Flood-driven formation and destruction of a forested flood plain and in-channel benches on a bedrock-confined stream: Wheeny Creek, southeast Australia

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Abstract Sandy vertically accreted flood plains are common on sand-bed streams near Sydney, Australia that are laterally confined by Triassic quartzose sandstone. They have well-developed natural levees with a number of inset benches. This paper investigates the relative roles of floods of varying magnitude and natural riparian vegetation in controlling the formation and destruction of flood plains and benches. Extensive radiocarbon dating of flood plain charcoal and stratigraphic and biogeomorphic investigations of flood plains and benches indicate that large floods have a major influence on the formation and destruction of fluvial landforms in these high energy forest streams. These impacts range from episodic cleanout of the complete valley floor trough by rainfall-generated cataclysmic events to the formation and destruction of in-channel benches during smaller events. The role of riparian vegetation, while considered minor in the long-term, is important for short-term in-channel bar and bench formation.

Key words catastrophic floods; cataclysmic erosion; vertical accretion; in-channel benches; natural levees; riparian vegetation; large woody debris (LWD); southeast Australia

INTRODUCTION

High vertically accreted flood plains are common on bedrock-confined, sand-bed streams near Sydney, Australia. A series of inset benches typically occurs below the flood plain resulting in a compound channel. To date, a model has not been derived that inter-relates the formation and destruction of both flood plains and benches on bedrock-confined streams. This paper aims to determine the dominant processes of flood plain and in-channel bench formation and destruction on one such stream that has not been disturbed by European settlement.

STUDY SITE

Wheeny Creek is a tributary of the Colo River in Wollemi National Park near Sydney with natural riparian vegetation and loadings of large woody debris (LWD) (Webb &

