Channel incision and sand compartmentalization in an Australian sandstone basin subject to high flood variability

W. D. ERSKINE

School of Environmental and Life Sciences, University of Newcastle – Ourimbah Campus, PO Box 127, Ourimbah, New South Wales 2258, Australia

wayne.erskine@newcastle.edu.au

Abstract Wollombi Brook in the Hunter Valley, New South Wales, Australia, is characterised by high flood variability on a global scale (Flash Flood Magnitude Index of at least 0.86). Channel incision has occurred throughout the 2000-km^2 basin since initial European settlement in the early 1820s. On the main stream, discontinuous incision occurred in the upper basin in a 7-km long reach and was caused by the localised exceedence of a valley-floor slope threshold by a large flood in 1927. Since then, 900 000 m^3 of valley fill has been eroded by knick-zone migration and subsequent channel widening, but the whole sand fraction has been deposited immediately downstream in a sand slug or intermediate floodout. Between 1927 and 1982, incision moved 7 km upstream, but has since stabilised due to engineering works. Non-synchronous incision of tributaries was recorded between 1838 and 1977, but the generated sand often did not reach the main stream because of deposition in intermediate floodouts/sand slugs on the tributaries. Incision of the largest tributary, Congewai Creek, was initiated by a catastrophic flood in June 1949, and was integrated with the main stream downstream of the intermediate floodout. Sand from Congewai Creek and Wollombi Brook, downstream of their junction, was transported continuously out of the basin until 1996 when channel recovery from the catastrophic 1949 flood was accelerated by substantial vegetation colonization and sand anchorage.

Key words Wollombi Brook, NSW, Australia; chain of ponds; floodouts; sand slugs; sand compartment; channel recovery

INTRODUCTION

Wollombi Brook is a 2000-km^2 drainage basin in the Hunter Valley, New South Wales, Australia (Fig. 1). Triassic sandstone and shale dominate in the upper two-thirds of the basin, whereas Permian shale, sandstone and conglomerate dominate in the lower basin. 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 17–18 June 1949 was the largest since first European settlement in the 1820s (Erskine, 1996), 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 Letter A" (Erskine, 1996) at the head of the Wollombi Brook basin (Fig. 1). Flood peak discharge was between 22 and 26 times greater than the mean annual flood (Erskine, 1996; Erskine & Peacock, 2002). Erskine (1996) described the variable impact of the 1949 flood on Congewai Creek and lower Wollombi Brook. This paper determines, among other things, the geomorphic effects of the 1949 flood on upper Wollombi Brook, upstream of the village of Wollombi (Fig. 1). Existing accounts of the geomorphic impacts of the 1949 flood on upper Wollombi Brook are contradictory. Ritchie (1957) noted up to 6 m of incision and a trebling of channel width upstream of Blaxlands Arm, whereas Page (1972) concluded that, for the same reach, the channel had been infilled with sand and substantial overbank deposition had occurred. Good (1952) found that the channel changes initiated by the 1949 flood were largely restricted to specific sections of all rivers in the Wollombi Brook basin. This paper corroborates Good's (1952) preliminary findings.

METHODS

Channel and flood plain conditions since 1820 were determined for five rivers (upper Wollombi Brook, Yango Creek, Blaxlands Arm, Watagan Creek, Congewai Creek–lower Wollombi Brook) in the Wollombi Brook basin (Fig. 1) from a combination of historical maps and plans (e.g. Matthews, 1830), land subdivision surveys (e.g. White, 1847), historical descriptions (e.g. Mitchell, 1839; Walker, 1910), gauging data, oral histories of land owners who observed the 1949

