The importance of sediment control for recovery of incised channels

W. D. ERSKINE[1], A. C. CHALMERS[1] & M. TOWNLEY-JONES[2]

1 *Sustainable Use of Catchments and Coasts, School of Environmental and Life Sciences, University of Newcastle – Ourimbah Campus, PO Box 127, Ourimbah NSW 2258, Australia*
wayne.erskine@newcastle.edu.au

2 *School of Mathematical & Physical Sciences, The University of Newcastle – Ourimbah Campus, PO Box 127, Ourimbah NSW 2258, Australia*

Abstract Dairy Arm drains a 39.8 km^2 catchment in the Hunter Valley, Australia, and recently began recovery from post-1949 incision. Recovery involved cessation of upstream progressing incision, leaving a 400-m long *upper intact alluvial zone*. Post-1985 incision in the 5.5 km *incised zone* re-exposed buried large wood and eroded bank-side trees, forming log steps which are natural energy dissipators. Degradation in a small section of incised channel bed stranded remnant parts as the contemporary flood plain. Stoloniferous and rhizomatous grass invasion of the developing flood plain accelerated overbank deposition and stabilised river banks. The lower 5 km *depositional zone* has started to erode over most of its length. In the upper section, pools and riffles formed by degradation, and the bed is now narrower and deeper than at any time since incision started in 1949. A recent decrease in annual rainfall reduced the frequency of flood disturbance, allowing vegetation to survive.

Key words river recovery; bed degradation; pool-riffle sequence; clonal and rhizomatous grasses; vegetation invasion; statistical *versus* practical significance

INTRODUCTION

Dairy Arm is a 39.8 km^2 tributary of upper Wollombi Brook in the Hunter Valley, Australia (Fig. 1) which incised rapidly during a catastrophic flood on 17–18 June 1949 (Erskine & Melville, 2008). Erskine (1996) demonstrated that Wollombi Brook has high flood variability by world standards, with Flash Flood Magnitude Indices (after Baker, 1977) of at least 0.86. The flood of the 17–18 June 1949 was the largest since first European settlement in the 1820s (Erskine, 1996; Erskine & Chalmers, 2009) but was greatly exceeded by at least three palaeofloods during the late-Holocene (Erskine & Peacock, 2002). The highest rainfall for 17–18 June 1949 was 508 mm at the head of the Dairy Arm basin (Erskine, 1996). Flood peak discharges ranged between 22 and 39 times greater than the mean annual flood, depending on the gauging station and the period of record used for flood frequency analysis (Erskine, 1996; Erskine & Peacock, 2002; Erskine & Chalmers, 2009). The basin is composed of intercalated sandstone and shale of Triassic Hawkesbury Sandstone and Terrigal Formation, and has many recently developed landslips on lower slopes (Fig. 1).

Channel incision and gully erosion have been major problems throughout the ancient and modern world following the introduction of new types of agriculture (Cooke & Reeves, 1976). However, agriculture is not necessarily a prerequisite for the initiation of channel incision (Cooke & Reeves, 1976; Schumm *et al.*, 1984; Erskine, 2005). Nevertheless, the biogeomorphic processes of channel recovery from incision and their controlling factors are largely unknown. This paper documents the partial recovery of the incised channel of Dairy Arm over the last 30 years due to a reduction in sand supply.

METHODS

We have observed channel changes on Dairy Arm and its tributaries since 1979. Quantitative data on recovery from channel incision have been obtained from all of the following sources. Thirteen permanently marked valley-floor cross sections were surveyed on Dairy Arm between 1981 and 1983. Various cross sections were resurveyed in 1985, 1996–1997 and 2008–2009. Five cross-sections were surveyed on Cullys Arm in 1985 and 2009 (Fig. 1). Longitudinal bed profiles

