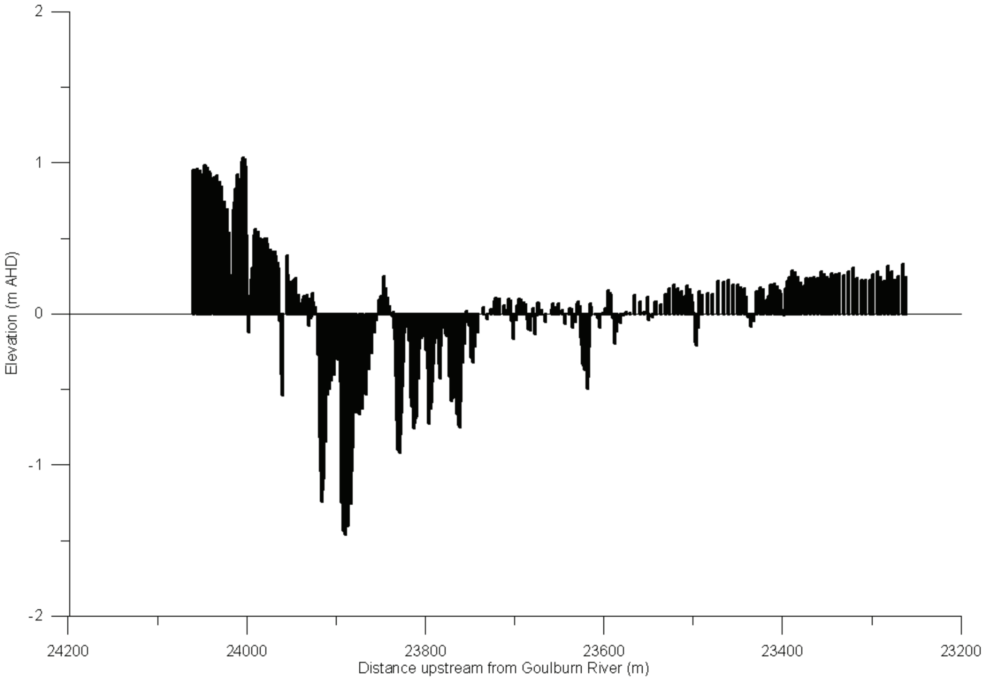

Fig. 3 Longitudinal bed profile of Widden Brook in the study reach in 2007 showing residuals from the thalweg regression line.

Wohl *et al.* (1993). Over the relatively short time period of 3 years there has been up to 1 m of bed degradation and an increase in slope, with the coefficient from the regression equation increasing from 0.0015 to 0.0021. It is clear from Fig. 2 that the longitudinal profile has shifted toward a steeper channel gradient, and hence greater stream power, with the development of the pool-riffle sequence. Pools and riffles are more pronounced in the mid reach of the longitudinal profile with a distinct oscillatory pattern.

Figure 3 depicts the pools and riffles of the longitudinal bed profile as positive and negative residuals from the 2007 thalweg regression line. This technique is appropriate for short reaches, such as the study reach (Richards, 1976b). The residuals clearly show bed aggradation upstream of the structure, the downstream scour pool immediately below the structure, a well defined pool-riffle sequence following bed degradation further downstream and aggradation of the downstream section of the profile. The refusal depth below the channel bed indicates that at least one pool has scoured to underlying coarse substrate or bedrock.

Bed material grain size characteristics

In 2004, the bed material in the study reach was predominantly medium to coarse sand with a small pebble gravel fraction. By 2007, many of the riffles exhibited a surficial pebble gravel armour layer which was one grain diameter thick, as shown in Fig. 4. The pebble gravel armour overlaid granular very coarse sand and was produced by the size-selective transport or winnowing of granules and sand from the original bed material during bed degradation. This is similar to the armouring that occurs downstream of dams. The armour layer is coarser and better sorted than both the underlying sediment and the pool sediments.

From Table 2, the bed material of the study reach is dominated by sand-sized sediment. On average, both the median and mean grain size diameters defined pools and runs as very coarse sands, while riffles were pebble gravels. Inclusive graphic standard deviation revealed the degree of sorting of the grain sizes in the bed materials. These values suggested that the sediments were poorly sorted, which is indicative of these bedforms. The inclusive graphic skewness determines the skewness of the tails of 90% of the curve, and is geometrically independent of sorting. The negative skewness of the pool bed material indicated an excess of coarse material. Using the verbal grain size classification scales of Folk (1980), pool sediments are poorly sorted, coarse skewed, mesokurtic, granular very coarse sands, whereas riffle sediments are poorly sorted, fine skewed, mesokurtic, sandy pebble gravels. These sediment textural characteristics demonstrate that pool-riffle sequences are associated with considerable spatial patterns in bed material size.

