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Suspended sediment concentrations and the geomorphic effect of sub-bankfull flow in a central Australian stream

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Abstract Data on suspended sediment concentrations (SSC) and channel change following a series of flows during 1995 are presented and compared with previously unpublished SSC for the region. Suspended sediment concentrations for the Todd River are generally lower than for other arid regions of Australia. Data are poorly correlated with discharge and peak concentrations reflect bed load entrainment at individual hydrograph peaks following troughs in multi-peaked flows. Peak SSC are higher for low flows, most likely, a dilution effect. Sub-bankfull flows are important agents of minor channel change and proto-flood-plain construction processes. Adjustments include the lateral filling of width irregularities, the formation and accretion of flood plain insets, the deposition of flood plain veneer and thalweg incision.

Key words sub-bankfull; ephemeral flow; suspended sediment concentration; channel erosion and deposition; Australia

INTRODUCTION

> *"Each piece of information, each measured flood, is fairly unique and has to be treated as a gem that gives insight ... For the geomorphologist, hydrologist and sedimentologist, this remains pioneering territory"* (Reid & Frostick, 1997).

Extreme floods in arid rivers often result in remarkable channel change. Channel widths are frequently reported to increase by between 60 and 300% in a single flood (e.g. Erskine, 1994; Osterkamp & Costa, 1987; Pickup, 1991; Scott, 1973). The geomorphic effects of lower magnitude flows in ephemeral streams and consequently their role in flood plain and channel formation is relatively unknown.

Although many have reported the importance of flood events in generating high suspended loads and the consequent evacuation of sediment from the basin, our understanding of suspended sediment sources, concentrations and sinks remains incomplete. Data from arid ephemeral systems, particularly in Australia remains sparse, as measuring and monitoring the effects of floods in remote regions are fraught with logistical difficulties. Often opportunities to collect data on an ephemeral flow arise opportunistically (e.g. Dunkerley & Brown, 1999) or alternatively valuable data sets, periodically collected by government agencies, remain unpublished. This paper is an investigation of the geomorphic work of a series of sub-bankfull flows. Suspended sediment concentrations (SSC) and channel change data were collected during and after a flood in 1995 on the Todd River in central Australia. These data are presented along with SSC collected in the late 1970s and 1980s by the Northern Territory Government.

STUDY AREA

The Todd River is an ephemeral sand bed channel that rises in the McDonnell Ranges in central Australia (23°40′S, 133°50′E) (Fig. 1). The channel gradient varies between 0.0027 and 0.0015 m m^{-1}; the channel width displays extreme variability with an average of ~80 m. The channel and flood plain are populated by *Eucalyptus cameldulensis* species. The sandy flood plains are late Holocene in age and adjacent alluvium has been emplaced by extreme palaeofloods (Bourke & Pickup, 1999). The city of Alice Springs with a population of 30 000 is located in the headwaters.

RAINFALL AND RUNOFF FOR THE 1995 EVENTS

Mean annual rainfall for the Alice Springs region is 274.4 mm. Rainfall totals for January 1995 was 255.7 mm (Stoke's Yard gauge), with a maximum of 99.4 mm falling on 15 January. The resultant runoff was rapid and produced a multiple events type hydrograph (Knighton & Nanson, 2001) (Fig. 2). Although a peak discharge of 260 m^3 s^{-1} was recorded on 18 January for this 72-h-duration event, the maximum flow