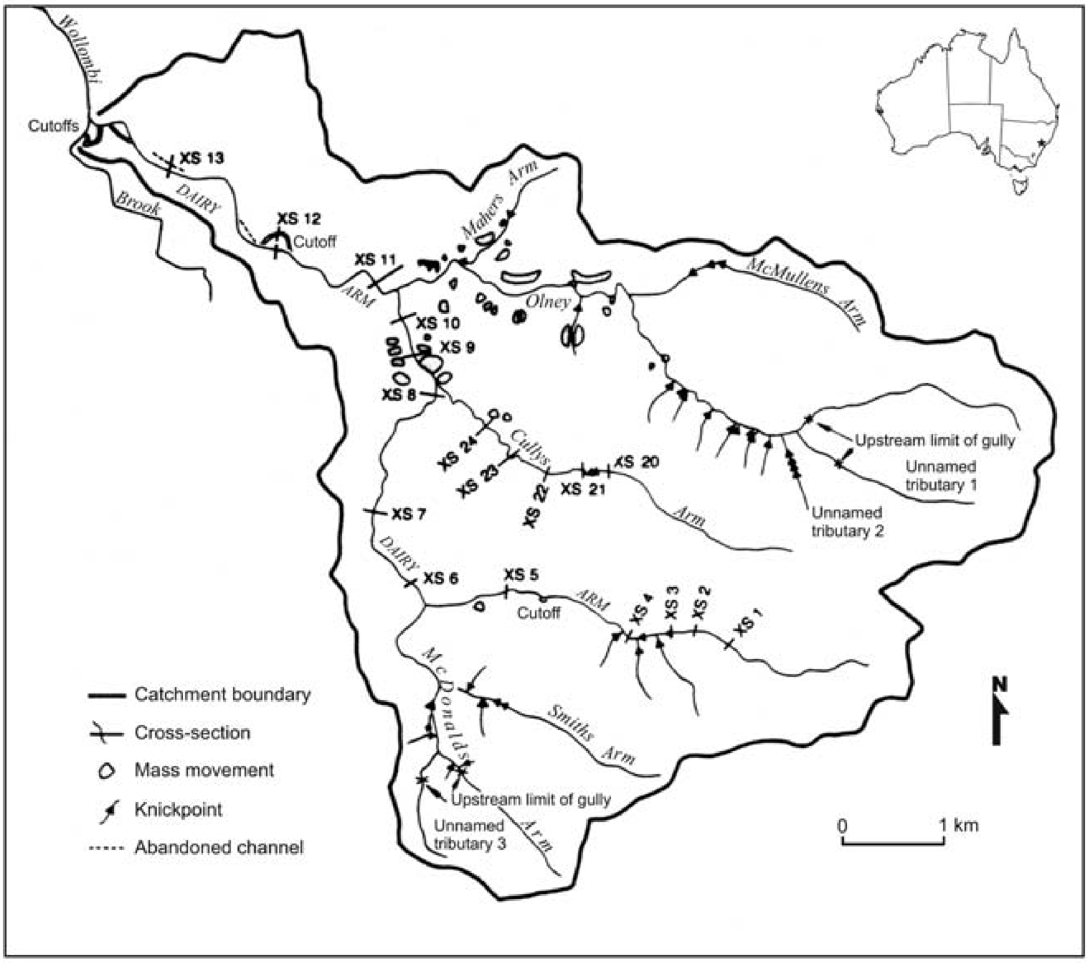

Fig. 1 The Dairy Arm drainage basin in the upper Wollombi Brook catchment, showing locations of the cross-sections.

centred on the cross-sections were also surveyed at the same times. Bulk bed-material samples were collected at each section at the time of survey. Samples were air-dried and sieved at φ/2 intervals. Trenches were dug through the flood plain at selected cross-sections and the sediments and sedimentary structures described. Plant species and their abundance were determined within 5 m × 2 m quadrats at selected cross-sections. Quadrats were placed in the bed, on both banks and within fenced river training works (where present) and, therefore, represented bed, bank, bench and flood plain habitats.

RESULTS AND DISCUSSION

There are many discontinuously incised channels in the Dairy Arm basin (Fig. 1). Figure 2 shows downstream changes in channel form and valley-floor width of Dairy Arm as in 1983. The alluvial section of Dairy Arm has been split into the following three zones based on their behaviour since European settlement, which are similar to those on the neighbouring Wollombi Brook (Erskine, 2008). The *upper intact zone* extended 400 m upstream of cross-section 2 (Fig. 1) in 1983 and covers the alluvial channel where it is unaffected by post-1949 incision (Fig. 2). Valley width is constricted by the resistant Mangrove Sandstone Member of the Terrigal Formation. A small capacity, sand-bed channel is flanked by a low flood plain covered by a moist forest with *Eucalyptus amplifolia* emergents. The *incised zone* extended 5.5 km from cross-section 3 to 9