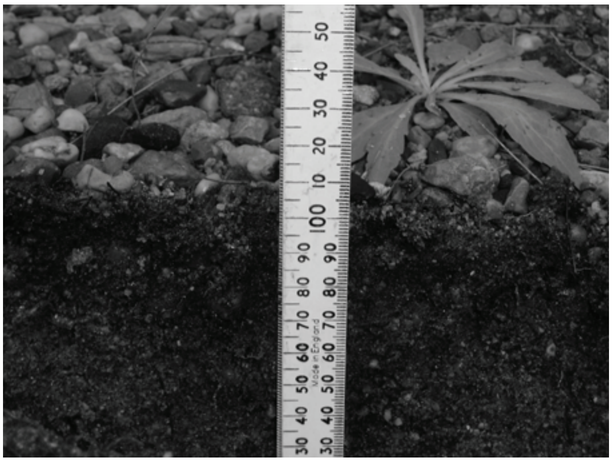

Fig. 4 Pebble gravel armour layer overlying granular very coarse sand of the study reach on Widden Brook.

Table 2 Bed material statistics in 2006 derived from Wolman grid-by-number gravel counts (Kellerhals & Bray, 1971) and cumulative frequency curves (Folk, 1980) of the study reach on Widden Brook.

Bedform	*n*	D_{50} (mm)	*Mz* (mm)	σ_I (phi)	Sk_I	K_G	K'_G
Pool	8	1.06	1.63	1.35	–0.12	0.95	0.49
Riffle	8	4.12	4.41	1.51	0.17	1.09	0.49
Run	6	1.14	1.73	1.41	–0.10	0.86	0.46

n, number sampled; D_{50}, median particle diameter corresponding to the 50th percentile; *Mz*, graphic mean; σ_I, inclusive graphic standard deviation; Sk_I, inclusive graphic skewness; K_G, graphic kurtosis; K'_G, transformed kurtosis.

CONCLUSION

Based on the pool-riffle morphology and bed material grain size data, we propose that relatively straight, sand-bed streams will rapidly form pool-riffle sequences when upstream sediment storage is increased to such a degree that a downstream bed-load deficit induces bed degradation into sediment that contains a small pebble gravel fraction. Riffles armour by the winnowing of granules and sand, and the formation of a cobble lag deposit. Degradation only occurs in a small part of the bed, also causing channel contraction. Reduced sand mobilisation has increased bed scour, pool formation and hydraulic diversity. Sand was sequestered in bars and benches, and stabilised by vegetation colonisation. This was facilitated by the presence of a series of in-stream structures. The development of these pool-riffle sequences has enhanced pool habitat for improved stream health and aquatic habitat. The fortuitous coincidence in time of the river rehabilitation works with a natural, climate-induced change in flood regime accelerated the reformation of pool-riffle sequences. The role of vegetation and stream and flood-plain management in the reformation of the pool-riffle sequence is crucial.

Acknowledgements We would like to thank Mr D. Butt and Mr L. Isaacson for their assistance with field sampling and Mr P. Cheeseman for grain size analyses at Southern Cross University.

Mr G. Harvey and his staff at Baramul Stud facilitated this research and their assistance is gratefully acknowledged. We thank Mr P. Andrews for his help and useful discussions over a long period of time. This research was supported by the Australian Research Council, ARC LP0455080.

REFERENCES

Beckett, J. (1988) The Hunter Coalfield: Notes to Accompany the 1:100 000 Geological Map. NSW Dept. Minerals Energy, Sydney, Australia.

Branagan, D., Herbert, C. & Langford-Smith, T. (1976) *An Outline of the Geology and Geomorphology of the Sydney Basin*. Science Press, Sydney, Australia.

Brookes, A. (1987) River channel adjustments downstream from channelization works in England and Wales. *Earth Surf. Processes Landf.* **12**, 337–351.

Carling, P. A. (1991) An appraisal of the velocity reversal hypothesis for stable pool-riffle sequences in the River Severn, England. *Earth Surf. Processes Landf.* **16**, 19–31.