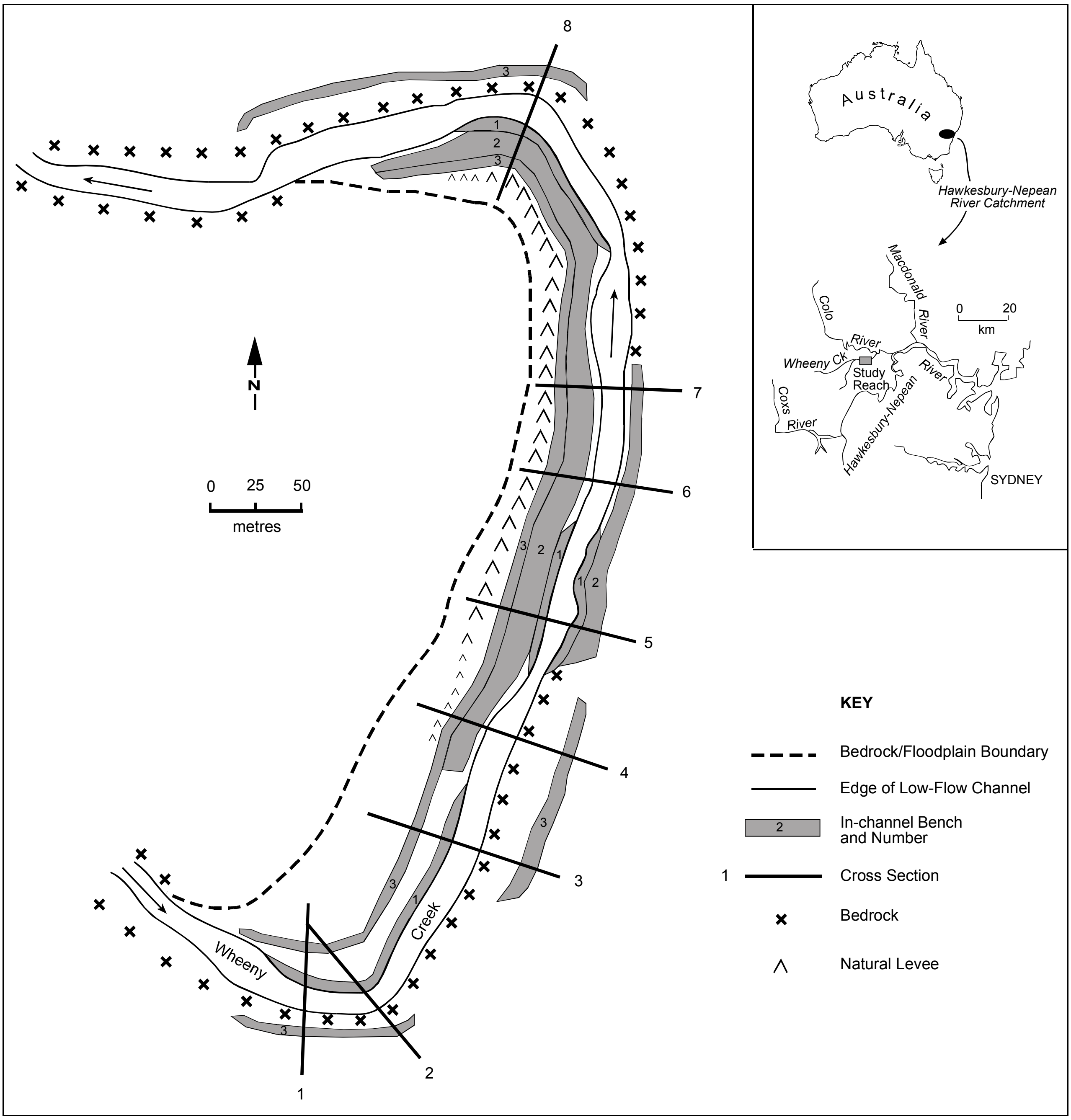

Fig. 1 Plan form of the study reach.

Erskine, 2001). The study reach is 850 m long where the drainage basin area is 133 km^2 (Fig. 1). Drainage basin geology is dominated by Triassic Hawkesbury Sandstone overlying undifferentiated Narrabeen Group sediments and mean annual rainfall is approximately 1000 mm. While the entrenched bedrock meanders of Wheeny Creek are sinuous (Fig. 1), the channel in the study reach has a low sinuosity (1.05) as it frequently impinges against bedrock in the concave bank. The valley floor trough (Warner, 1992) is approximately 80 m wide and spatially disjunct, high vertically accreted flood plains with distinct natural levees have developed on the inside of valley bends. The high flood plain forest comprises a *Eucalyptus saligna* Very Tall Open Forest (Webb & Erskine, 2001). Discontinuous in-channel benches occur between the stream bed and flood plain surface resulting in a compound channel. Three in-channel benches are present below the high, vertically accreted flood plain surface on the left bank. The benches are occasionally paired, discontinuous and usually only two benches are present at any cross-section. Benches are termed bench 1 through 3 with increasing elevation above the thalweg (Erskine & Livingstone, 1999). The benches are colonized by riparian vegetation dominated by multi-stemmed *Tristaniopsis laurina* and *Leptospermum polygalifolium* shrubs (Webb & Erskine, 2001).

Hydraulic calculations using Manning's equation at eight surveyed channel cross-sections (Table 1) combined with regional flood frequency analysis indicate that two of the benches, bench 2 and bench 3, have return periods that fall in the range normally quoted for bankfull discharge (Wolman & Leopold, 1957). Furthermore, an analysis of estimated mean annual floods indicates that benchfull capacity at bench 2 is similar to the mean annual flood (59.7 $m^3 s^{-1}$). The bankfull channel capacity, however, is 5.8 times greater than the mean annual flood (range 4.8–6.8).

Table 1 Summary of bankfull and benchfull morphology and hydraulics. Values are means ± two standard errors.