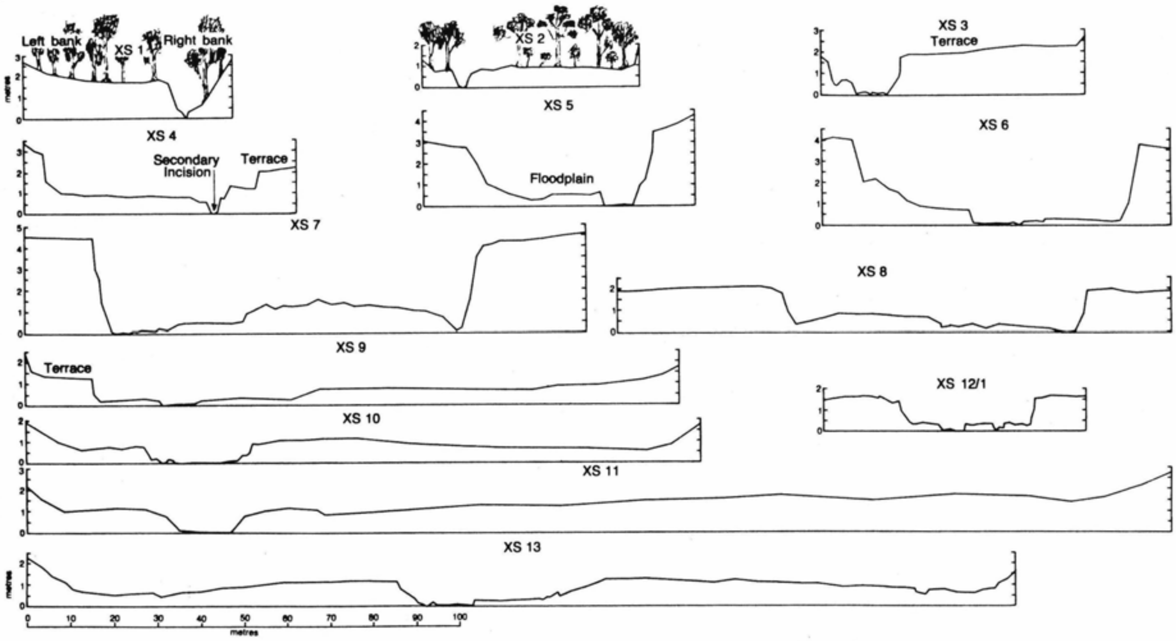

Fig. 2 Downstream changes in channel and flood plain morphology on Dairy Arm as in 1983. Location of cross-sections shown in Fig. 1.

(Fig. 1) in 1983 and has greatly widened and incised since 1949 (Erskine & Melville, 2008). There were a series of log steps between cross-sections 2 and 3 in 1983, which produced organic stepping. Log steps are small dams formed of large wood (logs, limbs and/or roots >0.1 m in diameter) which extend across the entire active channel resulting in an abrupt drop in water surface elevation by overflow of the log (Marston, 1982). They mark the upstream limit of historical channel incision. Riparian vegetation has been extensively cleared downstream of cross-section 3 and now consists of *Acacia* woodland (*A. parramattensis* and *A. parvipinnula*). The incised channel is very wide and deep, and is flanked by extensive sandy benches and bars (Fig. 2). The *depositional zone* extends 5 km from cross-section 9 to the junction with Wollombi Brook (Fig. 1) and has experienced substantial sedimentation since 1949 because of massive upstream channel erosion (Erskine & Melville, 2008). The channel is much wider and shallower than in the incised zone (Fig. 2). Recent channel changes in each zone are now quantified and explained.

Upper intact zone

This zone is now very short (<400 m) being sandwiched between the downstream incised zone and an upstream bedrock channel where Dairy Arm crosses the resistant Mangrove Sandstone Member of the Terrigal Formation. The length of this reach decreased incrementally as knickpoints eroded the bed as they moved upstream between 1979 and 1990. However, by 1996 all knickpoints had been replaced by stable log steps and the length of this zone has been constant since then. Only a 300-m long section of remnant alluvial channel has failed to incise since 1949. On Olney Arm, post-1949 incision extended right through the alluvial valley until it reached a stable ingrown meander cave cut into massive sandstone. Such incision also rejuvenated many tributaries (Fig. 1). On Cullys Arm, post-1949 incision only extended about 2 km upstream of Dairy Arm (Fig. 1) and left a swampy valley floor above the incised zone.

Incised zone

The catastrophic June 1949 flood started incision near cross-section 9. Many floods in 1950, and two floods in eight days in August 1952, continued the incision. By 1956, the incised channel was 5-km long and every major and most minor tributaries had also incised in response to drainage rejuvenation (Fig. 1). The catastrophic flood of March 1978 was the erosional finale of channel incision, greatly widening the incised channel and causing further upstream extension of incision. Between 1979, when we started our research, and 1990, the incised zone continued to progress upstream by knickpoint migration, as illustrated in Fig. 3. Between 1979 and October 1985, incision progressed a further 400 m upstream and deepened the channel by 0.5–1.2 m (Fig. 3). Some knickpoints were as high as 1.5 m and were usually capped by a resistant mud unit which overlay cross-bedded medium sand. As the main channel deepened, tributaries continued to be rejuvenated. Knickpoints are currently present on most tributaries in the incised zone (Fig. 1). However, by 1996, this incision had moved only an additional 40 m upstream from where it was in 1985 on Dairy Arm, despite a large storm in February 1990 which caused erosion on many alluvial fans (Scott & Erskine, 1994). By 1996, resistant logs had accumulated in such large numbers at the upstream end of this reach that stable log steps were very common. Log steps have contributed to the cessation of incision because knickpoints have now become ensconced on recently formed log steps.