Clifford, N. J. & Richards, K. S. (1992) The reversal hypothesis and the maintenance of riffle-pool sequences: a review and field appraisal. In: *Lowland Flood Plain Rivers: Geomorphological Perspectives* (ed. by P. A. Carling & G. E. Petts), 43–70. Wiley, Chichester, UK.

Cowan, W. L. (1956) Estimating hydraulic roughness coefficients. *Agric. Engng* **37**, 473–475.

Diplas, P. & Sutherland, A. J. (1987) Sampling techniques for gravel sized sediments. *J. Hydraul. Engng* **114**, 484–501.

Erskine, W. D. (1996) Response and recovery of a sand-bed stream to a catastrophic flood. *Z. Geomorphol*. **40**, 359–383.

Erskine, W. D. & Warner, R. F. (1999) Significance of river bank erosion as a sediment source in the alternating flood regimes of south-eastern Australia. In: *Fluvial Processes and Environmental Change* (ed. by A. Brown & T. Quine), 139–163. Wiley, Chichester, UK.

Folk, R. L. (1980) *Petrology of Sedimentary Rocks*. Hemphill Publishing Company, Austin, Texas, USA.

Folk, R. L. & Ward, W. C. (1957) Brazos River bar: a study in the significance of grain size parameters. *J. Sed. Res*. **27**(1), 3–26.

Gregory, K. J., Gurnell, A. M., Hill, C. T. & Tooth, S. (1994) Stability of the pool-riffle sequence in changing river channels. *Reg. Rivers: Res. Manage*. **9**, 35–43.

Hirsch, P. J. & Abrahams, A. D. (1981) The properties of bed sediments in pools and riffles. *J. Sed. Petrol*. **51**, 757–760.

Keller, E. A. (1971) Areal sorting of bed-load material: the hypothesis of velocity reversal. *Geol. Soc. Am. Bull.* **82**, 753–756.

Keller, E. A. (1972) Development of alluvial stream channels: a five stage model. *Geol. Soc. Am. Bull.* **83**, 1531–1536.

Keller, E. A. & Melhorn, W. N. (1978) Rhythmic spacing and origin of pools and riffles. *Geol. Soc. Am. Bull*. **89**, 723–730.

Kellerhals, R. & Bray, D. J. (1971) Sampling procedures for coarse fluvial sediments. *J. Hydraul. Div. ASCE* **97**, 1165–1180.

Knighton, D. (1998) *Fluvial Forms and Processes: A New Perspective*. Arnold, London, UK.

Leopold, L. B. (1970) An improved method for size distribution of stream bed gravel. *Water Resour. Res*. **6**, 1357–1366.

Leopold, L. B., Emmett, W. W. & Myrick, R. M. (1966) Channel and hillslope processes in a semiarid area, New Mexico. *US Geol. Survey Professional Paper* **352G**, 153–253.

Leopold, L. B., Wolman, M. G. & Miller, J. P. (1964) *Fluvial Processes in Geomorphology*. W. H. Freeman & Company, San Francisco, USA.

Lisle, T. E. (1982) Effects of aggradation and degradation on riffle-pool morphology in natural gravel channels, northwestern California. *Water Resour. Res*. **18**(6), 1643–1651.

Lisle, T. E. (1987) Using "residual depths" to monitor pool depths independently of discharge. *Pacific Southwest Forest and Range Experiment Station, USDA Forest Service, Research Note PSW-394.*

Milne, J. A. (1982) Bed-material size and the riffle-pool sequence. *Sedimentology* **29**, 267–278.

O'Neill, M. P. & Abrahams, A. D. (1984) Objective identification of pools and riffles. *Water Resour. Res*. **20**(7), 921–926.

Richards, K. S. (1976a) Channel width and the riffle-pool sequence. *Geol. Soc. Am. Bull*. **87**, 883–890.

Richards, K. S. (1976b) The morphology of riffle-pool sequences. *Earth Surf. Processes* **1**, 78–88.

Wellman, P. & McDougall, I. (1974) Potassium-argon ages on the Cainozoic volcanic rocks of New South Wales. *J. Geol. Soc. Aust.* **21**, 247–272.

Wohl, E. E., Vincent, K. R. & Merritts, D. J. (1993) Pool and riffle characteristics in relation to channel gradient. *Geomorphology* **6**, 99–110.

Wolman, M. G. (1954) A method of sampling coarse river-bed material. *Trans. Am. Geophys. Union* **35**(6), 951–956.

Yang, C. T. (1971) Formation of riffles and pools. *Water Resour. Res*. **7**(6), 1567–1574.