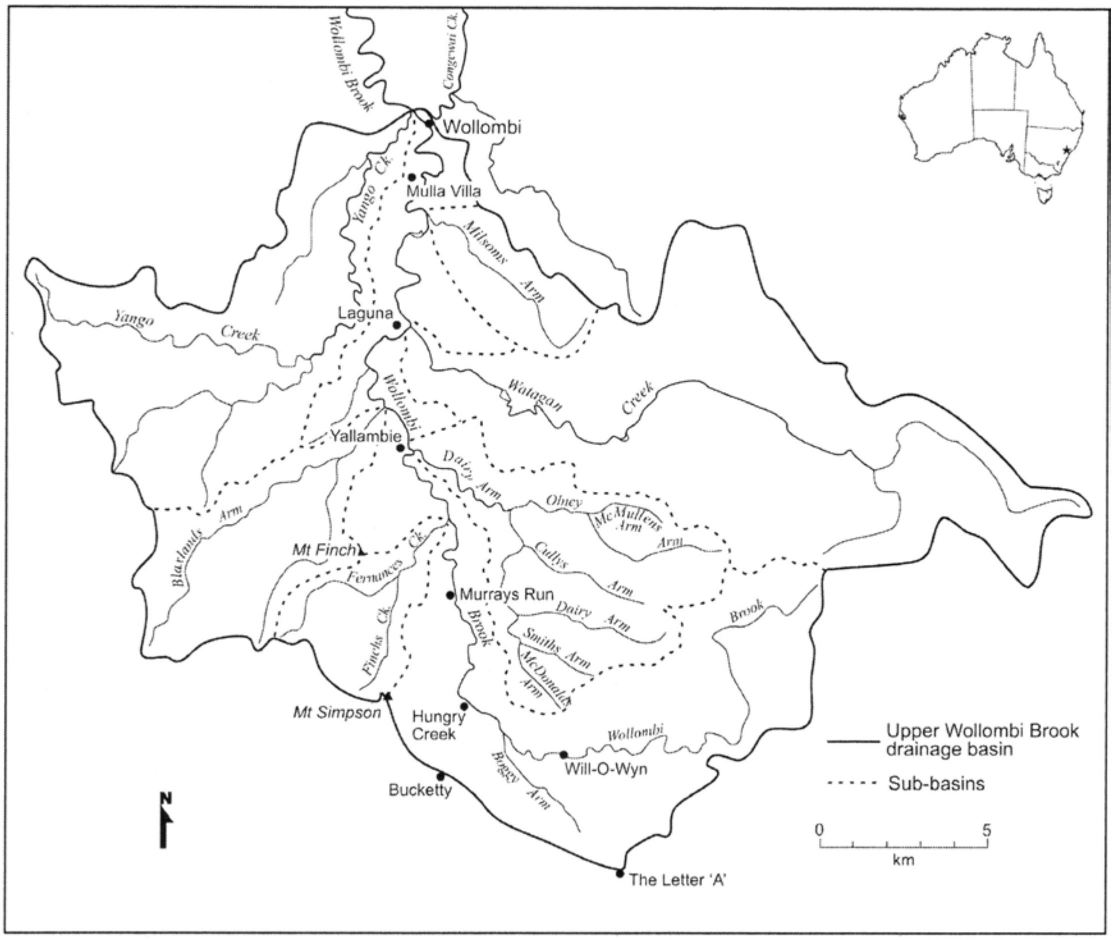

Fig. 1 Upper Wollombi Brook drainage basin showing the rivers investigated in detail, namely upper Wollombi Brook, Yango Creek, Blaxlands Arm, Watagan Creek and Congewai Creek-lower Wollombi Brook.

flood, channel surveys, flood-plain sedimentology and grain-size analyses of fluviatile sediments. The Holocene alluvial history of Wollombi Brook and some tributaries has been determined by Erskine & Peacock (2002) and Erskine & Melville (2008), and is used to assess the onset of fluvial conditions present at the time of initial European settlement. The probability of exceedence in a year of bankfull discharge was determined by Boyd's (1978) regional flood frequency method. Bagnold's (1980) equations for total, unit and threshold stream power were used.

RESULTS AND DISCUSSION

Upper Wollombi Brook

The 33.6 km of Wollombi Brook between Will-O-Wyn and the confluence with Congewai Creek at Wollombi exhibits four reaches, which are, in downstream sequence (Fig. 2):

– an *upstream unincised reach* with a vegetated, small capacity, sinuous channel containing occasional chains of ponds (Mitchell, 1839; Eyles, 1977a,b);
– a low sinuosity, *recently incised reach* with a large channel capacity, many cutoffs, and many drained and eroded chain of ponds;
– a *major sand slug or intermediate floodout* where the sand generated by historic incision has blanketed the whole valley floor and buried chain of ponds (Erskine & Melville, 2008); and
– a *downstream stable reach* with a fine-grained channel boundary, vegetated bed, sinuous pattern and floodplain lakes (Erskine & Melville, 2008).

