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Channel instability in a forested catchment: a case study from Jones Creek, East Gippsland, Australia

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Abstract

Jones Creek, a forested sub-catchment of the Genoa River, Victoria, Australia has experienced channel metamorphosis induced by a series of floods since 1971. In the flood of record, in 1971, the Genoa River widened by up to two times at the confluence with Jones Creek. This effectively shortened the course of Jones Creek, resulting in a lagged tributary response. Incision and bed steepening during floods in 1975 and 1978 triggered significant changes in channel form along Jones Creek. Channel changes between 1972–1997 resulted in a four-fold increase in cross-sectional area. Channel depth increased by up to 1.5 m, but has subsequently refilled by around 0.6 m. Initially, incision resulted in increased stream power as a result of increased mean depth, while sinuosity was maintained. This was followed by channel widening, a reduction in sinuosity and a continued increase in slope. Estimated stream power remains high as the channel continues to laterally adjust. This study highlights the dynamic nature of tributary–trunk stream relationships in a cut-and-fill landscape, demonstrating how trunk stream adjustments can induce profound tributary instability in a forested subcatchment. Channel widening of the trunk stream primed the tributary for change. Bedlevel incision and increases in bedslope breached the threshold of landscape stability in this steep alluvial tributary. Three periods of channel change can be identified, reflecting the complex response of the system to channel incision. Rather than developing simple cutoffs, Jones Creek now exhibits a range of lateral adjustment and realignment features. Responses to external disturbance provide insights into 'natural' recovery mechanisms in this forested setting. Lateral adjustment and associated sediment deposition have been accompanied by rapid rates of vegetation colonisation and stabilisation of realignment features, effectively reducing the volume of sediment that is available to be reworked through the channel network. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: channel instability; bed-level incision; forested catchment; channel recovery; riparian vegetation; Australia

1. Introduction

To date, nearly all studies of the geomorphology of the rivers in southeastern Australia have been framed in landscapes which have been dramatically altered in the period following European settlement. As such, our understanding of controls on the character and behaviour of these rivers may be skewed by

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the significant alterations in boundary conditions that these landscapes have experienced. For example, in virtually all instances in which channel metamorphosis has been documented, there has been extensive clearance of riparian and floodplain vegetation, modifying the geomorphic effectiveness of flood events (Brooks and Brierley, 1997). Although the Australian landscape is characterised by fluvial systems that have been destabilised since European settlement, there is little documented evidence of the mechanisms that induce the breaching of thresholds. In this study, the term channel stability refers to a change in channel pattern and form process association as a result of an altered sediment load or discharge regime (Chorley et al., 1984). This study presents data on the metamorphosis of an alluvial tributary in a relatively undisturbed forested setting and isolates controls on landscape stability.

Our understanding of channel instability largely stems from theoretical and experimental work and a range of case studies carried out in the northern hemisphere (Schumm and Lichty, 1963; Schumm et al., 1984; Osterkamp and Costa, 1987; Simon, 1989, 1992; Schumm, 1993). Most of these studies have been performed in landscapes that have been subjected to a history of human impact. It is only recently that literature on fluvial geomorphology has highlighted the unique character of the Australian fluvial landscape (cf., Tooth and Nanson, 1995; Brierley et al., 1996). The theoretical and documented processes on channel instability exemplified in the northern hemisphere need to be tested in an Australian setting. This issue is compounded by the fact that very few, if any, studies of channel instability have demonstrated how fluvial systems in temperate environments unaffected by human activity respond to large ‘natural’ disturbances. For example, while Prosser et al. (1994), Brierley and Fryirs (1998) and Fryirs and Brierley (1999) have demonstrated the distinct cut and fill nature of certain alluvial landscape settings in southeastern Australia, it has been difficult to ascertain the character of incisional processes in forested settings. To our knowledge, no studies have documented the character and mechanisms of channel incision and landscape recovery in catchments with an intact riparian forest. While a significant volume of literature from the northern hemisphere provides a basis with which to assess the role of riparian vegetation and woody debris on channel dynamics in a forested setting (cf., Keller and Swanson, 1979; Nakamura and Swanson, 1993), much of this work has been in fluvial settings which are fundamentally different to landscape settings in southeastern Australia.

Jones Creek is a forested tributary of the Genoa catchment, which straddles the New South Wales–Victoria border in southeastern Australia. Since 1972 Jones Creek has undergone significant changes in channel geometry and planform. In this period, the catchment has been subjected to ‘natural’ disturbances such as a series of floods and the 1983 Ash Wednesday fire. This study documents how Jones Creek has responded to these ‘natural’ disturbances. Insights are provided into recovery mechanisms that follow large scale channel instability in settings with an intact riparian zone. The role of within-channel vegetation, large woody debris and sediment retention are examined as integral components for the onset of channel recovery, thereby adding to the theoretical notions on channel behaviour following incision.

2. Regional setting

Jones Creek drains a 31 km^2 subcatchment of the Genoa River in far East Gippsland (Fig. 1). Upstream of Jones Creek confluence, the Genoa River is bedrock-controlled, but the confluence zone itself (termed Wangarabell Reach) is characterised by an area of valley expansion resulting in discontinuous floodplain formation. The geology of the upper part of Jones Creek catchment comprises Devonian granites and Ordovician metasedimentary rocks. Much of the middle part of the catchment comprises Tertiary sediment consisting of unconsolidated coarse sand and gravels with clay rich sands.

The lower 3.5 km of Jones Creek has an alluvial channel with a sinuosity of 1.58, mean bankfull width of approximately 33 m, and mean depth of 2 m. Although the forested floodplain increases in width downstream from 50 m to 500 m towards the Genoa River confluence (Fig. 2), there are no systematic downstream changes in channel width, mean

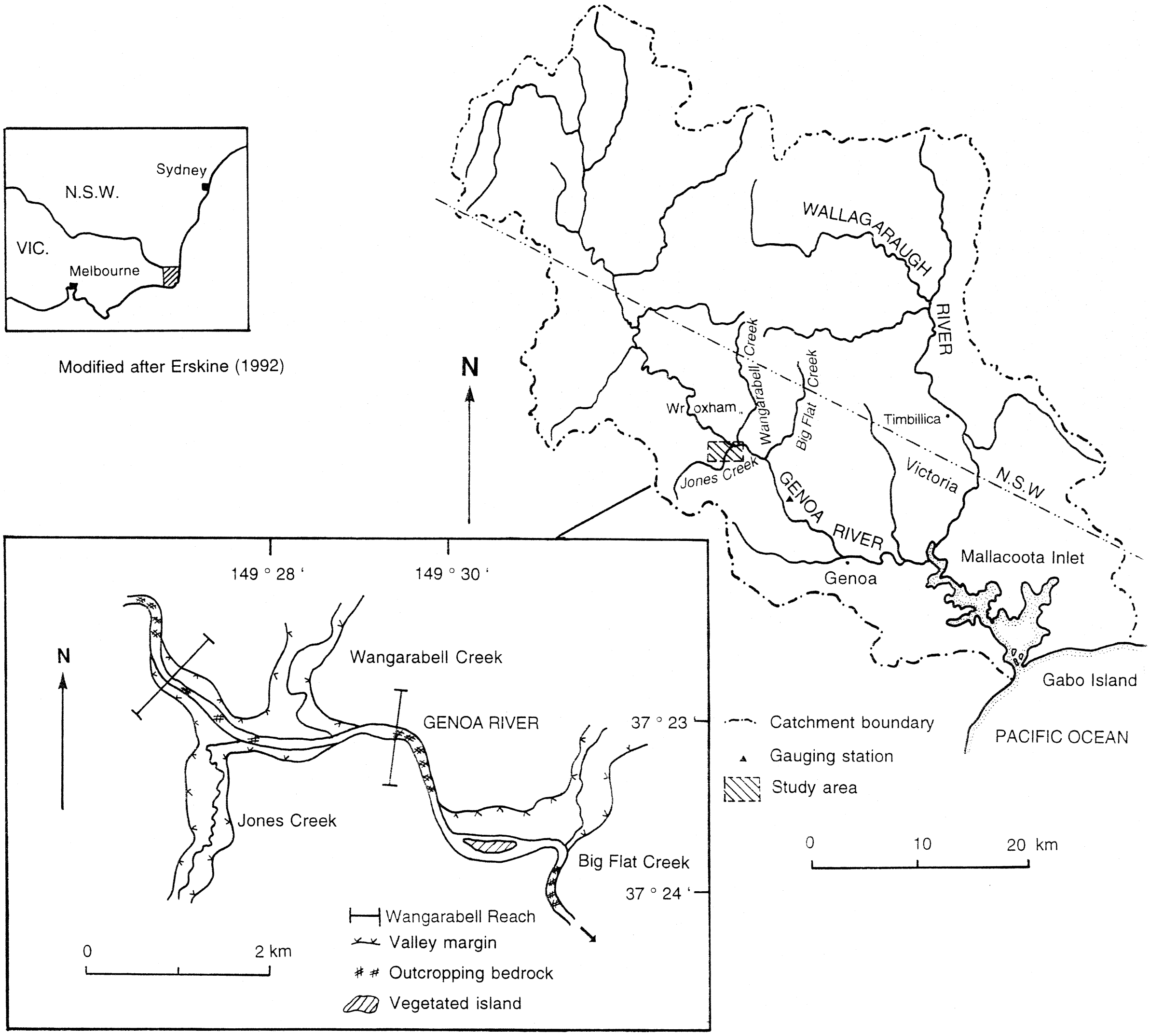

Fig. 1. Location map showing Jones Creek within Wangarabell Reach in the Genoa River catchment.