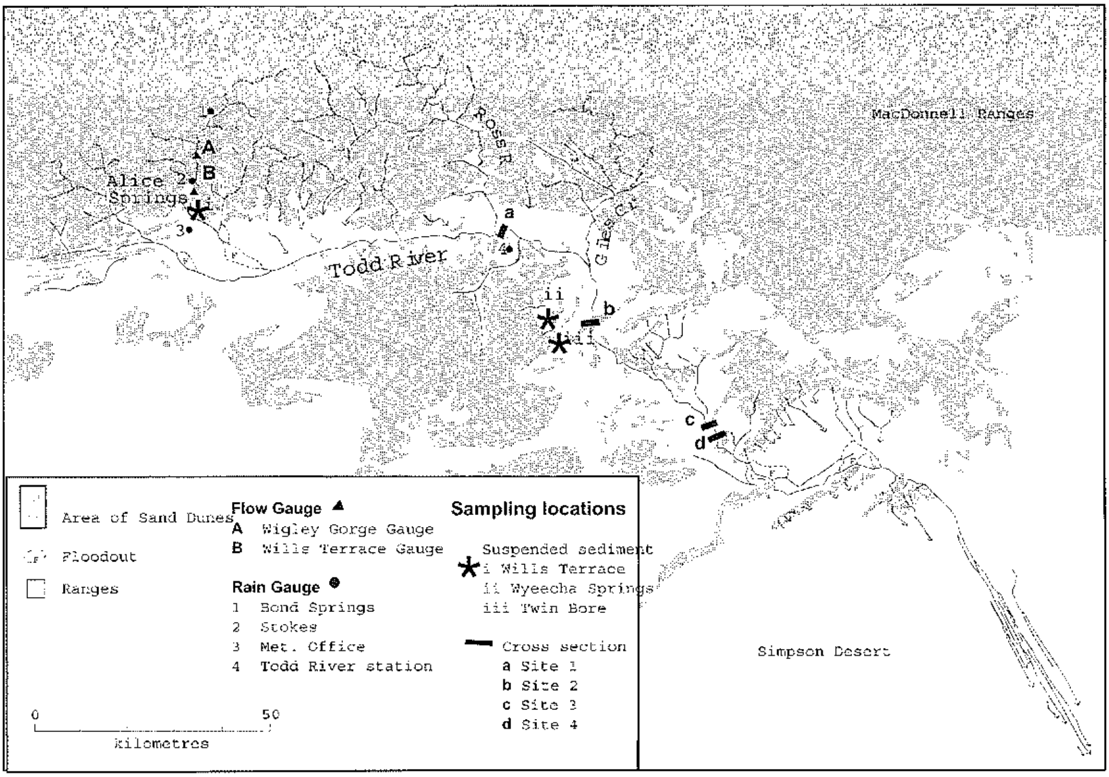

Fig. 1 Location of sampling sites in the Todd River basin.

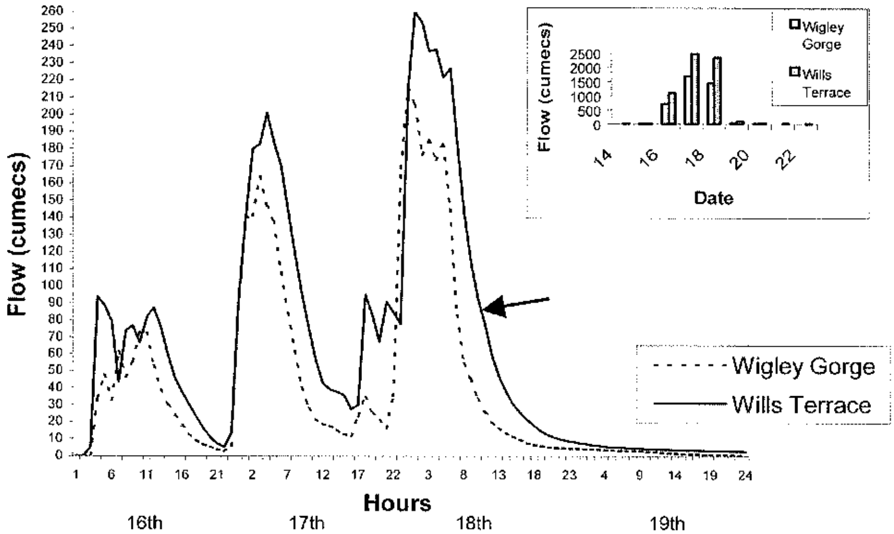

Fig. 2 Flow hydrographs for the January 1995 event upstream (Wigley Gorge) and downstream (Wills Terrace). This multiple peak event had a peak discharge of 260 m^3 s^{-1}. Inset is the total daily flow volume at both sites. Arrow indicates the initiation of SS sampling.