The incised channel margins and floodplain are now well vegetated by stoloniferous and rhizomatous grasses, such as *Isachne globosa* (Swamp Millet) and *Cynodon dactylon* (Common Couch). These grasses have stabilised the banks by creating a dense sward of above ground biomass, and by consolidating the sediment with rhizomes. As a result, bed degradation of up to 0.6 m has been active (Fig. 4(a) and (b)) since our first surveys and bed-material grain size has significantly increased since 1996/7.

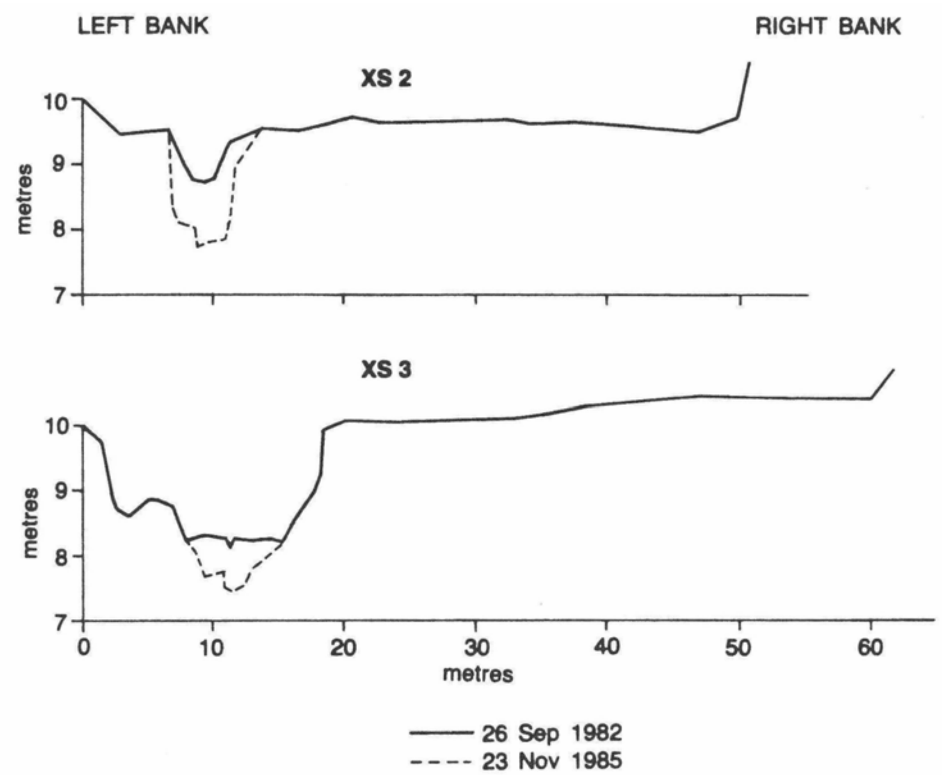

Fig. 3 Incision of upper Dairy Arm between September 1982 and November 1985 by the upstream migration of a series of knickpoints during the floods of November 1984 and October 1985. For location of cross sections, see Fig. 1.

Depositional zone

The catastrophic March 1978 flood also greatly aggraded the bed and deposited extensive sand splays over the flood plain in the depositional zone. A neck cutoff at cross-section 12 (Fig. 1) was