depth, cross sectional area, sinuosity or bed material size. The average floodplain slope in the lower section of the catchment is 0.0075 m/m, while overall channel slope within the study area is 0.0045 m/m. Jones Creek is an emphemeral system and is characterised by widespread bank erosion, with numerous examples of bank collapse and tree fall. Various abandoned channels are evident near the channel and on the floodplain.

Jones Creek is a mixed load system, transporting silt, sand and gravel. At present, Jones Creek transports significant volumes of sediment forming sand sheets, point bars and bank attached bars. The bed material size (assessed using the Wolman (1954) technique) averages 40 mm in the upper 2.5 km of the alluvial reach, but increases in size up to 320 mm adjacent to the Genoa River confluence, where older Genoa River gravels are reworked. The presence of these larger clasts indicates that the Genoa River has adjusted its position through the confluence zone in the past, with these coarser materials extending up to 400 m upstream from the confluence.

Bank materials are extremely variable, ranging from clay-rich uniform bank exposures to medium sands and gravels in channel fill sequences. Bankside vegetation in the study area often has exposed root zones which are well above present-day bedlevels. Large amounts of large woody debris (LWD — defined as wood > 10 cm in diameter and > 1 m in length) and log jams are evident within the channel.

Based on rainfall records from Wroxham (10 km NE of Jones Creek) and Timbillica (25 km NE of Jones Creek), the mean annual rainfall at Jones Creek is approximately 900 mm. Continuous flood discharge records for the Genoa River downstream of Wangarabell are available from mid 1971 onwards (the ‘gorge’ — station 221210). Based on the annual series from 1972–1996, the Genoa River has a steep flood frequency curve as indicated by a flash flood magnitude index of 0.74, which is high by world standards (Erskine 1992, 1993; Erskine and I.D.&A., 1997). Based on monthly and maximum 48-h rainfall at Wroxham since 1971, periods of above average rainfall can be discerned for 1971–1978, 1983–1988 and 1991–1995. These periods of high rainfall have been related to anecdotal and historical evidence to establish a flood record for Jones Creek.

Approximately 90% of Jones Creek catchment falls within Coopracambra National Park. There are no records of extensive timber extraction from the catchment in the last 25 years. Prior to this, the catchment has had a history of small scale timber extraction in the form of spot milling. The catchment is dominated by regrowth dry sclerophyll vegetation on the hillslopes and floodplain with more mesic communities in the gullies and headwaters. Species composition across the floodplain shows considerable spatial variability with a mosaic of vegetation patches. The tall open forest is dominated by *Eucalyptus viminalis subsp. viminalis* (Manna Gum), *E. elata* (River Peppermint) and *E. baueriana* (Blue Box). The mid-storey in the study area is dominated by *Acacia mearnsii* (Black Wattle), *A. melanoxylon* (Blackwood) and *Pomaderris aspera* (Hazel Po-

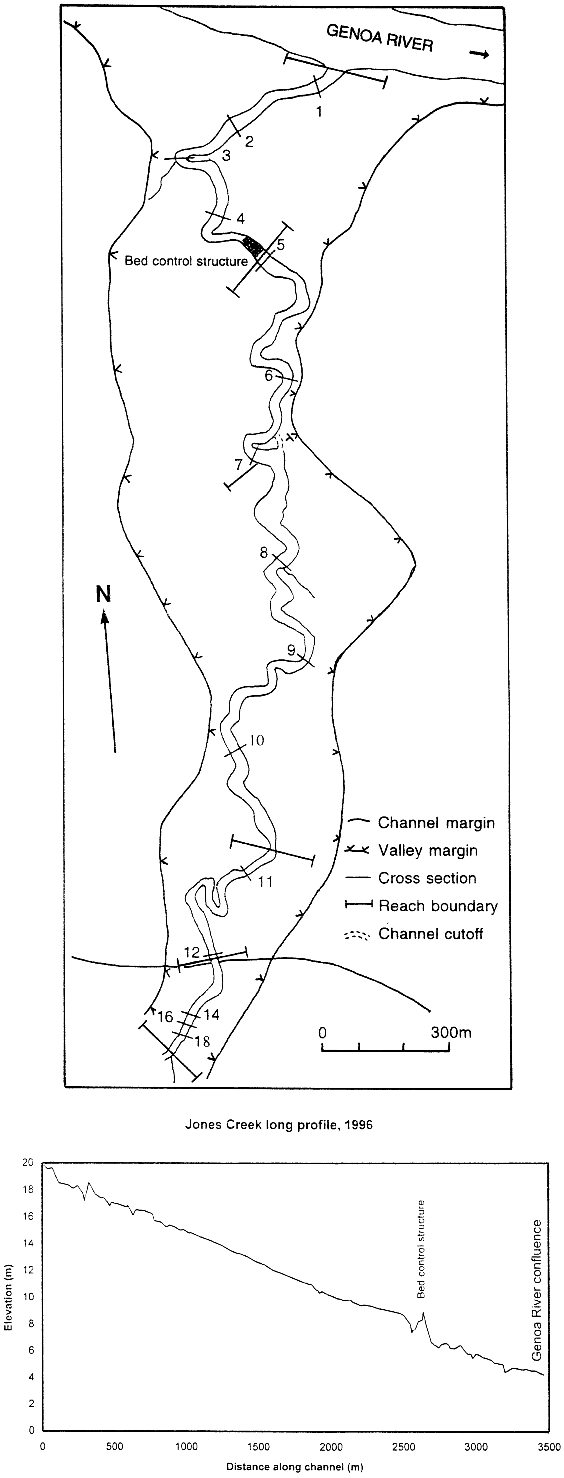

Fig. 2. Study area within Jones Creek, highlighting the contemporary planform and position of cross sections along with the 1996 longitudinal profile.

maderris). Ground cover is dominated by *Poa ensiformis* (Sword Tussock-grass), *Lomandra longifolia* (Spiny-headed Matrush) and *Blechnum nudum* (Fishbone Water fern).

Based on tree ages (dendrochronological evidence on *A. melanoxylon*), rainfall records from the 1800s, and historical information, Chesterfield et al. (1990) estimated that significant fires occurred in Jones Creek catchment in the early 1800s, late 1800s or early 1900s, 1952 and 1983. The intensity and percentage of the catchment burnt in fires prior to 1983, however, is unknown. The 1983 Ash Wednesday fire was the most intense fire on record in East Gippsland, and brought about profound changes to vegetation composition in many areas (Chesterfield et al., 1990; Loyn et al., 1992). All of Jones Creek catchment was intensely burnt in 1983, including warm temperate rainforest in the headwaters (D. Cameron, pers. comm.). After the 1983 fires the density of *Acacia* sp. and *Eucalyptus* sp. increased dramatically in the headwater areas, with densities ranging from 250 ha^{-1} to 100,000 ha^{-1} (Chesterfield et al., 1990). Prior to the 1983 fire, vegetation in the study area was of a more mesic association (D. Cameron, pers. com.). Riparian communities were significantly affected by the 1983 fires, with a shift towards a more sclerophyll based association. This resulted in a floodplain vegetation community that is now characterised by areas with high stem density of dry sclerophyll species. There are no quantifiable data on the direct impacts of the 1983 fire on channel processes such as sediment supply or changes to the hydrological regime.