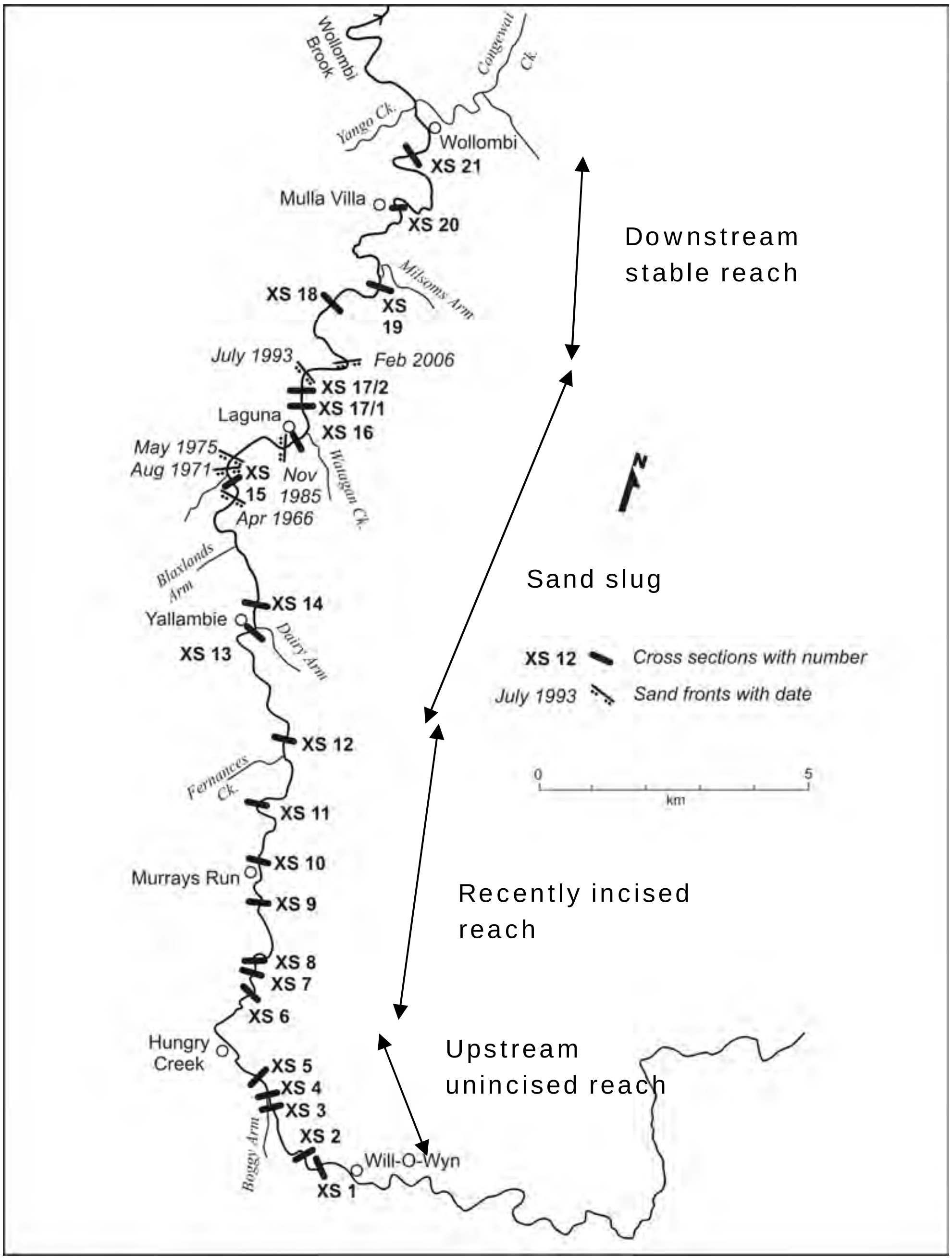

Fig. 2 Upper Wollombi Brook showing location of channel cross-sections, four channel reaches and downstream movement of the sand front (downstream end of the sand slug/floodout), over time.