volume occurred on the previous day (Fig. 2). The flow was close to a 1-in-5-year event (Fig. 3). Although there is a major tributary between the two gauges, comparison of the flow graphs indicate that tributary contributions did not significantly alter the hydrograph form (Fig. 2).

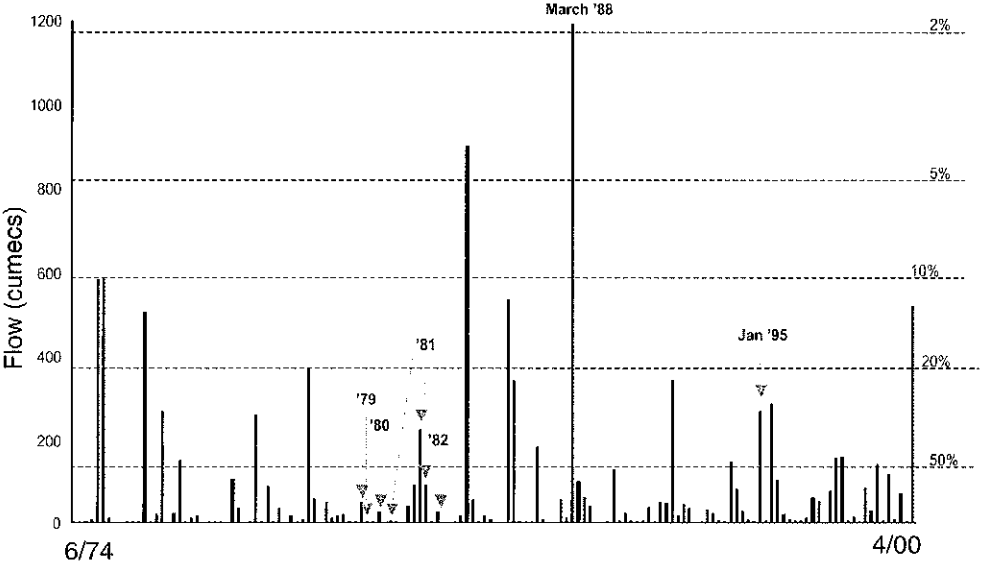

Fig. 3 All gauged flows at Wills terrace between June 1974 and April 2000. The dotted lines represent the log Pearson type III annual exceedance probability calculated from 36 years of record (from Barlow, 1988). Arrows indicate flows that were sampled for suspended sediment concentrations.

METHODS

Suspended sediment concentrations Data presented are from several floods. The suspended sediment concentrations sampled in 1995 at the Wills Terrace gauge, which has a drainage basin area of 405 km^2 are from the recessional flow of the 18–19 January ($n = 30$), and the rising and falling limb of a minor flow on 31 January ($n = 2$). While there are considerable limitations to the usefulness of partial data sets, this must be balanced with the need and opportunity to collect data. Runoff from a local thunderstorm on 30 January was opportunistically sampled midstream in two small creeks southeast of Alice Springs (Fig. 1). The sample at Twin Bore Creek was taken at the flood peak ($n = 1$) and the samples at Wyeecha Spring ($n = 2$) were sampled close to the flow peak (at 0.2 depth) and on the recession limb (at 0.4 depth). Older data sets collected at Wills Terrace were sampled during sub-bankfull flows between 1979 and 1985 by the Department of Lands Planning and the Environment (Fig. 3).