3. Methods

Aerial photographic interpretation (at a scale of 1:4000–1:5000), along with field mapping of geomorphic and vegetation attributes (including dendrochronology of *A. mearnsii* growing in cutoffs), provide the basis for documenting the nature and timing of channel changes in Jones Creek since 1967 (see Cohen, 1997 for further details). Many of the channel cutoffs in the study area are not fully preserved. Rather, they are infilled, inset features at the margins of the wide channel. These features are not classic channel cutoffs and have been termed realignment features. Realignment features reflect lateral channel adjustment, in contrast to channel cutoffs which represent bends or sections of the channel that have been separated from the contemporary channel (Fig. 3).

Based on their morphology and position, two categories of palaeochannels were identified in the field. These are termed the 1983 and 1972 channels. Identification of 1983 cutoff channels and realignment features was initially made from the 1983 aerial photo (taken after the fire). These were confirmed in the field by their dimensions and eroded asymmetric cross-sectional morphology, their proximity to the contemporary channel, and the lack of vegetation older than 14 years. The 1972 channels are characterised by smaller hydraulic dimensions with symmetrical cross-sections. These channels are not clearly shown on any of the photographs, although the 1967 photograph indicates fragments of their presence and rough dimensions. The 1972 channels are considered to be representative of channel form in Jones Creek prior to the latest period of channel change. Cross-sections of 1972 and 1983 palaeochannels were surveyed to measure their cross sectional area.

Prior bedlevels of Jones Creek were determined using a range of indicators. Most evidence is provided by the depth of abandoned sections of the 1972 channel and 1983 realignment features and channel cutoffs. This has been defined by the marked boundary between fine grained channel fill and coarse bedload (cf., Erskine et al., 1992). A further indicator of prior bedlevel is provided by a series of gravel lag outcrops perched above the contemporary channel bed. Finally, prior water tables evidenced by gleying and blocky fabric on bank exposures are indicative of bed degradation (see Cohen, 1997 for a full description of prior bedlevel assessment). Each of these indicators was surveyed in to the present thalweg bedlevel to assess bedlevel adjustments throughout the study area.

Eighteen channel cross sections were surveyed along the study reach. Twelve of these sections were resurveys of cross-sections emplaced by the then East Gippsland River Management Board in 1993. The longitudinal profile of Jones Creek was also resurveyed at 30 m increments along the thalweg (Fig. 2).

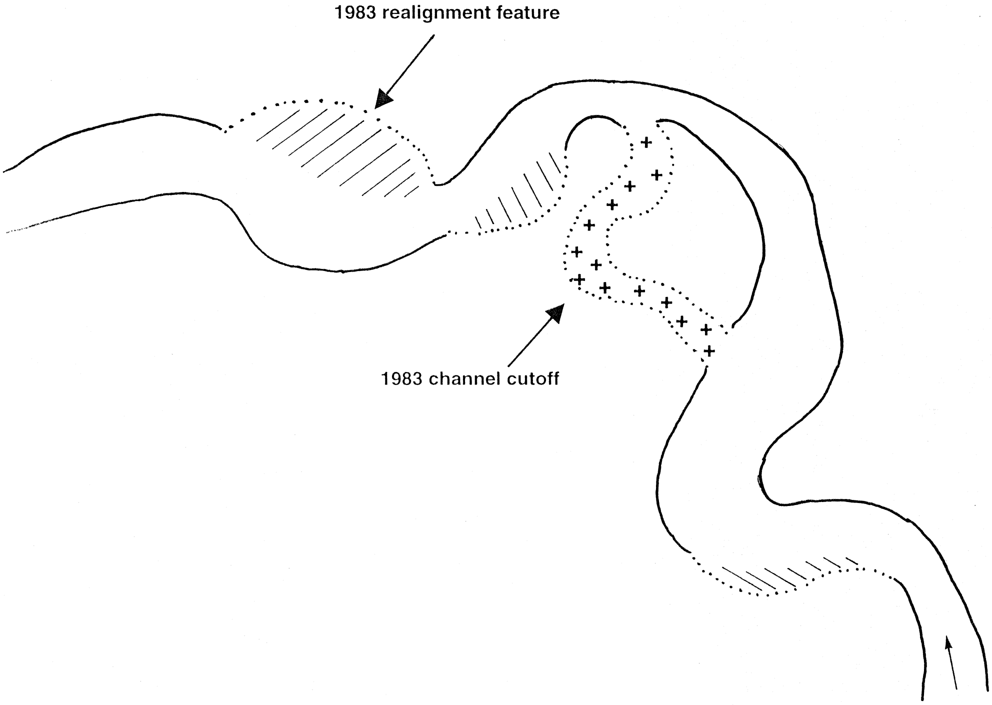

Fig. 3. Schematic example of a lateral realignment feature in contrast to a section of the 1983 channel that has been separated from the channel. Realignment features reflect lateral adjustment of the channel planform and shift in the focus of bend migration.

Sedimentological attributes of bed and bank materials were analysed at each of the surveyed cross sections. Samples were wet sieved at 63 μm to determine the percent silt/clay. Sediment storage on the channel bed was assessed at three positions at each cross section using a bed-level probe, with the depth to a coarse gravel lag used to assess volume of sediment stored on the channel bed. Sediment storage in all realignment features and channel cutoffs was also assessed.

4. Channel changes on the Genoa River and Jones Creek, 1967–1998

Aerial photographs from 1967, 1972, 1986, 1992 and 1994 indicate that the Genoa River and its tributaries in Wangarabell Reach have undergone considerable change in form since 1971. These changes were initiated by a sequence of floods in the 1970s.

The enlarged 1967 aerial photograph of Genoa River–Jones Creek confluence shows no evidence for active erosion along the Genoa River. At this time, the Genoa River was around 35–40 m wide, and was characterised by regularly spaced, large pools (see Fig. 4A). The tributary confluence was dissected, and there were a series of vegetated bars up and downstream of the confluence.

In 1967, Jones Creek was a small, indistinct tributary with dense riparian and floodplain vegetation. Bankfull widths measured from the 1967 air photo range between 12–15 m. Field evidence confirms this, with measured palaeochannels (termed 1972 channels in this study) having bankfull widths of 10–18 m.

In 1971, the Genoa River experienced the largest flood on record since European settlement. This flood had an estimated peak instantaneous discharge of 2611 m^3 s^{-1}, 12.4 times greater than the mean annual flood (Erskine, 1992, 1993). The 1971 flood resulted in floodplain inundation, sand splay deposition on the floodplain, extensive channel margin