The chains of ponds are oval to round, reed-lined, deep waterholes often, but not always, with an interconnecting channel (Mitchell, 1839; Eyles, 1977a,b). Where ponds are found in association with channels, their dimensions are generally at least one order of magnitude greater than pools forming part of a pool-riffle sequence and are a truly distinctive channel form.

Figure 3 shows downstream variations in the probability of occurrence of bankfull discharge, bankfull total stream power (Ω), bankfull unit stream power (ω) and threshold stream power for sediment transport (ω_o) at each of the 21 channel cross-sections on upper Wollombi Brook (Fig. 2). The above four reaches are clearly illustrated. The *upstream unincised reach* experiences frequent overbank flow, has low bankfull total and unit stream power (Fig. 3) and has a sinuosity of 1.53. The channel is currently stable because the peak discharge of catastrophic floods is routed

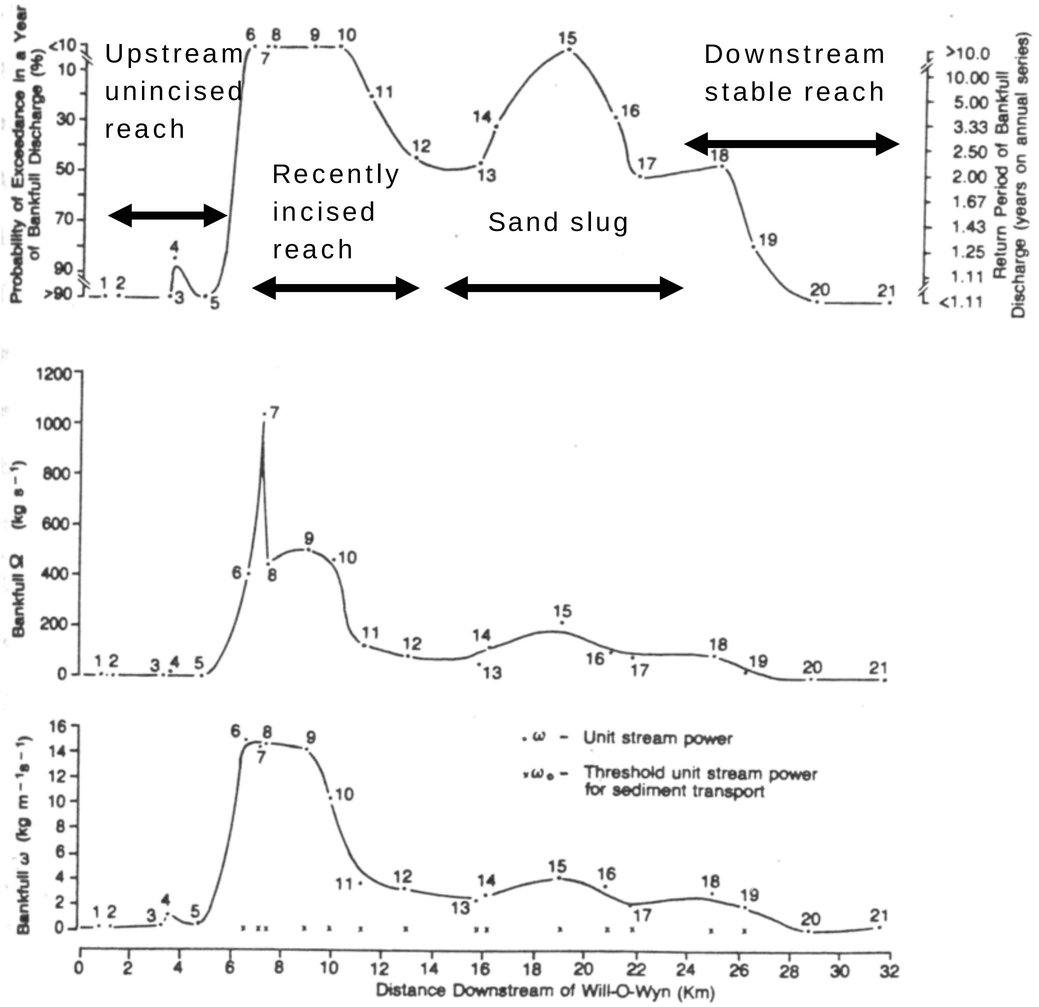

Fig. 3 Downstream trends in the probability of occurrence of bankfull discharge, and bankfull total, unit and threshold stream power for sediment transport on upper Wollombi Brook. Location of channel cross-sections is shown in Fig. 2.