During the 1995 flow, samples were taken at 3-h intervals over a 36-h period from 9.30 a.m. on 18 January (at 0.2 and 0.6 flow depth). Samples were taken by standing in-stream, 1.5 m from the right bank, at Wills Terrace. In addition, suspended sediment was sampled at four equidistant points across the channel at 7.00 p.m. on 18 January. Flow depth at the gauge dropped from 73 to 70 cm during the 25-minute sampling period and it is assumed that this is sufficiently minor so as to make the data in the cross-section directly comparable. Where depth permitted, samples were taken at 0.2, 0.6 and 0.8 flow depth. Samples were collected by standing directly in the flow using a depth sampler and were transferred to opaque containers. In the laboratory, sample containers were placed in an ultrasonic bath and agitated for five minutes before being placed in the Millipore vacuum filtration assembly. The membrane filters and sediment were placed in the oven for 1 h at 35°C.

Channel morphology Channel morphology was measured in January 1995 and September 1995 using an EDM theodolite. Four locations were selected from a series of sites that had been surveyed in 1993. No flow had occurred in these downstream locations between 1993 and 1995 (I. Lovegrove, personal communication). The effects of the January flood were measured within days of the flow and the cumulative effects of flows in March and May were surveyed at sites 1 and 2 in September 1995. See Fig. 1 for location of sampling sites.

RESULTS

Suspended sediment concentrations

Suspended sediment concentrations for the 18–19 January flow in the Todd River were sampled after the peak discharge and therefore represent recession curve concentrations. Concentrations were between 1081 and 70 mg l^{-1} and are strongly correlated with discharge (R^2 0.9906). Peak suspended sediment concentrations were measured in three locations for smaller flows later in the month. The results indicate significantly higher concentrations of suspended sediment particularly at Twin bore (23 555.5 mg l^{-1}) and Wyeecha Creek (1702 mg l^{-1}). Data from previous unpublished studies in the region report maximum concentrations of 6655 mg l^{-1}. Thus, the data from Twin Bore Creek currently stands as the highest SSC measured for central Australia. Generally the concentrations are significantly lower than those reported for sub-bankfull flows in arid areas of NSW (25 700 and 39 000 mg l^{-1}, Dunkerley & Brown, 1999), but are higher than those measured in the more temperate Hunter Valley region (~40–1500 mg l^{-1}, Olive & Rieger, 1985). This may indicate a significant variation in yield between basins, perhaps controlled by lithology. Alternatively, the Todd data may underestimate the peak concentrations as the cross channel data set indicates that concentrations sampled 1.5 m from the bank were between 65% and 71% of those taken at similar depths further out in the channel.

There is no evidence of a progressive impoverishment of SSC for the 11 successive floods sampled between 1979 and 1985 although there is variability within the data set. The highest value was recorded during the fourth flow event. Interestingly, this was recorded at the end of a year that had a rainfall deficit of 135 mm. In addition, the SSC for 1983, a high rainfall/discharge year was relatively low (818 mg l^{-1}). This suggests that antecedent rainfall may be an important control on sediment supply as it may trigger ground cover growth in sediment source areas. A similar observation for sediment yield trends at the larger scale of regional drought has been previously reported (Pickup, 1991).

The growth of vegetation following rainfall and flow may also be an important control on in-channel sources of sediment in the Todd River. Channel banks and beds are composed of loose sand that is relatively easily entrained. However, in recent decades, an aggressive colonization of channel banks, islands and benches by an introduced Couch grass (*Agropyron repens*) has occurred. This species effectively binds the loose sand and increases the erosion threshold thus reducing sediment availability. This may account for the observed reduction in SSC between flows of similar and or greater magnitude (e.g. the flows in 1981–1982, Fig. 5). However, any relationship between antecedent rainfall and SSC is complex and is not statistically significant for the data set as a whole.