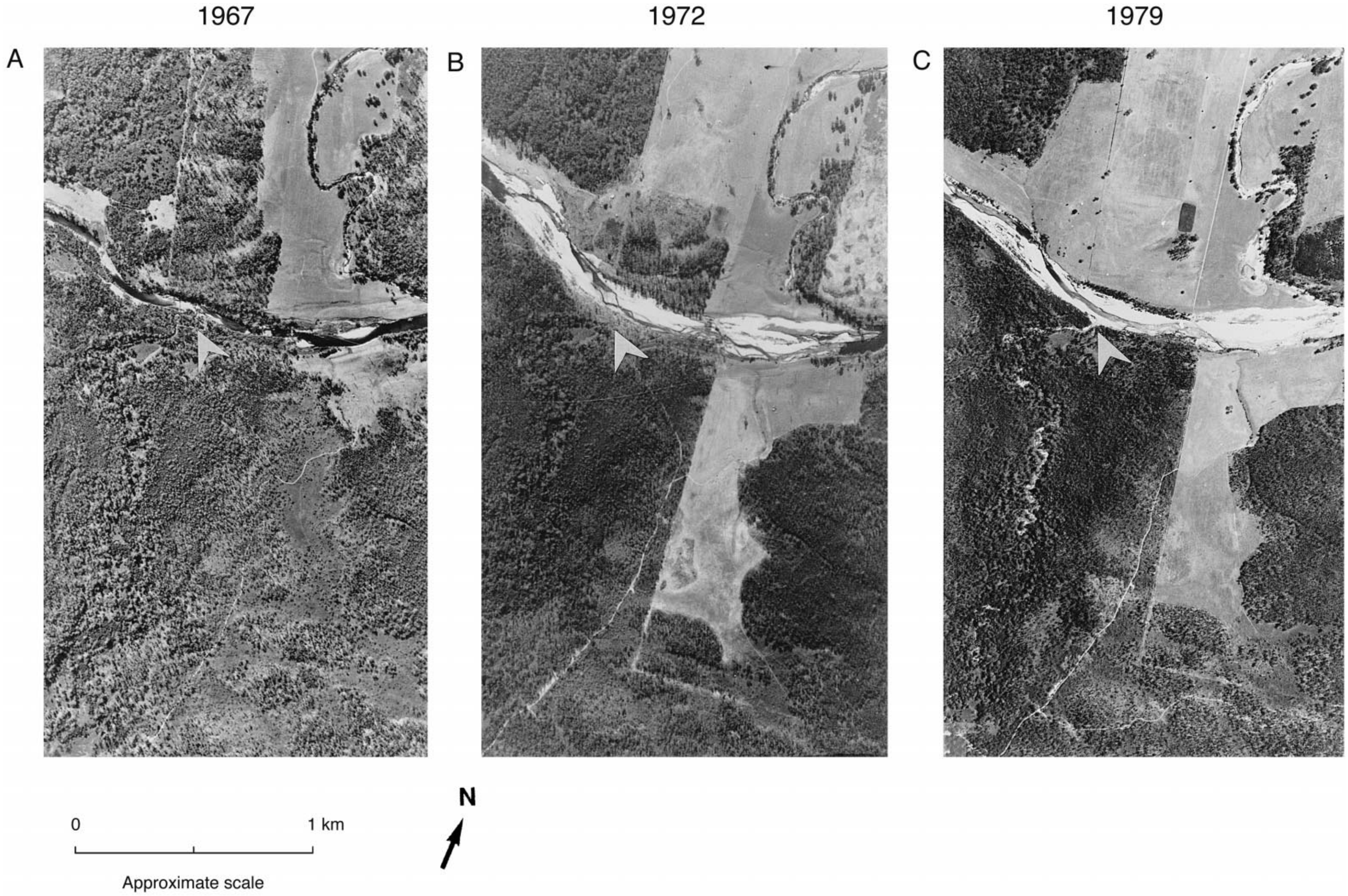

Fig. 4. Genoa River at Wangarabell Reach showing the changes in channel morphology from 1967 to 1979. Arrow denotes position of Jones Creek confluence. Note the destabilisation of Jones Creek by 1979. Flow is from left to right.

stripping and changes in channel planform in the lower reaches of the Genoa River. Around 5 ha. of floodplain and channel margin land were removed between Jones Creek confluence and Wangarabell Creek confluence (Erskine, 1992, 1993) (see Fig. 4B). Channel widening of the right bank occurred at Jones Creek confluence, resulting in bankfull dimensions of 106–132 m. This indicates a 230% increase in channel width since 1967. Vegetated and non-vegetated bars at Jones Creek confluence were completely removed, while vegetation was stripped from bars upstream of, and on the bank opposite to, the confluence of Jones Creek.

Although the 1971 flood resulted in extensive changes in channel form on the Genoa River, the tributaries within Wangarabell Reach (Jones Creek and Wangarabell Creek) remained stable. However, the geomorphic responses of the Genoa River and associated tributaries in Wangarabell Reach to a series of closely spaced, moderate to high magnitude floods in 1971, 1975 and 1978 were spatially and temporally variable. The 1975 and 1978 floods on the Genoa River, which had estimated recurrence intervals of 6.5 and 13 years, respectively, maintained erosion along the Genoa River, and resulted in the destabilisation of the tributaries in Wangarabell Reach, including Jones Creek and Wangarabell Creek. Fig. 4C shows the Wangarabell Reach in 1979, highlighting the widened character of the Genoa River with continued bank erosion at the confluence with Jones Creek. It was not until the subsequent floods of 1975 and 1978 that tributary instability occurred

It is difficult to ascertain a definite planform for Jones Creek prior to it becoming destabilised. However, insights can be gained from a series of narrow and symmetrical palaeochannels, which have a sinuosity of approximately 2.1–1.71, mean bankfull width of 15.1 m and a mean depth of 1.15 m (see Table 1). Supporting evidence for these channel dimensions is provided from anecdotal sources. For example, D. Cameron (pers. comm.) identified Jones Creek as having a channel that was small and indistinct in the mid 1970s, with permanent pools and dense mesic riparian vegetation. All bedlevel indicators from 1972 paleochannels are above the bedlevel of the contemporary channel (Table 2), ranging from 0.61–1.45 m above present day bedlevel, with a mean of 0.84 m.

Table 2
1972 bedlevel indicators

1972 Palaeochannel location	1972 Channel bedlevel (+ (m): above present day thalweg; − (m): below present day thalweg)
U/s of XS 10 (Auger)	+0.964
U/s of XS 10 (Auger)	+0.795
Adjacent to XS 10 (Pit)	+0.721, +0.764
D/s of XS 10 (Auger)	+0.886
D/s of XS 10 (Auger)	+0.807
D/s of XS 10 (Auger)	+0.788
D/s of XS 10 (Pit)	+0.722
U/s of XS 4 (Auger)	+1.004
U/s of XS 4 (Auger)	+1.448
D/s of XS 2 (Auger)	+0.611
Gravel lag u/s of XS 2[a]	+0.821
Gravel lag u/s of XS 2[a]	+0.628
Mean 1972 bedlevel	+0.843

[a] Outcropping gravel lag in channel.
Point of bedlevel is taken as the bedload channel/fill contact boundary.

Table 1
Channel dimensions for Jones Creek 1972–1997

Mean	1972 Channel	1983 Channel	1993 Channel	1997 Channel	% Change 1972–1997
Cross sectional area (m^2)	17.2	35.9	60.1	66.1	+385
Bankfull width (m)	15.1	16	32.3	33.3	+120
Mean bankfull depth (m)	1.15	2.23	1.86	1.99	+73
Max. bankfull depth (m)	3	4.1	3.8	3.5	+16
W/D	5	3.9	8.5	9.5	+78
Sinuosity	2.1–1.71	1.73	1.56	1.58	−7.6

W/D ratio calculated using maximum channel depth.
Increase in mean depth between 1993 and 1997 is a function of largeincreases in cross sectional area at cross section 10 and 8, rather than increases in absolute depth.

Channel expansion of the Genoa River in the 1971 flood effectively shortened the length of Jones Creek by 75–100 m. On the 1979 aerial photograph (Fig. 4B) Jones Creek had estimated bankfull dimensions that range from 15–31 m, with a sinuosity of 1.71. The study area was actively eroding, with some reaches characterised by within-channel bars and debris accumulations. It is clear, however, that channel changes between 1972–1979 were not spatially uniform.

On the 1983 aerial photograph (taken after the fire) the channel was actively eroding its banks, with a sinuosity of 1.73 and bankfull dimensions that ranged from 18–32 m. Channel width was highly variable, with areas undergoing cutoffs having wider bankfull conditions. Measured mean bankfull width was 16 m, while mean bankfull depth was 2.23 m (Table 1). Detailed field analysis of channel cutoffs and realignment features indicate that the active (1983) channel was asymmetrical with near vertical upper banks, in stark contrast to the symmetrical 1972 channel.

The period of tributary instability between 1972–1983, as constrained by the aerial photograph record, has been termed the first phase of channel change in Jones Creek. Following a series of inferred floods on Jones Creek between 1972–1979, the mean depth of Jones Creek increased by 93% as a result of bedlevel incision, while cross sectional area increased by 108%. Although erosion was widespread in this first phase of channel change, sinuosity was maintained, and the width:depth ratio decreased as the channel deepened.

Between 1983–1992, cutoffs and channel realignment occurred throughout the study area with a reduction of sinuosity from 1.73 in 1983 to 1.56 in 1992, most likely during a series of floods between 1983–1988. Dendrochronological evidence confirms that colonisation of 1983 channel cutoffs and realignment features occurred from late 1984 to early 1985. Bedlevel indicators from 1983 realignment features in the middle of the study area indicate that 1983 bedlevels ranged from 0.236–1.515 m below present day thalweg bedlevel, with a mean of 0.66 m (Table 3). Mean channel width in this period increased by approximately 100% to 32.3 m and cross sectional area increased by a further 67% (Table 1). Mean depth decreased by approximately 17% as the channel became wider and shallower along with large increases in the width:depth ratio. These changes are referred to as the second phase of channel change in Jones Creek. Fig. 5 highlights the character of planform changes in a segment of the study area between 1972 and 1997.