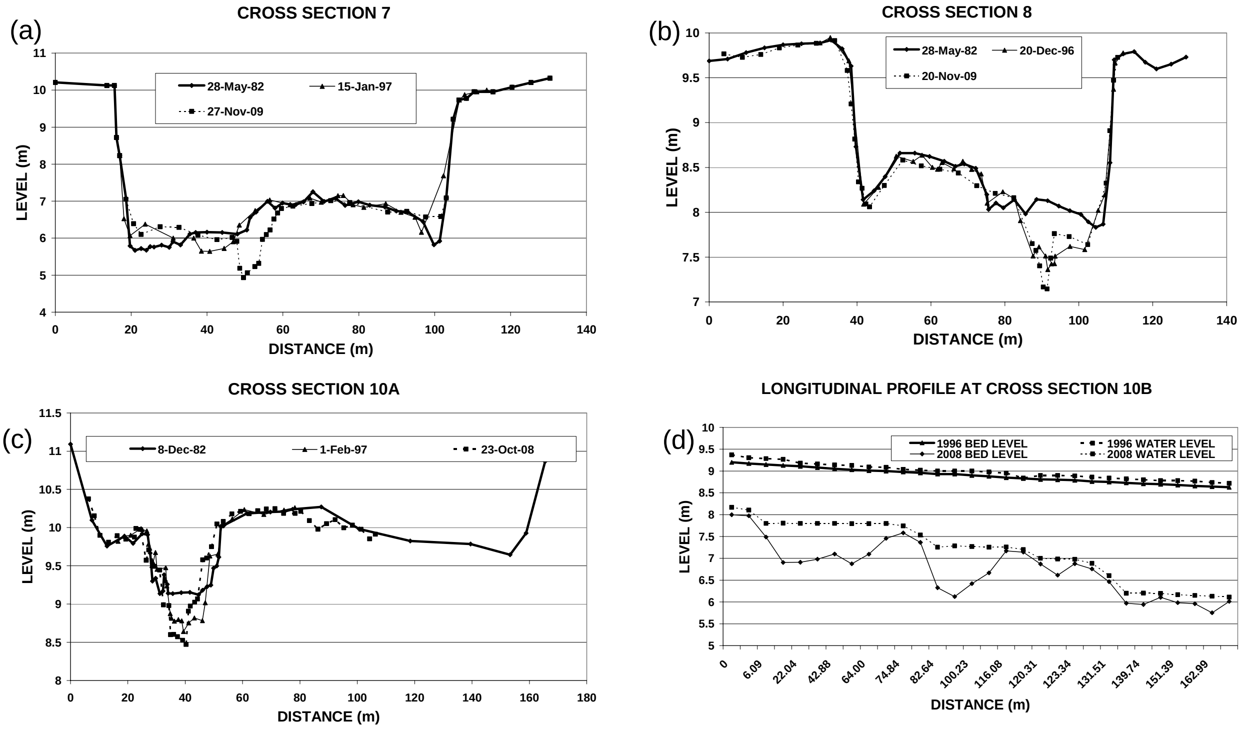

Fig. 4 Recent channel changes on Dairy Arm: (a) channel changes at cross-section 7 (fig. 1) between 1982 and 2009, showing bed degradation and lateral migration; (b) channel changes at cross-section 8 (Fig. 1) between 1982 and 2009 showing progressive bed degradation; (c) channel changes at cross-section 10A (Fig. 1) between 1982 and 2008 showing progressive bed degradation; (d) long profile changes at cross-section 10B between 1996 and 2008 showing bed degradation and development of a pool-riffle sequence. Cross-section 10B is located immediately downstream of cross-section 10A, whose location is shown in Fig. 1.

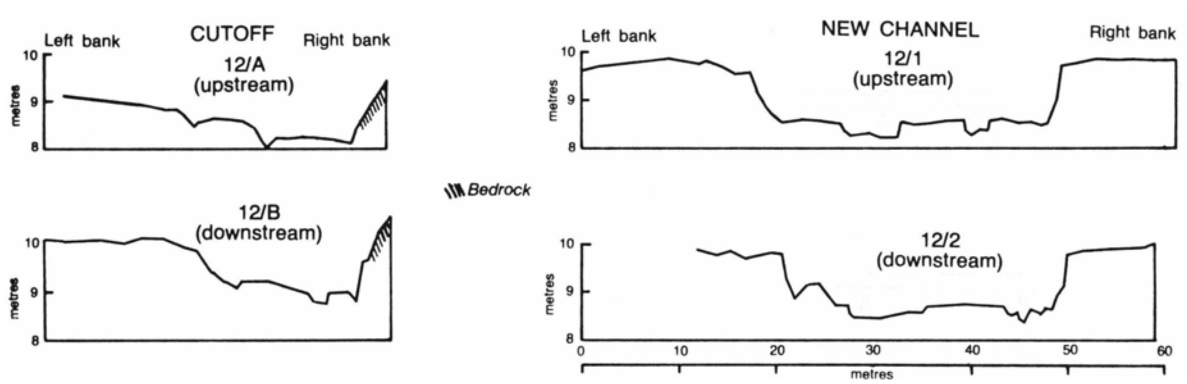

Fig.5 Channel widening by the catastrophic March 1978 flood in the depositional zone of Dairy Arm. The cutoff was completely abandoned by this flood and the new channel was formed in about two days. See Fig. 1 for location of cross-section 12.