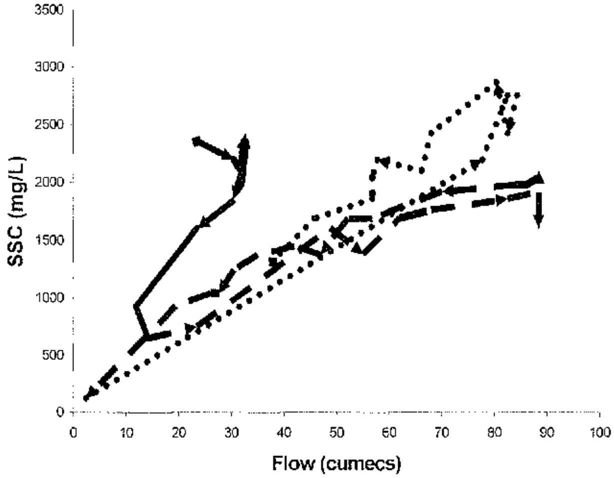

Fig. 4 A plot of the complex sequence of hysteresis loops for the February 1982 flow. Each flow peak is designated a different line pattern.

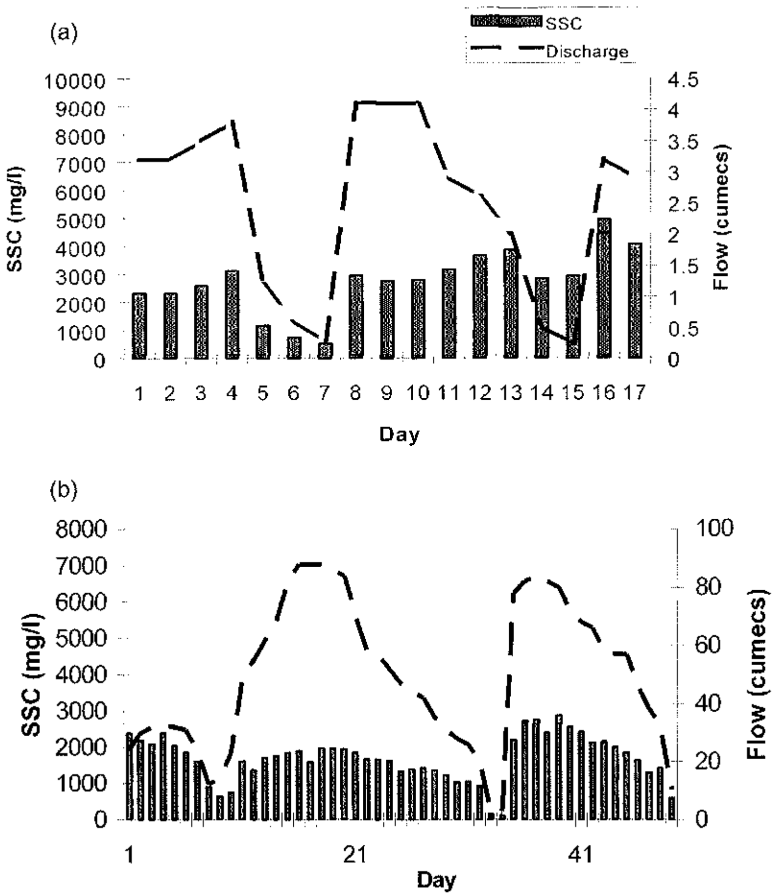

Fig. 5 Suspended sediment concentrations and discharge for two flows at Wills Terrace: (a) January 1981, (b) February 1982.

Suspended sediment and discharge The complex relationship between water discharge and suspended sediment concentration in flows has been recognized in data sets in a range of environments (e.g. Lenzi & Marchi, 2000). Studies reveal that SSC peaks may precede, coincide or lag behind the peak discharge. Some have found that peak SSC occur on the flood bore followed by either a monotonic decline (Dunkerley & Brown, 1999), or in the case of multi-peaked flow, a synchronous increase with discharge (Frostick *et al.*, 1983). The latter study suggested the causative mechanism to be either a wave of sediment-laden water from a tributary or a momentary increase in turbulence that forces bed material into suspension.