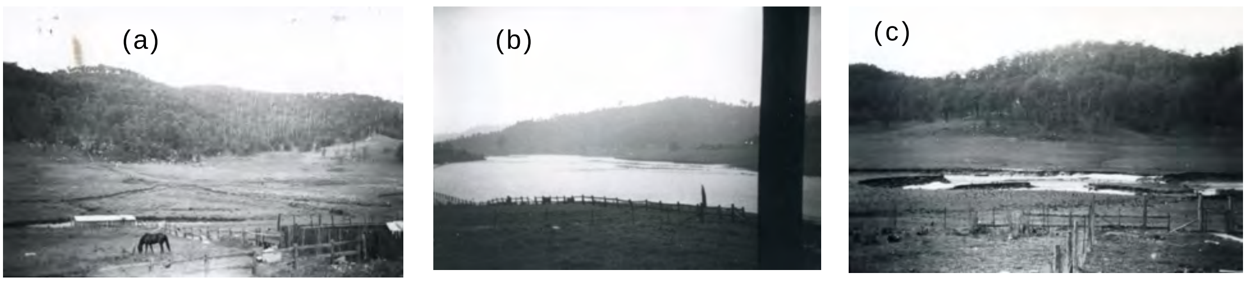

Fig. 4 (a) Wollombi Brook near cross-section 10 before the 1949 flood, showing a vegetated, small capacity channel. (b) Near the same location as (a) on morning of 18 June 1949, after the flood had receded below the peak reached the previous night. (c) Near the same location as (a) immediately after the June 1949 flood, showing the recently incised channel. Location of cross-section shown in Fig. 2. Photographs kindly supplied by the late H. C. Nichols, property owner at cross-section 10.

across a broad, vegetated, polygenetic flood plain (Erskine & Melville, 2008). The *recently incised reach* is characterised by the greatest channel capacity and stream power (Fig. 3). Bed slope also increases significantly and sinuosity decreases to 1.16 due to 10 cutoffs since 1949. The knick zone (after Schumm *et al.*, 1984) at the head of incision moved 7 km upstream after incision was initiated about 600 m upstream of the Fernances Creek junction, on a locally steeper section of flood plain, by a large flood in 1927 (Hal Nichols, property owner, pers. comm., 1981). Initially a 2-m high "waterfall" cut into "topsoil" overlying "sand" was present during the large floods of 1927 and 1929. Between 1929 and June 1949, the headcut was effectively stationary. However, the headcut rotated into a 1-km long knick zone (Schumm *et al.*, 1984) during the catastrophic flood of 17–18 June 1949 and migrated 3.5 km upstream in two days. Figure 4 shows the valley floor near cross-section 10 before, during and immediately after the June 1949 flood. Between July 1949 and 1982, the knick zone migrated a further 3.5 km upstream. Figure 5 shows the upstream extension of incision by 1.4 km and subsequent channel widening between August 1969 and July 1979. A number of chains of ponds mapped in 1825 (Dangar, 1825) were drained and eroded by such incision and widening. Channel erosion was caused by the large bankfull stream power (Fig. 3). However, the catastrophic June 1949 flood inundated the whole flood plain (Fig. 4(b)), as did the subsequent large flood in March 1978. Although government-sponsored river training works were commenced on upper Wollombi Brook in 1967, no attempt was made to stabilise the knick zone until 1982. It was maintained that the "clay bars" near cross-sections 6 and 7 (Fig. 5) would stop upstream migration of the knick zone. These "clay bars" are never finer than sandy clay loams and are part of the Boggy Formation of Erskine & Melville (2008), which becomes indurated on exposure by erosion. Large floods in March 1977 and March 1978 totally breached the bars and, as a result, upstream incision continued (Fig. 5). Four consecutive rock weirs were built in 1982 and they have proved successful in stopping the incision. At least 900 000 m^3 of valley fill was eroded by historical incision between 1927 and 1982.