	Channel width (m)	Channel area (m^2)	Channel capacity ($m^3 s^{-1}$)	Flood return period (years on the annual maximum series) [range]	Specific stream power (W m^{-2})	Mean boundary shear stress (N m^{-2})
Bench 1	15.6 ± 5.3	17.5 ± 2.4	12.6 ± 6.6	1.1 [1.0–1.2]	6.9 ± 2.6	9.6 ± 2.3
Bench 2	23.6 ± 6.8	53.1 ± 9.1	61.1 ± 13.7	1.9 [1.5–2.1]	23.5 ± 9.2	19.9 ± 4.6
Bench 3	38.2 ± 6.0	85.8 ± 6.1	98.6 ± 13.3	2.9 [2.5–3.3]	23.3 ± 5.3	19.8 ± 2.9
Bankfull	65.1 ± 9.2	228 ± 32.8	347.4 ± 60.2	33 [18–56]	46.3 ± 7.1	30.1 ± 2.8

METHODS

The stratigraphy and sedimentology of the flood plain pocket and in-channel benches in the study reach were determined by the excavation of trenches and hand augering, combined with field descriptions and representative laboratory grain-size analyses. A total of 24 auger holes were dug in the flood plain sediments to a maximum depth of 7.5 m and trenches were excavated and described in the bench sediments on cross-sections 3, 5 and 8 (Fig. 2). Ten charcoal samples were collected from the flood plain and bench sediments (Fig. 2) for accelerator mass spectrometry (AMS) radiocarbon dating. Results of the dating combined with the sedimentology, stratigraphy and biogeomorphic evidence were used to determine the chronology and processes of flood plain and in-channel bench formation and destruction in the study reach.

BENCH AND FLOOD PLAIN STRATIGRAPHY

Benches are inset into vertically adjacent benches and the flood plain (Fig. 2), and are always separated by an erosional contact. The stratigraphy of bench 1 corresponds to the *stratic* sediments of Erskine & Livingstone (1999). Textures are predominantly coarse to medium sands and small-scale fining upwards sequences dominate. Flow structures