A plot of the February 1982 flow (Fig. 4) indicates a complex sequential pattern. The flow was multi peaked and the hysteresis reflects this with the first peak displaying clockwise behaviour and the two following peaks displaying anticlockwise behaviour. Note that at the maximum discharge for each flow peak there is random behaviour with a smaller opposite hysteresis imbedded within the trend. Flow stage may be important in explaining these trends. For flow events in 1981 and 1982 (Fig. 5) SSC increases on the rising limb of each flow peak. The highest SSC occurs after a combination of the lowest flow stage followed by a high peak. In both cases this occurs on the final peak of the multi-peak flow and not at the peak discharge. It is proposed that this is an important mechanism in systems where a principal source of sediment is derived from within the channel. This mechanism is similar to that suggested by Reid & Frostick (1987) where the turbulence associated with a flash flood bore is capable of disturbing the bed material.

Interestingly, when all data sets for central Australia were plotted against discharge (Fig. 6), the data suggest two different populations. The lower magnitude discharges appear to generate the higher SSC. Factors such as hydrograph shape, flow duration, antecedent flows, and antecedent rainfall were not consistent for each group and therefore not considered causative. Such high concentrations at low flow stages (often following flow peak) may again be an indication that bed load contributes to high SSC. However, it is more likely that the trends are the result of a dilution effect. Although the higher concentrations are transported by smaller flows, total loads are greater in the higher magnitude flows.

Channel morphology change

The geomorphic effects of sub-bankfull flows include channel bed aggradation and incision, channel widening and deposition of suspended sediment load on benches,

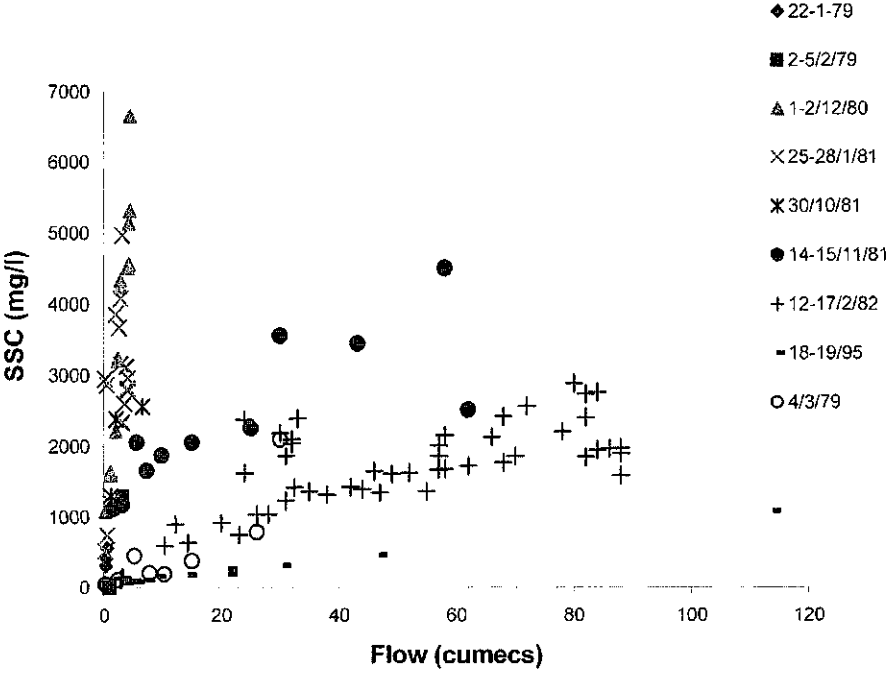

Fig. 6 A plot of suspended sediment concentrations and discharge for the Todd River. Data appear to fall into two groups. The data presented are predominantly from the recession curve (some include the peak discharge), although, two flows (25 January 1981 and 12 December 1982) include the rising limb. As these latter flows occur in each group, the observation is not thought to be purely a flow recession phenomenon.