The depositional zone downstream of the recently incised reach has a 100% trap efficiency for sand. This *sand slug* or *intermediate floodout* now extends from cross-section 12 to downstream of cross-section 17 (Fig. 2). Intermediate floodouts are sites where channelised flow ceases and floodwaters spill across the valley floor before rejoining as a channel further downstream (Tooth, 1999). While Wollombi Brook now has a continuous channel through the sand slug, this has not always been the case since 1927. Fernances Creek, Dairy Arm, Blaxlands Arm and Watagan Creek all flow into Wollombi Brook in the sand slug. However, only Dairy Arm has contributed significant amounts of sand to Wollombi Brook. While the sand slug first formed in 1927, it is only since April 1966 that the downstream movement of the front of the sand slug (sand front in Fig. 2) has been mapped by Page (1972) and this author. Massive overbank deposition at cross-sections 14, 15 and 16 has greatly exceeded bed aggradation and has rapidly formed high natural levees, which locally increase bankfull channel capacity and stream power (Fig. 3). These over-bank deposits correspond to the Fernances Formation of Erskine & Melville (2008), and are certainly post-European settlement in age because they bury introduced fruit trees at cross-section 14; they completely bury fence posts at cross-section 16; and they buried an old convict stone crossing of a flood chute at cross-section 13. The sand slug has buried extensive chains of ponds that were formerly connected by a small sinuous channel (Dangar, 1825; Matthews, 1830). A 2-km long pond was present at cross-section 15 (Dangar, 1825). The then Surveyor General, Major T. L. Mitchell (1839) first described a chain of ponds on Wollombi Brook in this reach during his expedition into the interior of Australia in November 1831. Sinuosity currently varies between 1.15 and 1.20, and is comparable to the incised reach. A neck cutoff at cross-section 11 was abandoned in 1949 and used to form part of an extensive pond system that was fished by local residents before the cutoff occurred (Nev Thompson, land owner, pers. comm., 1985).

The *downstream stable reach* extends from the sand front to within 0.5 km of the Congewai Creek junction (Fig. 2). The channel has a small capacity of low, to extremely low, stream power (Fig. 3). Sinuosity increases from 1.28 between cross-sections 17 and 19, to 1.58 at cross-section 21. However, some short sections have sinuosities as high as 1.95. Bedrock is exposed in the bed between cross-sections 17 and 19 and the flood plain becomes progressively confined by a resistant sandstone bed of the Triassic Narrabeen Group near Wollombi. Although Page (1972) maintained that active lateral migration was occurring near cross section 21, the channel trace for Wollombi Brook between Wollombi and Laguna has not changed measurably since Matthew's (1830) survey. Furthermore, the distal flood-plain facies of Yallambie Formation at cross-section 21