Table 3
Bedlevel indicators for 1983 channels

1983 Realignment feature/cutoff location	1983 Channel bedlevel (+ (m): above present day thalweg; − (m): below present day thalweg)
U/s of XS 10 (Auger)	−0.368
U/s of XS 10 (Pit)	−0.27
D/s of XS 10 (Auger)	−0.76
D/s of XS 10 (Auger)	−1.515
U/s of XS 9 (Auger)	−0.236
D/s of XS 9 (Pit)	−0.673
U/s of XS 7 (Auger)	−0.687
Adjacent to XS 7	−0.8
Mean 1983 bedlevel	−0.66

Point of bedlevel is taken as the bedload channel/fill contact boundary.

Aerial photographs from 1992–1994 indicate little change in channel planform of Jones Creek. The last three months of 1995 were characterised by high maximum monthly rainfall producing a bankfull event on Jones Creek on the 5th and 6th of December with an estimated discharge of around 130 $m^3 s^{-1}$. The 1995 flood induced little change in planform in the study reach. A flood in June 1998, which was approximately three quarters bankfull, resulted in a cutoff in the upper part of the study area. The period from 1992 to the present has been characterised by continued channel expansion, bar deposition and lateral adjustment and is identified as the third phase of channel change in Jones Creek. Bankfull widths and cross sectional area increased slightly with small fluctuations in mean depth (see Table 1). Straightening is still operative with 1–2 cutoffs in the process of occurring. The contemporary behaviour of Jones Creek is characterised by localised increases in cross sectional area, with shifts in the erosional foci being the dominant process as exemplified by Fig. 6.

Data from Tables 2 and 3, summarised in Fig. 7, indicate that Jones Creek was characterised by bedlevel incision in the first phase of channel change

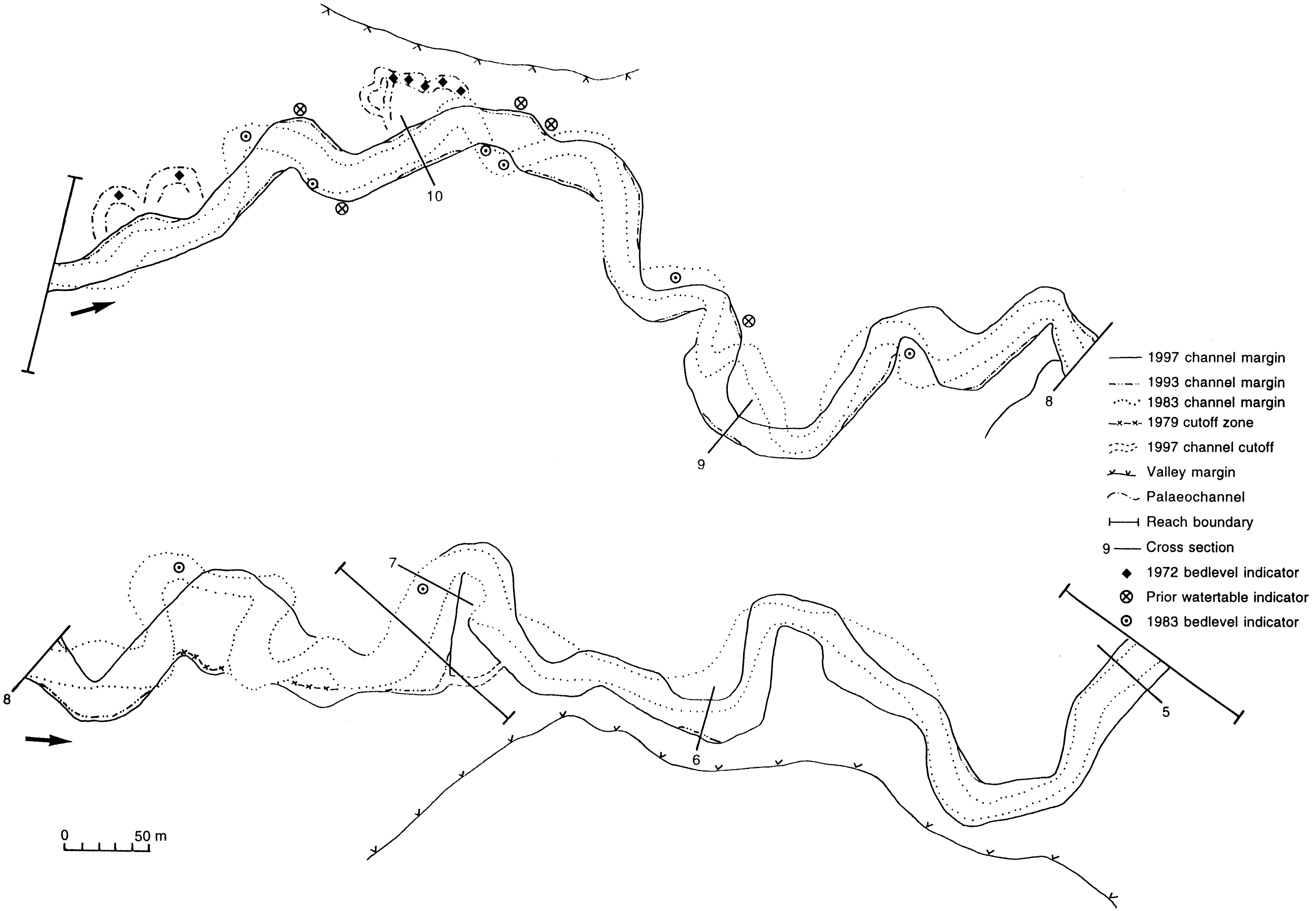

Fig. 5. Planform changes in the middle of the study area of Jones Creek between 1972 and 1997, showing nature of lateral adjustment as Jones Creek progressively straightened. Symbols indicate location of bedlevel indicators.

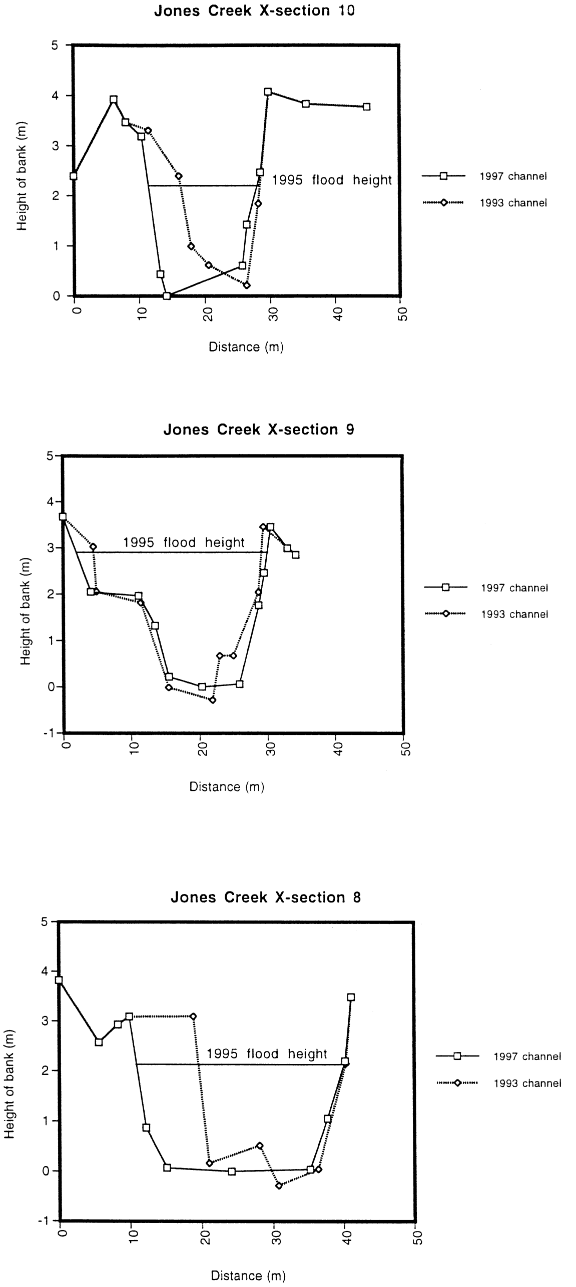

Fig. 6. Cross sectional changes in the middle section of Jones Creek between 1993 and 1997 highlighting localised increases in cross sectional area and lateral adjustment of channel geometry.