insets and as flood plain veneer. The geomorphic effects of the 1995 flows on a tributary junction have been described elsewhere (Bourke & Pickup, 1999). All four sites show minor channel bed aggradation as a result of the January 1995 flow. At Site 1, (Fig. 7(a)) there was a 3% increase in channel width and an in-channel bench was removed (f1). At Site 2 the channel bed aggradation mirrors the 1993 bedform assemblage with aggradation and progradation of a lateral bar by 0.6 m. The resultant flow deflection against the right bank removed surfaces f1 and f2 and part of surface f3 (Fig. 7(b)) and channel width increased by 15%. At Site 3 the channel boundary is more resistant (indurated Pleistocene alluvium) and the cross-section displays general stability. Adjustments include the resurfacing and lowering of the central island and the incision of a 12.5-m^2 channel. At Site 4 there is evidence of net aggradation of the channel bed by 0.5 m. Channel width has been reduced by 5 m primarily by the construction of a bench (flood plain inset approximately 2.5 m wide) against the right bank and the aggradation of a bar against the left bank. Significant suspended load sinks were new bench construction (1 m high, 2 m wide), particularly in elliptical bank scours.

A geomorphic signature of channel widening is the presence of a series of narrow steps on the flood plain surface (flood plain remnants, Bourke, 1994). While widening is known to occur during overbank flows, data from the 1995 event suggests that sub-bankfull flows also contribute to channel widening. However, one difference is that lower magnitude events tend to preferentially erode one bank.

The combined effects of the March and May flows (Site 1 and 2, Fig 7(a), (b)) show a tendency to incise the channel bed. Although the March 1995 flow had a slightly higher peak discharge of 269 $m^3\ s^{-1}$ at the Wills Terrace gauge, the resultant cross-section change at Site 1 is dominated by tributary flow.

Observations at other locations include the widespread deposition of vertical accretion deposits on flood plain insets and benches to depths of between 10 and 30 cm. These sediments were light red in colour (7.5R 7/6) and contrasted with the white (10R 8/1) channel bed sediments. This contrast in colour is inferred to be a function of the relatively lower abrasion rates of suspended load that enables the retention of a haematite coating in grains. This may explain the variable colour of deposits in flood plain facies in the region and may be a useful diagnostic tool to determine the transport history of flood plain sediments, particularly if a minor traction phase follows deposition from suspension. Flood plain veneer was deposited on many sloping surfaces and was observed extending from low channel insets to the channel floor.

SUMMARY

Others have identified that suspended sediment concentration is not solely dependent on discharge and can be influenced by the depletion of sediment supply, the ability to detach sediment from the bed (Olive & Reiger, 1985) and the characteristics and locations of active sediment sources (Lenzi & Marchi, 2000). In central Australia factors such as flow stage, the magnitude and sequence of flow troughs and peaks and the enhanced sequestration of sediment by invasive species following antecedent rain and flow contribute to a system that may preclude prediction of SSC.