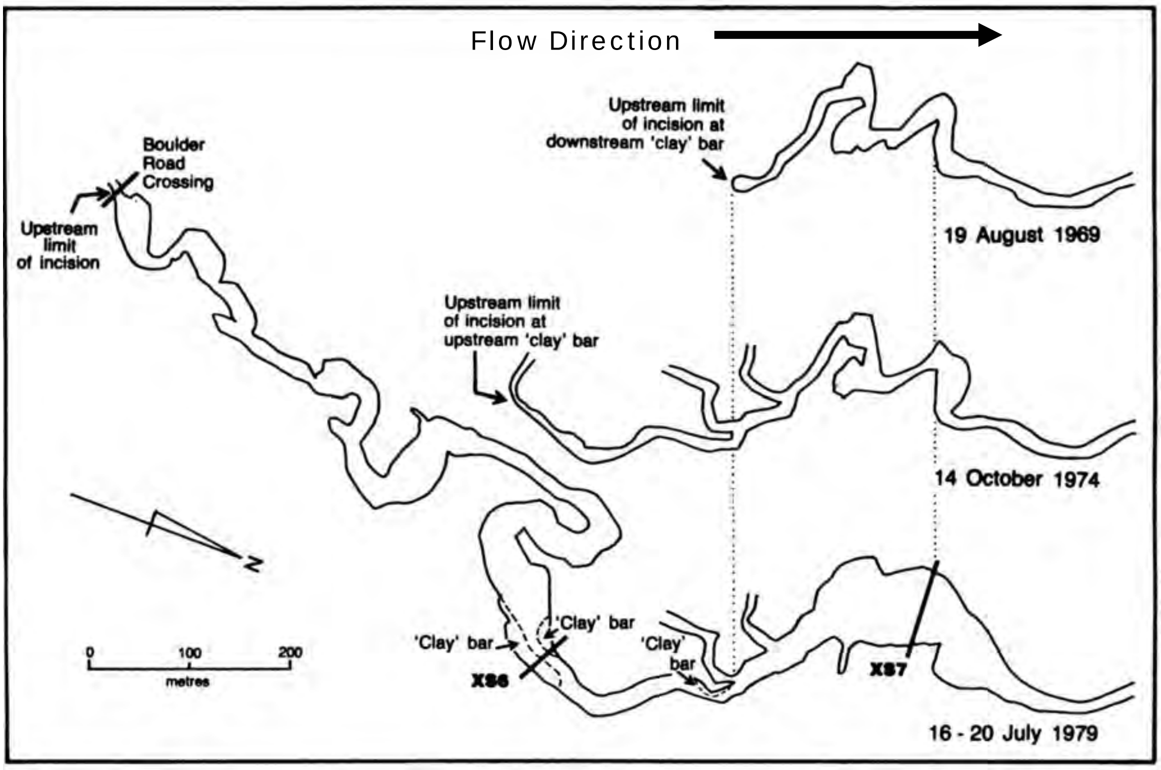

Fig. 5 Upstream extension of channel incision and widening of Wollombi Brook at Hungry Creek between 1969 and 1979, as determined by field surveys. Location of cross-sections shown in Fig. 2.

consists of a coarsening-upward sequence of heavy clay to silt loam and was deposited in a backwater environment over at least the last 1800 years (Erskine & Melville, 2008). This is incompatible with a meandering stream, as implied by Page (1972). The absence of perceptible lateral migration is caused by a combination of low stream power and high bank resistance. The lower 0.5 km of channel immediately upstream of the Congewai Creek junction, has eroded since 1949, and has been treated by extensive rock protection works.

Yango Creek

Yango Creek is a 59.5-km^2 tributary of Wollombi Brook, which it joins at Wollombi (Fig. 1) in the downstream section, and has eroded since 1949. Discontinuous incision was initiated by the 1949 flood and was rapidly extended by the 1955 flood (late F. Cagney, land owner, pers. comm., 1981). Channel incision eroded a swampy valley floor with no well-defined channel on the upper reaches, and a small capacity, grassed channel with chains of ponds and reeds on the middle reaches. Large quantities of sand were supplied to the channel further downstream, where a sand slug or intermediate floodout developed. The channel is ill-defined in much of the sand slug. Knickpoint migration rates measured on tributaries of the upper incised channel over a 6-year period between 1988 and 1993 ranged from 10.2 m/year to 28.8 m/year, and indicate that these tributaries are still being rejuvenated by main stream incision. Early land survey plans referred to “flooded land” and “swamps” on the upper reaches and “waterholes”, “chain of ponds”, “rich alluvial soil” and “black mould soil” on the middle reaches where a thick sand sheet (sand slug) now mantles the whole flood plain. This sand has not yet reached the lower 4.15 km of Yango Creek, where the channel is still shallow, sinuous and well vegetated with isolated ponds. Some of these ponds are still in the same location today as when first mapped in the 19th century. Surveyor J. Rogers (1852) commented that “this creek is well watered at intervals, may properly be called a chain of ponds”.