formed by this flood. Channel widening is illustrated in Fig. 5 by a comparison of the cutoff and new channel dimensions. Before the flood, mean bankfull channel width was 20.25 m and after the flood it was 30.38 m, an increase of 50% (Fig. 5). In May 1982, the then NSW Water Resources Commission commenced limited structural river training works and more extensive stock-proof fencing of willow and poplar plantings along the lower 5.5 km of Dairy Arm, downstream of the Cullys Arm junction on the channel alignment and width created by the March 1978 flood (Water Resources Commission, 1981). These works have largely been successful and the areas subject to

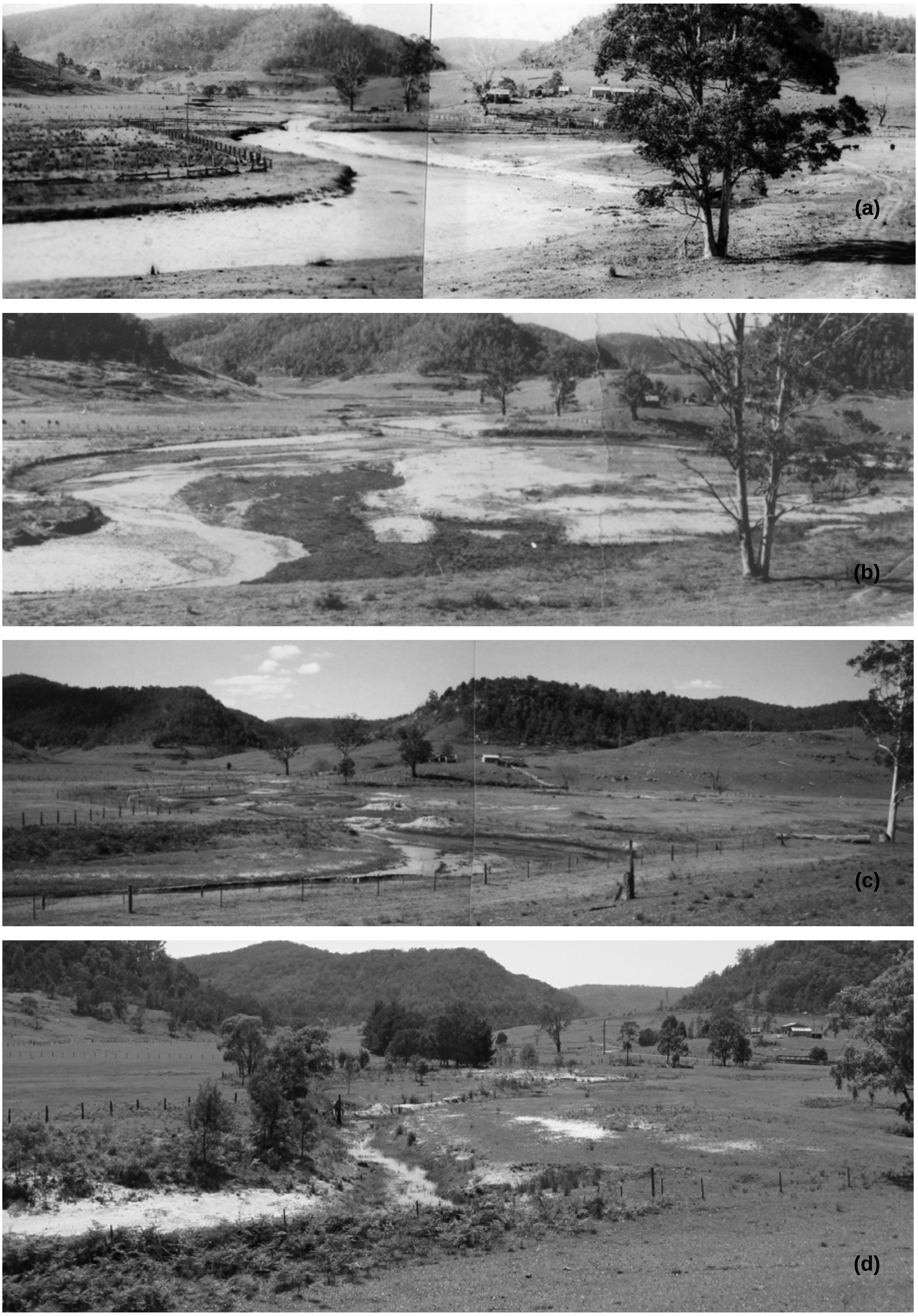

Fig. 6 Channel changes on Dairy Arm at the junction with Olney Arm (see Fig. 1 for location). Photo (a) was taken on 7 June 1965, (b) on 30 May 1979, (c) on 7 December 1983 and (d) on 20 November 2009. Note channel contraction and incision between 1979 and 2008. (a) and (b) photos taken from Water Resources Commission (1981).

stock-proof fencing have experienced supplemental plantings of native tree and shrub species by local landowners. Channel width is currently less than half of what it was in March 1978, the bed has incised by up to 1.5 m and an extensive bench now flanks the channel inside the alignment fenced by the Water Resources Commission.