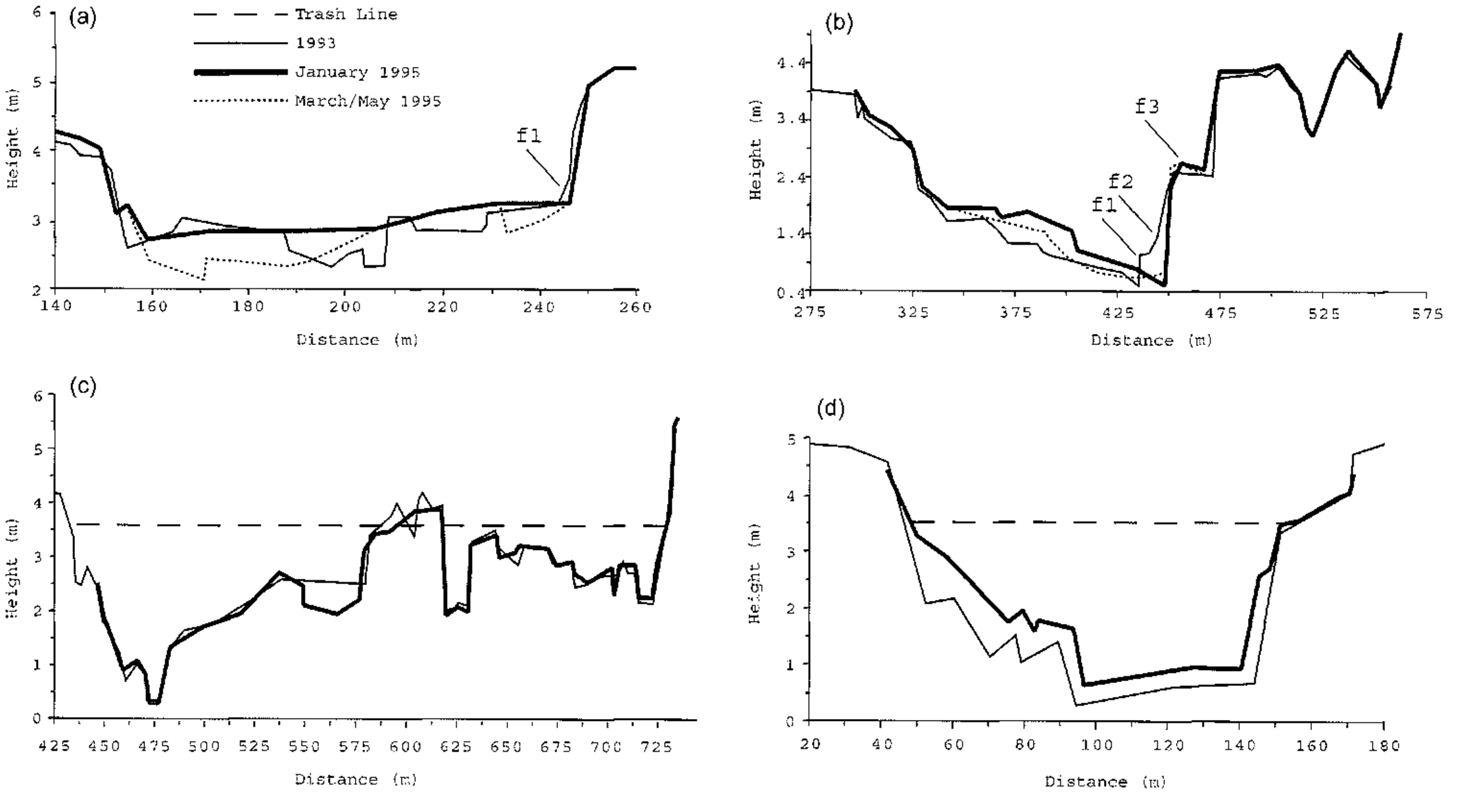

Fig. 7 Channel change following flows in January and March and May 1995. Pre-flood survey lines were measured in 1993/94. No flows were reported to have reached these sites in that time interval. Parts (a) to (d) are Sites 1 to 4.

Sub-bankfull flows in ephemeral sandy channels can effect significant geomorphic change. Three sites aggraded the channel bed by ~0.5 m and channel widening of up to 15% was recorded. These data indicate that certain flood plain processes dominate during lower magnitude events: these include the lateral filling of width irregularities with suspended load sediments, the formation and accretion of flood plain insets and the deposition of flood plain veneer.

Finally, this study identifies some of the sediment sinks of suspended concentrations in ephemeral channels. Despite apparent low concentrations, the deposition of suspended sediment achieves significant aggradation of channel margin surfaces.

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