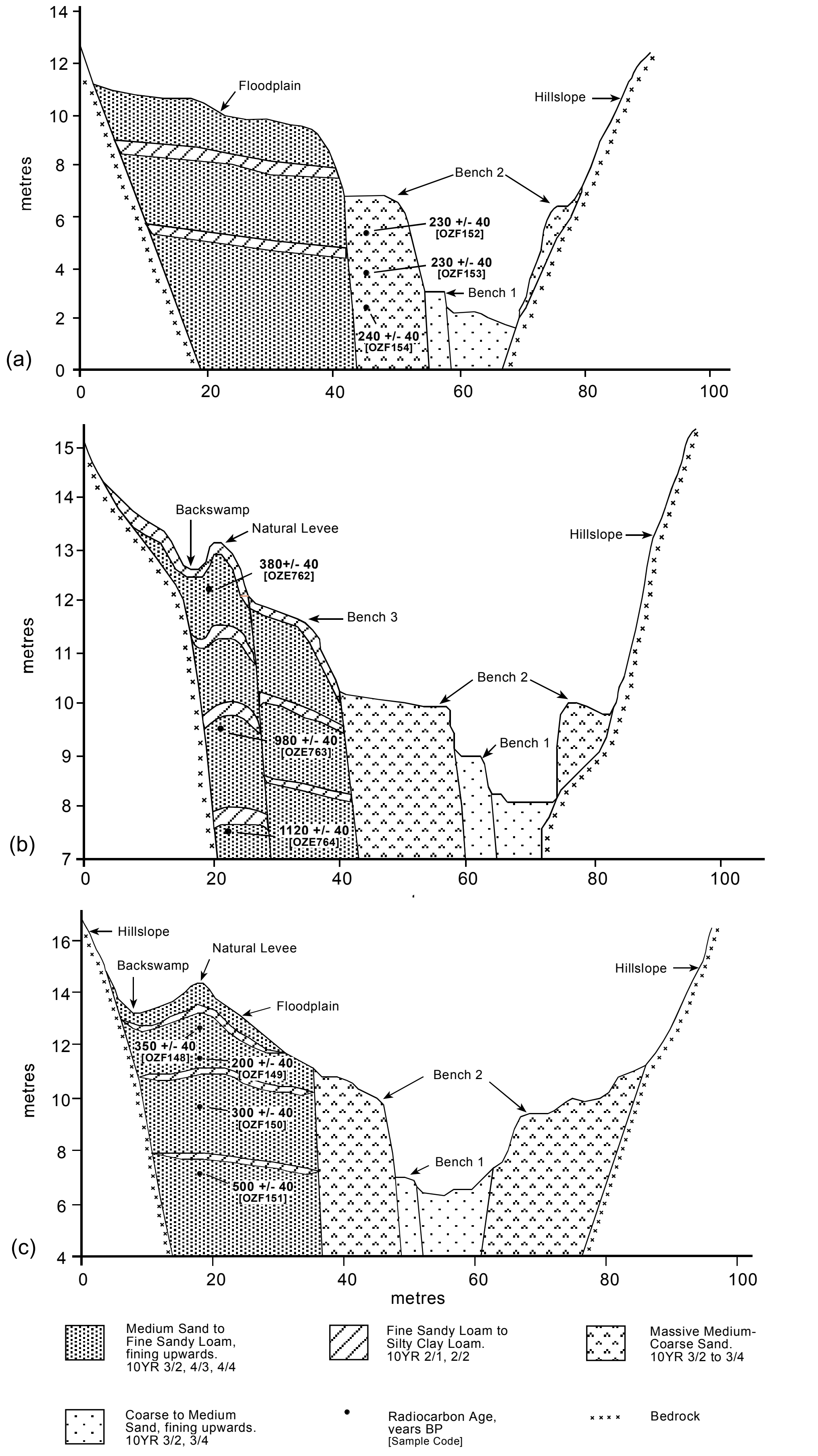

Fig. 2 Flood plain and bench stratigraphy at (a) cross-section 3; (b) cross-section 5; and (c) cross-section 8.

such as planar tabular cross lamination are often preserved in these benches with little evidence of post-depositional modification. The stratigraphy of bench 2 on the left bank corresponds to the *massive* sediments of Erskine & Livingstone (1999). Overlying a slightly coarser (medium-coarse sand) base are thick layers of massive medium sand. There is a slight fining upwards trend from the basal sediment to the middle of the profile but above this the sediment coarsens again. The stratigraphy of bench 2 on the right bank similarly comprises massive sediments. However, morphologically this bench is different to bench 2 on the left bank in that it overlies quartzose sandstone bedrock and abuts the bedrock valley side (Fig. 2). The stratigraphy of bench 3 is different again in that it contains thickly bedded sandy units that fine upwards from a medium sand base to loamy fine sand near the bench surface (Fig. 2). These units are interbedded with thinner layers of finer material comprising fine sandy loam and/or silty clay loam and are most likely deposited on the falling stage of a flood.

Erskine & Livingstone (1999) noted that "many apparent flood plains exhibited well developed soils with bleached A_2 horizons and with colour, texture, fabric, structure and/or consistence B horizons". The flood plain sediments at Wheeny Creek exhibit no evidence of pedogenesis. None of the sediment profiles described had an A_2 horizon, and none of the sediments were bleached. The flood plain sediments consist of thickly bedded sandy units that fine upwards from a medium sand base to fine loamy sand near the surface, similar to the stratigraphy of bench 3. These units are also interbedded with thinner layers of finer material comprising fine sandy loam and/or silty clay loam material as found in bench 3. However, in the flood plain sediments these layers are closer spaced and slightly thicker than in the bench 3 profiles (Fig. 2).