Figure 6 shows channel changes of Dairy Arm at the junction with Olney Arm since 1965. While massive sand storage was apparent after the June 1949 flood and up to the March 1978 flood (Erskine & Melville, 2008), channel contraction and bed degradation are now active (Fig. 6). Bed degradation between 1982 and 2008 at the nearby cross-section 10 is shown in Fig. 4(c). As a result, mean bed-material size has coarsened and pools have now formed, as illustrated by changes in the long profile between 1996 and 2008 at cross-section 10B (Fig. 4D). The current phase of bed degradation extends from cross-section 6 to 13 (Fig. 1), but pool development has only occurred between cross-sections 9 and 11. Nevertheless, the road crossing between cross-sections 11 and 12 (Fig. 1) was composed entirely of sand in 1978, but degradation since 1981 has now exposed a formerly buried concrete causeway. The vertical drop over the causeway to the downstream bed is now 1.5 m. Downstream progressing bed degradation and subsequent pool formation will continue further downstream as upstream sand supply continues to decline. Some pools now contain permanent water which was not the case before 2000.

Vegetation invasion has been important for the storage and retention of sand on the developing banks, benches and flood plain next to the degrading channel (Fig. 7). This vegetation consists of grasses, such as *Isachne globosa*, *Cynodon dactylon*, *Phragmites australis* and *Microleana stipoides*. Herbaceous ground cover was, on average, >75% on the banks, benches and flood plain. Overstorey cover provided by woody species (mostly shrubs) was low on all landforms. The cover of woody species on the banks was due to a combination of deliberate planting as part of river training works (depositional zone) and natural recruitment of *Acacia* species (incised zone).

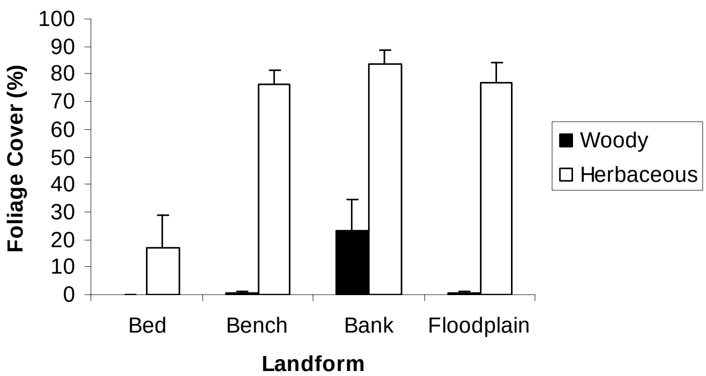

Fig. 7 Percentage foliage cover of woody and herbaceous (non-woody) vegetation in the bed (n = 5), and on benches (n = 7), banks (n = 6) and flood plain (n = 7) of Dairy Arm.

Recent rainfall changes

Monthly rainfall records for four Bureau of Meteorology rainfall stations that are located in, or close to, the catchment of Dairy Arm were obtained for the complete period of record, 1959–2008 (Table 1). Missing data were estimated by least squares linear regression with a neighbouring station (Table 1). All regressions were statistically significant ($p < 0.01$) and had coefficients of determination of at least 0.777, but usually much higher. The time series were subjected to the same analyses as undertaken by Erskine & Townley-Jones (2009) for a much larger data set for the Central Coast of NSW. CUSUM analysis showed that annual rainfall was consistently higher between 1959 and 1990, and decreased between 1991 and 2008. However, Wilcoxon Rank Sum tests demonstrated that CUSUMS for each time period were not significantly different, despite a decrease in mean annual rainfall of between –9.0 and –20.7% (Table 1). While this decrease in annual rainfall has not been statistically significant, we believe that it has been practically

Table 1 Changes in mean annual rainfall between 1959–1990 and 1991–2008 at four Bureau of Meteorology stations within and near the Dairy Arm catchment.

Station	Station number	% estimated record	Mean ± SE for 1959–1990 (mm)	Mean ± SE for 1991–2008 (mm)	% reduction in mean
Kulnura North	61165	6	1158.1 ± 53.3	918.3 ± 51.6	–20.7
Laguna (Murrays Run)	61164	1.8	973.6 ± 50.1	885.6 ± 63.7	–9.0
Watagan Central	61201	11.7	935.4 ± 44.8	813.6 ± 49.8	–13.0
Yallambie	61205	1.2	892.4 ± 41.8	746.2 ± 44.7	–16.4

significant in terms of reducing the magnitude and frequency of flood disturbance and has hence aided river recovery by vegetation invasion. A large flood in June 2007 (maximum daily rainfall of 185 mm) did not damage the recovered channel despite having a daily rainfall greater than in March 1978 (maximum daily rainfall of 166.2 mm). The lack of a major flood between 1990 and 2007 enabled the vegetation to become established to such an extent that it was capable of withstanding a major flood. Unfortunately there are no river gauging stations in the general area to investigate actual changes in flood magnitude and frequency.