(1972–1983), but that aggradation occurred from 1983–1997. These data on bedlevel adjustments are seemingly confirmed by analysis of prior water tables (Table 4), which range from 0.48 to 1.83 m above present day bedlevel, with a mean of 1.29 m. This is approximately 45 cm above the 1972 mean bedlevel, indicating the range of water level fluctuations in the 1972 channel. While these data display a range of elevations above the 1972 mean bed elevation, they still confirm that the mean watertable was above the mean 1972 bedlevel, indicating watertable lowering in the incision process. Based on these bedlevel assessments, it is estimated that channel changes between 1972–1983 resulted in up to 1.5 m of bedlevel incision, whereas an average of 0.66 m of bed aggradation occurred between 1983 and 1997. The assessment of bedlevel indicators highlighting channel incision is supported by aerial photographic evidence of channel straightening and channel shortening on Jones Creek between 1972 and 1983.

While periods of channel change can be identified for Jones Creek, changes on the Genoa River since 1979 have involved extensive deposition of bank-attached bars opposite the confluence of Jones Creek. The other dominant process in this period has been the recovery of instream and bank vegetation following the 1983 fires (cf., Schumm and Lichty, 1963; Friedman et al., 1996). This has resulted in a narrower channel of similar character to that which was evident in 1967.

Finally, detailed field survey of channel dimensions, along with augering and probing of sediment thickness on the channel bed and in realignment features and cutoffs, has enabled a summary assessment of the alluvial sediment budget of the study reach to be performed (see Table 5). From the three periods of channel change identified in Jones Creek, between 1972 and 1997, it is estimated that a total of 171,100 m^3 of material have been eroded. Sediment analysis of bank material suggests an estimated mean ratio of sand to mud of 58:42 and it is likely that the mud fraction has been predominantly flushed through the system (representing 71,862 m^3 of sediment). Of the remaining 99,200 m^3 of sediment, an estimated 29,950 m^3 of sand are stored in point bars and realignment features, with another 3170 m^3 of sand stored on the bed of Jones Creek. The total of 33,120 m^3 of material stored within the channel zone represents 33.4% of the sand fraction eroded during the three periods of channel change. Of this volume, 65% is consolidated in vegetated realignment fea-

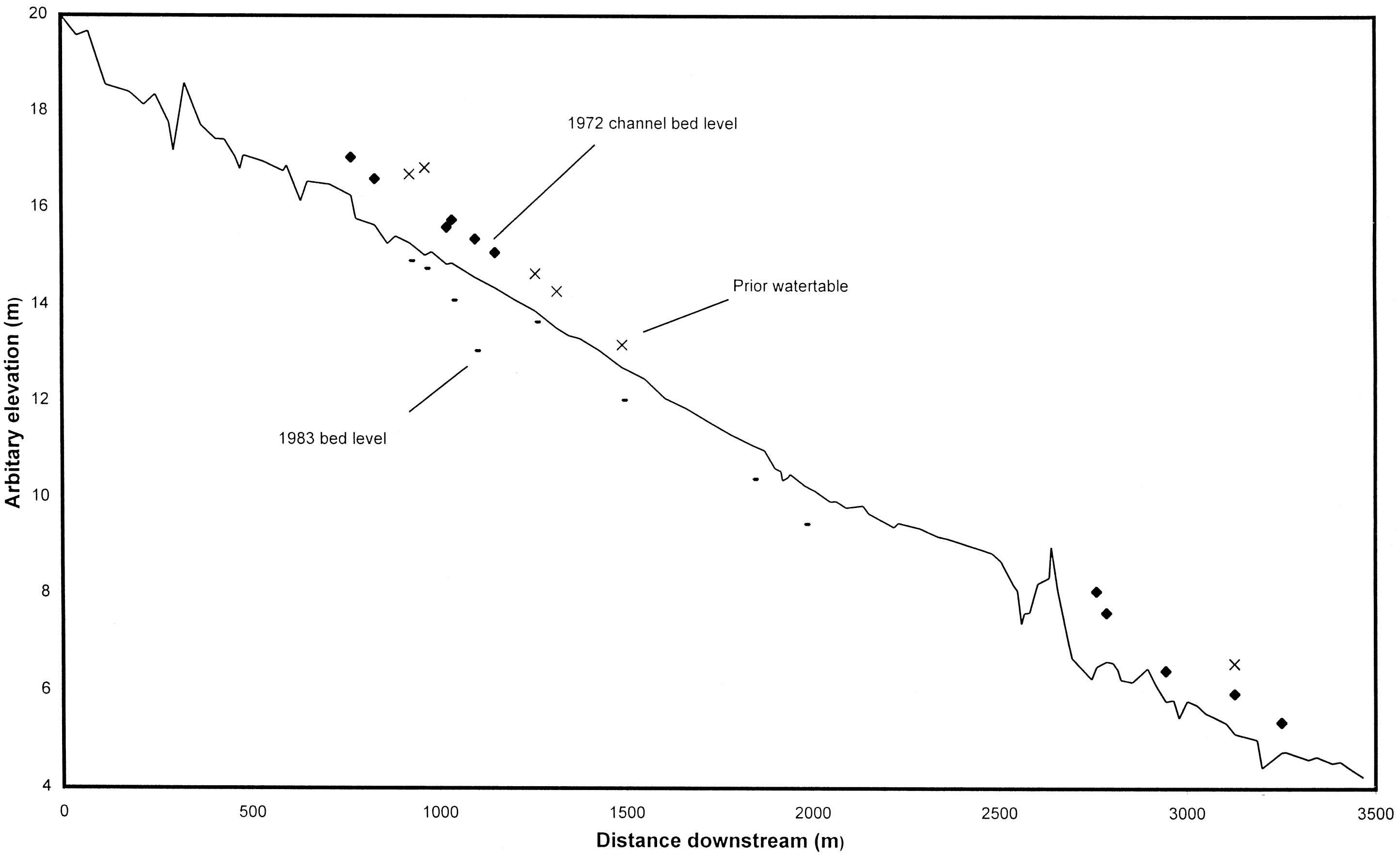

Fig. 7. Jones Creek 1996 longitudinal profile showing location of prior bedlevels highlighting that prior to destabilisation bedlevels were on average 0.84 m above present day thalweg elevation, while 1983 bedlevels were on average 0.66 m below present day bedlevel.

Table 4
Prior watertable bedlevel indicators

Prior watertable location	Prior watertable (+ (m): above present day thalweg; − (m): below present day thalweg)
U/s of XS 10	+1.814
U/s of XS 10	+1.83
U/s of XS 10	+1.381
U/s of XS 10	+1.467
U/s of XS 9	+1.13
U/s of XS 9	+0.771
D/s of XS 9	+0.478
U/s of XS 2	+1.436

tures. Following incision, an estimated 66,000 m^3 of sand have been flushed through Jones Creek into the Genoa River, resulting in increased rates of aggradation in the trunk stream. Perhaps the most significant aspect of this alluvial sediment budget is that realignment features and cutoffs within the enlarged channel of Jones Creek have already trapped up to 33% of sands released upon channel expansion. Trapping of these deposits is considered to form the primary platform for subsequent channel recovery.

5. Channel instability in a forested catchment

The three periods of channel change identified along Jones Creek since 1972 are shown schematically in Fig. 8. It must be noted that the processes documented within these periods have not occurred in isolation, but have been part of a continuum of change as a result of alterations to variables within the fluvial system. Prior to destabilisation Jones Creek had a symmetrical cross-sectional form with a mean width of 15.1 m and cross sectional area of 17.2 m^2 (Fig. 9). By 1983, bedlevel lowering had increased mean channel depth and mean channel cross-sectional area around 100%. This resulted in an estimated increase in bedslope from 0.0033–0.0037 m/m in 1972 to 0.0044 m/m in 1983 (around 30%). Estimated specific stream power (ω) values for Jones Creek prior to destabilisation ranged from 30–35 Wm^{-2} (Table 6). This falls within approximations by Nanson and Croke (1992) for medium energy floodplains and is on the threshold of channel 'stability' presented by Brookes (1990). During the first phase of instability, estimated specific stream power increased by up to five times, as bedlevel lowering increased mean depth, greatly increasing the capacity of the system to transport sediment (cf., Brizga and Finlayson, 1990).