CHRONOLOGY AND FORMATION OF THE FLOOD PLAIN AND BENCHES

The oldest radiocarbon age obtained on Wheeny Creek flood plain charcoal towards the base of the natural levee at cross-section 5 was 1120 ± 40 years BP (Fig. 2). This age when calibrated to calendar years has a 2-sigma (95% probability) range of from 935 to 1170 years BP (Stuiver *et al.*, 1998) and suggests that the formation of the high flood plain began well after sea-level stabilized at its current level (~6000–7000 years BP). Nanson (1986) proposed a model of flood plain formation by vertical accretion and episodic destruction by catastrophic floods in bedrock-confined rivers. More recently, the term *cataclysmic* flood has been used to describe rainfall-generated events approaching the magnitude of the probable maximum flood that are capable of totally destroying alluvial landforms within the valley floor trough (Webb *et al.*, 2001; Erskine & Peacock, 2002). A plausible explanation for the young age of the flood plain is that prior to 935–1170 years BP a cataclysmic flood completely destroyed this flood plain pocket of Wheeny Creek, along with the flood plain forest. An abundance of charcoal preserved in the flood plain sediments suggests that a large fire may have burnt at least some of the catchment and possibly flood plain vegetation prior to the cataclysmic event. The relatively young age of the flood plain is similar to dates (550–1430 years BP) obtained by Hickin & Page (1971) in what Hickin (1970) had formerly described as a terrace formed between 10 000 and 6000 years BP at upper Colo on the nearby Colo River. Hickin (1970) believed the “terraces” of the lower Colo, which are of similar dimensions and morphology to the flood plain and benches of Wheeny Creek, were formed during a time of much lower sea levels. Saynor & Erskine (1993) obtained a radiocarbon date of 940 ± 60 years BP at depth in a disjunct pocket of flood plain at Wallacia on the nearby Nepean River.

Evidence of palaeofloods preserved in slackwater deposits in the nearby Wollombi Brook and Nepean River catchments supports the occurrence of cataclysmic floods on Wheeny Creek prior to European settlement. Erskine & Peacock (2002) concluded that at least four floods larger than any recorded in historical time had occurred on Wollombi Brook during the late Holocene. A cataclysmic event occurred between 4280 ± 120 and 3380 ± 90 years BP while palaeoflood 3 occurred between 3380 ± 90 years BP and 1890 ± 60 years BP. Saynor & Erskine (1993) used tandem AMS to date charcoal deposited by a very large palaeoflood on the nearby Nepean River at 3756 ± 72 years BP that may have been synchronous with palaeoflood 3 on Wollombi Brook. Palaeoflood 2 occurred after 1300 ± 70 years BP while palaeoflood 1 occurred after palaeoflood 2 but before European settlement in the late 1820s (Erskine & Peacock, 2002). The cataclysmic flood on Wheeny Creek may have coincided with either palaeoflood 1 or 2 on Wollombi Brook. Nevertheless, these examples confirm that Wheeny Creek is located in a region of high flood variability prone to episodic erosion by rainfall-generated cataclysmic floods.

Due to a limited number of dates taken from only one cross-section at each site Nanson’s (1986) model of flood plain formation following stripping, though conceptually important, does not take account of upstream or downstream processes of levee formation. The collection and radiocarbon dating of four charcoal samples from the levee at cross-section 8 has attempted to address this shortcoming. The basal radiocarbon date at cross-section 8 (Fig. 2) is 500 ± 40 years BP which corresponds to a 2-sigma calibrated age of 500–620 years BP (Stuiver *et al.*, 1998). This age is much younger than found 150 m upstream at cross-section 5 and indicates that the formation of this pocket of flood plain, following cataclysmic erosion, has not been spatially synchronous. Nanson’s (1986) model assumes that such pockets of flood plain form by uniform vertical accretion. The dates obtained from the flood plain pocket at Wheeny Creek indicate that the flood plain has formed by the downstream progradation of natural levees from an upstream tabular nucleus. It should also be noted that the basal date at cross-section 8 was obtained from a greater depth (7.0 m) than the basal date at cross-section 5 (5.7 m), which further supports this conclusion. This finding conflicts with observations made by Hickin (1970) in relation to similar features on his “high terrace” at Meroo bend on the Colo River. Hickin (1970) believed that the levees on the Colo River, which he termed “the terrace fore-edge”, were formed by erosion of the “backs of terraces” (the backswamp) and not by the downstream progradation of natural levees. He also concluded that the “coarse to fine gradation of sediment from the terrace fore-edge to the area at the back of the terrace is not to be confused with the similar sediment pattern usually attributed to overbank flooding and levee construction” (Hickin, 1970: page 283). These features, on the basis of evidence presented here, are not formed by scour of the high flood plain. Instead they are formed by downstream progradation of natural levees from a tabular upstream nucleus. At cross-sections 5 and 8 (Fig. 2), the three-dimensional architecture of the flood plain sediments corresponds to the levee morphology, demonstrating that the levees and backswamps have formed by deposition, not by the erosion of the "backs of terraces" as envisaged by Hickin (1970).