CONCLUSIONS

A substantial reduction in sand supply to the channel has occurred in the Dairy Arm catchment since the catastrophic flood of March 1978. This reduction has been achieved by a combination of channel incision progressing as far upstream as it is likely to reach under existing bioclimatic conditions and by vegetation invasion of the river banks, marginal benches and flood plain by stoloniferous and rhizomatous grasses. Some structural works, stock-proof fencing and plantings assisted vegetation recovery. A non-significant decrease in mean annual rainfall of between 9% and 21% since 1990 has reduced the frequency of flood disturbance and accelerated the recruitment and survival of grasses and scattered *Acacia* individuals. This vegetation has now stabilised the channel banks effectively stopping most bank erosion. Reduced sand supply, particularly since 1990, has induced a secondary phase of bed degradation which is much less than the primary incision initiated by a catastrophic flood in June 1949 (Erskine & Melville, 2008). Furthermore, the development of a new pool–riffle sequence has commenced and is providing aquatic habitat and water storage for the first time since the incision-initiating flood of June 1949. Sediment control is essential for the recovery of incised channels because episodic pulses of large volumes of sand are generated by catastrophic floods and overwhelm the channel in areas subject to high flood variability (Erskine, 1996, 2008). While sediment supply will eventually decline naturally once all alluvial reaches are incised, vegetation in conjunction with structural works can be used to stabilise banks and knickpoints, and hence assist channel recovery during periods of little flood disturbance. Methods of predicting periods of little flood disturbance are essential for river restoration in Australia.

REFERENCES

Baker, V. (1977) Stream-channel response to floods, with examples from central Texas. *Geol. Soc. Am. Bull.* **88**, 1057–1071.

Cooke, R. & Reeves, R.W. (1976) *Arroyos and Environmental Change in the American South-West*. Clarendon Press, Oxford, UK.

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

Erskine, W.D. (2005) Gully erosion. In: *Water Encyclopedia: Surface and Agricultural Water* (ed. by J. H. Lehr, J. Keeley, J. Lehr & T. B. Kingery III), 183–188. Wiley-Interscience, Hoboken, The Netherlands.

Erskine, W. D. (2008) Channel incision and sand compartmentalization in an Australian sandstone drainage basin subject to high flood variability. In: *Sediment Dynamics in Changing Environments* (ed. by J. Schmidt, T. Cochrane, C. Phillips, S. Elliott, T. Davies & L. Basher) (Proc. Christchurch Symp. Dec. 2008), 283–290. IAHS Publ. 325. IAHS Press, Wallingford, UK.

Erskine, W. D. & Melville, M. D. (2008) Geomorphic and stratigraphic complexity: Holocene alluvial history of upper Wollombi Brook, Australia. *Geografiska Annaler* **90A**(19–35).

Erskine, W. D. & Peacock, C. T. (2002) Late Holocene flood plain development following a cataclysmic flood. In: *The Structure, Function and Management Implications of Fluvial Sedimentary Systems* (ed. by F. J. Dyer, M. C. Thoms & J. Olley) (Proc. Alice Springs Symp. Sept. 2002), 177–184. IAHS Publ. 276. IAHS Press, Wallingford, UK.

Erskine, W. D. & Townley-Jones, M. (2009) Historical annual rainfall changes on the Central Coast of NSW: Further evidence of alternating rainfall regimes. In: *Proc. H2009 32nd Hydrology & Water Resources Symp*. (Newcastle), 36–47.

Marston, R. A. (1982) The geomorphic significance of log steps in forest streams. *Ann. Assoc. Am. Geogr.* **72**, 99–108.

Schumm, S. A., Harvey, M. D. & Watson, C. C. (1984) *Incised Channels*. Water Resources Publ., Littleton, Colorado, USA.

Scott, P. F. & Erskine, W. (1994) Geomorphic effects of a large flood on fluvial fans. *Earth Surf. Processes Landf.* **19**, 95–108.

Water Resources Commission of NSW (1981) Proposal for the control of Dairy Arm in the vicinity of Yallambie. Submission to the Hunter Valley Conservation Trust, Maitland, New South Wales, Australia.