Blaxlands Arm

Blaxlands Arm is a 27.4-km^2 tributary of Wollombi Brook which it joins at Yallambie in the sand slug (Fig. 1). Ogilvie (1833) showed that the lower reaches of Blaxlands Arm had a small channel with irregularly spaced ponds, whereas the middle and upper reaches consisted of swamp. In 1850, many isolated ponds, called "chain of mulet (sic) holes" (mullet refers to two species of Australian freshwater fish, *Myxus petardi* Castelnau and *Mugil cephalus* Linnaeus), were mapped by Charlton (1850) on the lower reaches near Noulanans Arm (Fig. 1). By 1855, these ponds had been abandoned and replaced by a continuous channel on a different alignment (Rogers, 1855). Pond deposits (organic clay lenses at least 2 m thick), buried by up to 1.3 m of stratified sand, were found at two of the locations where Charlton (1850) depicted ponds. However, not all of the ponds on the lower reaches were abandoned. Rogers (1862) showed a number of ponds near Wollombi Brook and one of these is still present today. Channel incision was initiated immediately upstream of Noulanans Arm between 1850 and 1855. Surveyor Rogers referred to a large flood on the neighbouring Yango Creek in 1855, and this event probably started channel incision. Since 1855, incision has migrated 2.8 km upstream, following closely the alignment of a low inset fill. Sand generated by incision has been deposited over the flood plain for up to 1.7 km downstream of Noulanans Arm, infilling a number of ponds. The 1949 flood not only extended and widened the incised channel on lower Blaxlands Arm, but also incised new channels in the middle and upper reaches. The "rich flatland" and "rich alluvial land" noted on early land survey plans are now either incised or buried with sand.

Watagan Creek

Watagan Creek is a 94-km^2 tributary of Wollombi Brook, which it joins at Laguna in the sand slug (Fig. 1). Only 4 km of channel immediately downstream of the headwaters have been eroded since 1949. However, Watagan Creek mainly experienced lateral migration and bank erosion rather than incision. Nevertheless, the rate of erosion was still great enough to overload the channel with sand. A sand slug with a front formed, and has migrated 3 km downstream of the eroded section since 1949, infilling pools and ponds, and aggrading the flood plain. Nevertheless, the lower 19 km of channel have remained stable. No measurable lateral migration of the lower channel has occurred since 1829 when Watagan Creek was first mapped by Finch (1829) and Rogers (1829). Furthermore, field evidence, such as natural levees, old trees growing on the river banks, a lack of point bars and fine-grained flood-plain sediments also indicate little recent lateral migration. Lower Watagan Creek is similar to Wollombi Brook at cross-sections 20 and 21 (Fig. 2) in that it is a sinuous (1.75 to 1.84), small capacity but non-migrating channel.

Congewai Creek–Lower Wollombi Brook

Congewai Creek flows into Wollombi Brook at Wollombi (Fig. 1) where Congewai Creek has the larger channel. The 1949 flood started bank erosion and substantial channel widening, which were continued by a sequence of large floods between 1950 and 1956 on lower Congewai Creek and Wollombi Brook (Erskine, 1996). Substantial channel incision was also initiated on Congewai Creek by the 1949 flood upstream of Wollombi near Cedar Creek. A knick zone formed and migrated upstream, deepening the channel by about 2 m, undermining the banks and widening the channel (Erskine, 1994). A series of cutoffs also occurred (Erskine, 1994). Five gabion weirs were built after the 1955 flood and four have survived. There has been no channel incision upstream of the weirs (Erskine, 1994). Wollombi Brook downstream of Wollombi was widened by about 100% and aggraded by up to 4 m by the 1949 flood (Erskine, 1996). Hydraulic adjustments caused by the channel changes significantly reduced the sand transport capacity (Erskine, 1996). Nevertheless, channel recovery by bed degradation, and channel contraction by bench formation, started within 10 years of the 1949 flood (Erskine, 1996). However, it has only been since 1996 that significant vegetation colonisation and sand anchorage has occurred in the channel. Wollombi Brook is not currently contributing significant amounts of sand to the Hunter River.

CONCLUSIONS

Historical channel incision on many rivers in the Wollombi Brook basin has been non-synchronous, despite the occurrence of a catastrophic flood in June 1949. Incision has destroyed chains of ponds and swamps, and produced well-defined downstream sand slugs which have buried chains of ponds. The incised reaches are major sand sources, while the sand slugs are substantial sand storages. The combined source and storage zones are called *sand compartments* because essentially all of the eroded sand is temporarily stored immediately downstream. Sand compartments are usually fully contained within each tributary; Dairy Arm near Yallambie (Fig. 1) is a significant exception. As a result, historical channel incision has not increased the export of sand from the upper Wollombi Brook basin because all of the sand is still stored within sand slugs. However, lower Wollombi Brook, which is integrated with Congewai Creek, discharged sand into the Hunter River until 1996 when vegetation colonisation and sand anchorage started. Not even the June 2007 flood significantly disturbed this colonising vegetation on lower Wollombi Brook.

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