Initial work by Woodyer (1968) suggested that in-channel benches were stable over time and formed by channel incision which stranded former parts of the bed above the thalweg. However, Abrahams & Cull (1979) concluded that benches were formed by massive deposition and reworking during high magnitude floods. Erskine (1996) observed the total destruction of alluvial landforms during catastrophic floods followed by recovery by bench deposition in the erosional void during smaller floods. More recently, Erskine & Livingstone (1999) have extended these observations and documented that catastrophic floods destroy in-channel benches, liberating sediment and creating sand slugs or bed load waves. Subsequent smaller events laterally reworked this material on decadal time scales, depositing in-channel benches.

In the context of Wheeny Creek, the model of Erskine & Livingstone (1999) indicates that the benches should be much younger than the high flood plain. To test this, three charcoal samples were collected from the bench 2 profile at cross-section 3 (Fig. 2) for radiocarbon dating. The radiocarbon ages obtained from the three depths are much younger (230 ± 40, 230 ± 40, 240 ± 40 years BP) than the flood plain sediments obtained at cross-sections 5 and 8. Due to the high variability of the Intcal98 calibration curve post-250 years BP (Stuiver *et al.*, 1998), the 2-sigma (95% probability) calibrated ranges of the three dates were 5–420, 5–420 and 5–425 years BP, respectively precluding an accurate assessment of bench age. However, on the basis of the dates, the relatively homogeneous sediments and the small diameters and multi-stemmed growth habit of *Tristaniopsis laurina* trees growing on the benches (Webb & Erskine, 2001), it is concluded that they are subject to frequent disturbance by floods and episodic reworking and massive deposition, as described by Erskine & Livingstone (1999). The lack of any discussion of lateral and/or temporal variations in stripping and formation of benches and flood plain is another shortcoming of the model proposed by Nanson (1986). Despite the dominance of floods in controlling the formation and deposition of benches, field observations suggest that riparian vegetation and LWD contribute to bench and/or bar formation on a small scale in the short term. Following relatively small floods with a stage equivalent to bench 1, the deposition of sediment has been observed on the leewardside of *Leptospermum polygalifolium* and *Tristaniopsis laurina* shrubs and LWD on bench 1 and also on mid-channel bars.

CONCLUSIONS

The entire flood plain and benches of Wheeny Creek, including riparian vegetation, are obliterated during high magnitude, rainfall-generated cataclysmic floods. Subsequent formation of the flood plain in the erosional void is spatially non-synchronous and characterized by downstream progradation of natural levees from a tabular upstream nucleus. In-channel benches are destroyed and reformed by catastrophic floods of greater frequency and lower magnitude. Riparian vegetation and large woody debris, while important for alluvial deposition in the short term (10^0 years), have little influence in the long term (10^1–10^3 years) on channel and flood plain stability in Wheeny Creek. The formation and destruction of alluvial landforms within this bedrock-confined valley is flood-determined and flood-dominated.

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