Between 1983–1992 the mean channel width of Jones Creek increased by a further 70%, while mean depth was reduced by around 16%. As the bedslope increased during channel incision (Phase 1), increased energy within Jones Creek eroded the bed and banks, resulting in the input of large volumes of sediment. The channel was unable to maintain a high sinuosity given the high stream powers and the increased sediment load. Hence, the channel straight-

Table 5
Volumes of sediment excavated in the periods of channel change in Jones Creek 1972–1997

Period of channel change	Total volume of sediment eroded (m^3)	Proportion of sand size sediment eroded (m^3)	Dominant process	Volume of silt/mud flushed (m^3)*	Volume of sand stored (m^3)	Location of sediment storage	Proportion of stored sediment available to be reworked (m^3)
1972–1983	65,400	37,932	bedlevel incision	27,468	?	?	?
1983–1993	84,700	49,126	channel widening	35,574	?	?	?
1993–1997	21,000	12,180	lateral activity	8820	29,950 and 3170	realignment features and bed storage	11,592
1972–1997	171,100	99,238	NA	71,862	33,120	NA	11,592

? refers to an unknown volume of sediment or unknown location of sediment storage.
Sediment budget is based on the assumption that the mud fraction has been flushed through the system (Sand/mud ratio = 58:42).

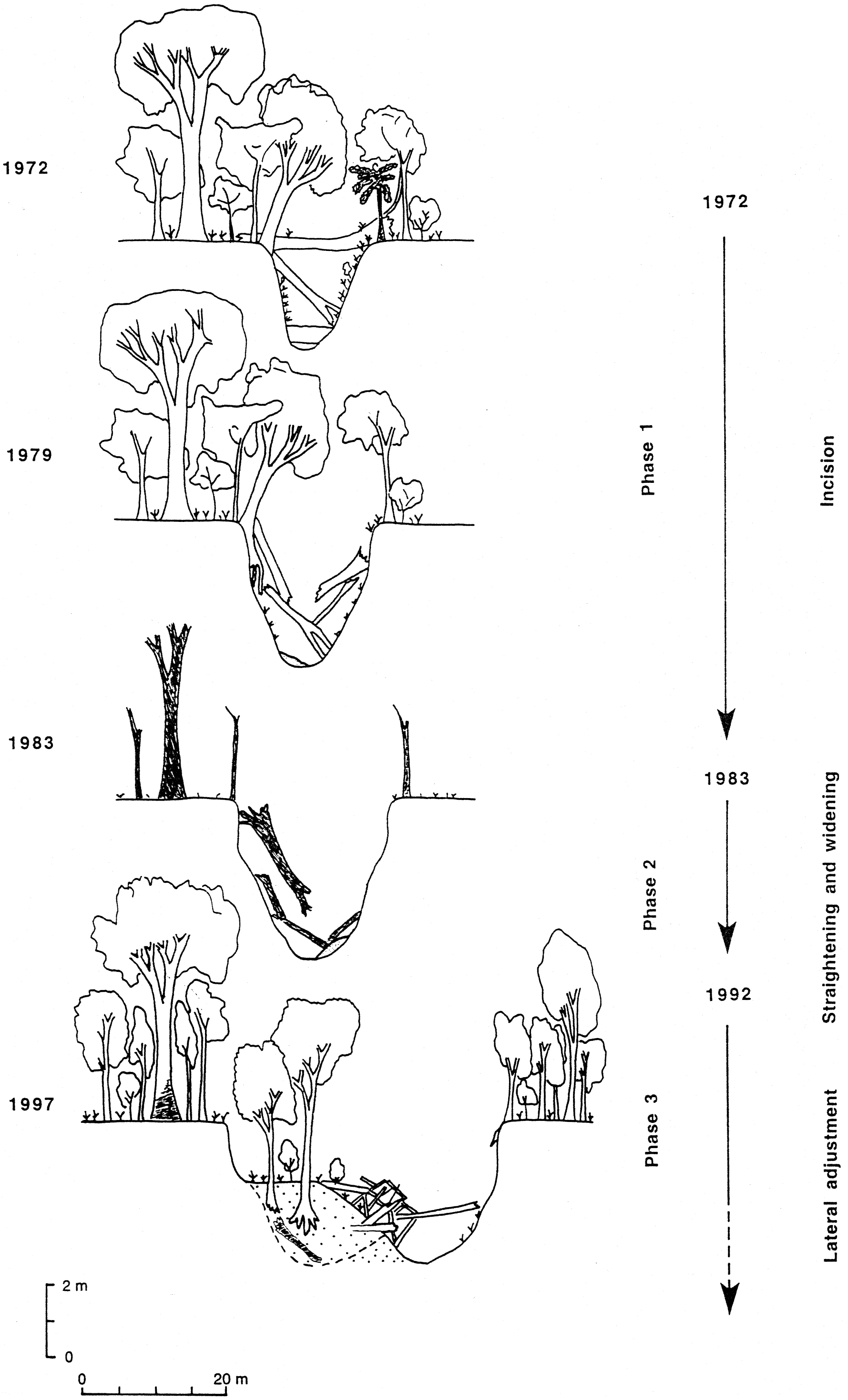

Fig. 8. Schematic diagram of the 3 phases of channel change in Jones Creek from 1972 to 1997.

Fig. 9. Downstream view of a 1972 channel in Jones Creek, prior to destabilisation. Note the narrow symmetrical channel.

ened its course, reducing its sinuosity from 1.71 in 1983 to 1.56 in 1992, thereby further increasing bedslope. This period of channel adjustment is termed Phase 2. Channel changes in this phase can be related to known floods in 1983, 1985, 1988 and 1992. As a result of these planform changes, the width:depth ratio of Jones Creek in 1992 had increased by 74% since 1972. The dimensions of the enlarged channel virtually preclude floodplain inundation, effectively concentrating the geomorphic impacts of high magnitude events within the channel zone (Brizga and Finlayson, 1990; Nanson and Croke, 1992).

Phase 3 (1992 to present) has been a period of ongoing channel expansion and straightening, with a reduction in sinuosity to 1.5 (Fig. 10). Estimated specific stream powers are approximately four times higher than in 1972. There has been continued aggra-

Table 6
Changes in estimated bedslope, discharge and streampower in Jones Creek 1972–1997

Mean	1972 Channel	1983 Channel	1993 Channel	1997 Channel	% Change 1972–1997
Slope	0.0033–0.0037	0.0044	0.0047	0.0046	+ 24–39.4
Lc (estimated length of channel) (m)	4000–3500	3330	3070	3000	− 14–25
Estimated drop in elevation (m)	13.06	14.56	14.4	13.9	− 6.5
Estimated bankfull discharge (m^3 s^{-1})	15.1	70	118.4	132.7	+ 778
Estimated Manning's n	0.07	0.05	0.05	0.05	− 28.6
Bagnold's stream power (W m^{-2})	29.9–35.4	185.7	171.8	174.8	+ 394–485

Discharge estimates used for Bagnold's stream power are based on the Manning's equation. + indicates an increase in a channel attribute. Slope estimates for 1972–1983 based on changes to elevation associated with bedlevel indicator data.

Fig. 10. Upstream view of the contemporary channel in Jones Creek highlighting the widened nature of the current channel.

dation of realignment features and bed-level aggradation, with localised bed-level degradation. These changes in channel form are a result of known floods in 1995 and 1998.

The change in channel pattern of Jones Creek conforms to classical notions of complex response within incised channels (cf., Schumm et al., 1984). Initial incision increased channel depth, bedslope and unit stream power (Phase 1). As degradation slowed, channel widening occurred to disperse available energy and achieve a degree of stability (Jackson and Beschta, 1984; Schumm et al., 1984; Simon, 1992), resulting in a reduction in sinuosity. This supplied large volumes of sediment to the channel as part of a negative feedback system, where the channel aggrades as it adjusts to new energy gradients (Phase 2). The development of alternate bars and point bars enhances the widening process by promoting lateral adjustment. This is the initial step in the eventual development of a sinuous inner channel (Schumm et al., 1984). In Jones Creek, the present behaviour is characterised by continued expansion, lateral adjustment, downstream shifts of the erosional foci and the deposition of alternate bars (Phase 3).

The channel-floodplain relationship along lower Jones Creek has been fundamentally transformed since 1972. Prior to incision, channel changes in Jones Creek resulted in cutoffs forming and then infilling via overbank and backfilling processes. Sediment composition of these channel fills is highly variable, ranging from 25–78% mud. However, channel fill samples from 1983 realignment features and cutoffs show mud fractions that range from 3–5% (cf., Erskine et al., 1992). The confinement of flood flows within the enlarged channel, and associated increases in stream power, have resulted in realignment features and cutoffs which are comprised of medium-coarse sands. This is a likely consequence of an increase in the grain size that is transported as suspended load.

It is not possible to accurately assess rates of channel fill in Jones Creek prior to channel incision.

However, field observations of shallow depths of fill in 1972 channels (1–1.5 m) contrast starkly with the maximum depth of aggradation in 1983 realignment features and cutoffs (2.7–3.0 m). This indicates that there has been a maximum annual aggradation rate in realignment features of 190–215 mm yr^{-1} since 1983. However, aggradation rates in Jones Creek are episodic, due the ephemeral nature of the system. This suggests that the realignment features have formed rapidly in a small number of events since 1983. Rapid deposition at the channel margin has formed an incipient floodplain which is now stabilised by *A. mearnsii* and *P. ensiformis*. This has resulted in coarser grained facies proximal to the channel throughout the channel network.

Channel adjustments along Jones Creek reflect the sensitive balance between a forested subcatchment (Jones Creek) and a trunk stream prone to channel expansion (Genoa River). It is uncertain how characteristic the style of trunk stream expansion of the Genoa River in 1971 was, or whether it represents accelerated rates of channel expansion as a result of human impacts in Wangarabell Reach. Erosional scars on the Genoa floodplain suggest that periodic reworking of discontinuous floodplains is a recurrent component of floodplain processes within this mixed load system. However, given the presence of numerous palaeochannels along Jones Creek, with dimensions akin to the 1972 channels, it is reasonable to assume that this style of tributary/trunk stream instability occurs infrequently.

Between 1972–1983 approximately 1.5 m of bed degradation occurred along lower Jones Creek as a secondary response to trunk stream controls. The destabilisation of the fully vegetated riparian zone of Jones Creek was preconditioned by the 1971 flood, which removed the tributary confluence bar and shortened the length of Jones Creek. Catastrophic widening and/or bedlevel lowering (i.e., changes to bed sediment storage) in the Genoa River initiated dramatic changes in channel morphology of the alluvial Jones Creek tributary. As the bed-level of Jones Creek adjusted to new energy gradients, the system became destabilised. Such a threshold response has been documented on tributaries of the Mississippi River (Schumm et al., 1984), and elsewhere in Australia (e.g. the Avon River, Victoria; Erskine et al., 1990).

A discernible lag of up to 7 years was evident between widening of the trunk stream and destabilisation of the tributary, conditioned by the timing of subsequent flood events on the tributary (cf., Schumm et al., 1984; Kochel, 1988; Erskine et al., 1990). Based on rainfall records, localised flood intensity in Jones Creek is inferred for 1975 and 1978. Indeed, the 1978 flood event along Genoa River reflected the highest 48 h rainfall over the 25 year record. It is inferred that upstream-progressing degradation in Jones Creek was the dominant control in initiating bedlevel incision and is confirmed by tributaries within the catchment displaying knickpoints. As Galay (1983) noted, however, upstream-progressing degradation may often be accompanied by downstream-progressing degradation. In Jones Creek this may have occurred as a result of the inferred localised flood intensities between 1975 and 1978.

Changes in the channel slope to valley slope relationship have been documented as an important control on channel form and behaviour (Erskine et al., 1990; Schumm, 1993; Schumm et al., 1972, 1984, 1996). Steep valleys with meandering channels carrying a mixed load that undergo bed degradation experience rapid changes to channel morphology as bedslope adjusts to valley slope. It is suggested that the valley slope to channel slope relationship in Jones Creek was near a threshold (Schumm, 1979), whereby the increase in channel slope (approximately 30%) associated with bedlevel lowering significantly altered the channel pattern. In Jones Creek, changes in mean depth were considerable (exceeding the average depth of the root zone of riparian vegetation), resulting in widespread bank instability and channel metamorphosis. From these data, changes to channel depth and associated increases in bedslope have been the dominant controls on subsequent adjustments to channel morphology in Jones Creek.

6. Channel recovery in a forested catchment

System recovery in Jones Creek is dependent on within-channel aggradation and subsequent stabilisation of depositional surfaces. The deposition and colonisation of channel marginal features or incipient floodplains are part of this process. Long term channel recovery is dependent on the reduction of stream power, increase in sinuosity (within a wider channel), decrease in channel width, and subsequent reconnection of the channel to its floodplain, so that floodplain inundation results (Schumm et al., 1984). Based on volumetric analysis undertaken in this study 33% of the sand sized material eroded in the periods of channel change is presently stored within the channel in realignment features, cutoffs, point bars and bed storage. The storage of this material is part of the recovery process, as noted by Williams (1978), Nadler and Schumm (1981) and Eschner et al., (1983) who have highlighted the role of vegetation in sediment storage and the reduction in channel capacity. Further analysis of this 33% shows that 65% of this stored material is 'locked up' in vegetated realignment features and unavailable to be reworked.

Rates of vegetative colonisation of depositional surfaces are extremely high in Jones Creek with *A. mearnsii* being the dominant early successional species. Each year this species sets seed prolifically, covering the bed of the channel. Greater vegetation cover increases the roughness and trapping capacity of the channel zone, thereby reducing flow velocity, stream power and long term sediment flux, and promoting further channel recovery. The rate at which colonising species grow and withstand burial is an important aspect to the stabilisation of realignment features. Trees aged between 15 and 13 years have heights of 10–15 m, with diameters up to 25 cm. While *A. mearnsii* is an important successional species, secondary canopy species with similar growth rates, such as *E. elata* and *E. viminalis*, provide the longer term stabilisation of these inset floodplains. Other secondary species, such as *Pomaderris apera*, *L. longifolia* and *P. ensiformis*, result in these surfaces becoming densely vegetated, further enhancing their stability.

While not quantified within this study, LWD, log jams and within-channel vegetation provide important roughness elements that reduce flow velocity and stream power in Jones Creek (cf., Hupp and Osterkamp, 1985, 1996; Friedman et al., 1996). Four rush and sedge species tend to dominate and grow in the sand bed, on bars and within LWD. These are *Juncus usitatus*, *Cyperus eragrostis*, *Phragmites australis* and *L. longifolia*. Other successional species occur within the channel as a result of bank failure which introduces floodplain alluvium into the channel.

Channel recovery in Jones Creek is seemingly being achieved by restabilisation on a reach by reach basis, as certain reaches experience bed aggradation and reduced rates of bank erosion. This has allowed within-channel and channel marginal species to establish. While recovering reaches remain susceptible to sediment transfer, variations in within-reach sediment storage will not result in significant changes in channel geometry or channel position. Once parts of the channel network have been stabilised, and as sediment flux is reduced, a sinuous inner channel will develop, allowing the channel margin to become vegetated. This process is co-dependent on sediment depletion rates from upstream and the stabilisation by vegetation of the inset channel zone.

7. Conclusion

This study has provided an insight into channel response in a forested catchment to flood disturbances induced at the trunk stream confluence. In Jones Creek, channel metamorphosis was a lagged response to flood activity on the Genoa River. Incision and subsequent channel expansion were not a direct response to the 1971 flood. Rather, channel widening of the Genoa River at Jones Creek confluence effectively shortened the course of the creek in this forested tributary catchment and primed the tributary for change. Subsequent floods, most likely in 1975 and 1978, induced dramatic channel adjustments along the tributary river. The over-riding control on the pattern and extent of channel adjustments was probably induced by changes to the channel bedslope (associated with increases in depth), as exceedance of a stability threshold induced a series of secondary channel adjustments. The sensitivity in the relationship between the Genoa River and Jones Creek highlights that landscapes in southeastern Australia can be on the threshold of instability, only requiring a suitable trigger.

The style of response documented within this forested setting conforms to the notion of a complex response scenario for incised channels. However, the character of lateral adjustment and the formation of realignment features (forming an incipient floodplain) do not necessarily conform to simple cutoff/straightening models. Indeed the spatial variability of channel morphology seen within the study area highlights the non-uniformity in response to breaches in thresholds. Feedback and recovery mechanisms within the incised, 'natural' system have been documented. Sediment storage associated with within-channel vegetation and large woody debris has initiated the early stages of channel recovery and is an aspect of incised channel behaviour that has not been previously been documented in the Australian landscape.

Further studies of alluvial rivers in forested systems in Australia will improve our understanding of the 'natural' range of river behaviour in southeastern Australia and thus provide an assessment of river character and the variability of processes that occurred prior to European settlement.

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