Effects of catastrophic floods on sediment yields in southeastern Australia

WAYNE D. ERSKINE & M. J. SAYNOR
School of Geography, University of New South Wales, Sydney, New South Wales 2052, Australia

Abstract Catastrophic floods are defined as events with a flood peak discharge at least 10 times greater than the mean annual flood. They occur more frequently on rivers with high flood variability because of the steep flood frequency curves. Detailed investigations of three catastrophic floods on rivers with differing flood variability in southeastern Australia showed that such events generate between 11 and 283 times the mean annual sediment yield from channel erosion alone. Much of the eroded sediment is temporarily stored in the channel and/or on the flood plain. The time needed to evacuate the flood-deposited sand from the river bed is directly correlated with flood variability. On rivers with low flood variability, the stored sediment is removed over time periods much shorter than the frequency of the catastrophic flood but on rivers with high variability, the stored sediment is removed over time periods approaching the frequency of the catastrophic flood. In the short term, catastrophic floods can generate **all** of the sediment yield by channel erosion.

INTRODUCTION

McMahon *et al.* (1992) have conclusively demonstrated from their detailed study of comparative global hydrology that the variability of both annual streamflows and flood peak discharges for Australian and southern African rivers is much higher than anywhere else in the world. Flood variability is usually expressed as the standard deviation of the $\log s_{10}$ of the annual maximum series flood frequency curve (Baker, 1977). The terms, Flash Flood Magnitude Index and Index of Variability, have been used by Baker (1977) and McMahon *et al.* (1992), respectively for this measure of flood variability.

The results of McMahon *et al.*'s (1992) analysis of the annual flood series for 931 river gauging stations located throughout the world are summarized in the first three lines of Table 1. Rivers in Australia and southern Africa have Flash Flood Magnitude Indices which are at least twice as large as those in other parts of the world. However, some regions of Australia such as the Hunter Valley in central eastern New South Wales and the Genoa and Cann Rivers in East Gippsland, Victoria exhibit Flash Flood Magnitude Indices which are at least three times as large as those for the rest of the world (Table 1). For geomorphic purposes, large flood variability refers to Flash Flood Magnitude Indices greater than 0.6. Rivers with high flood variability experience large floods relatively frequently because they have such steep flood frequency curves (Baker, 1977; Erskine, 1993, 1994, 1996).

Table 1 Flood variability indices for selected regions (from McMahon *et al.*, 1992; Erskine, 1986, 1993, 1994).

Region	Number of gauging stations	Mean Flash Flood Magnitude Index[a]
World rivers	931	0.28
Australian and southern African rivers	280	0.45
Rest of the world rivers	651	0.21
Hunter Valley, NSW	24	0.65
Genoa and Cann rivers, Victoria	4	0.62
Ovens and King rivers, Victoria	8	0.40

[a]This is the standard deviation of the $\log s_{10}$ of the annual maximum flood series (Baker, 1977).

Catastrophic floods are large perturbations of the magnitude-frequency distribution of flood flows. They must be relatively infrequent events which are large enough to exceed equilibrium thresholds of channel stability (Baker, 1977). For geomorphic purposes, catastrophic floods should be defined solely on the basis of magnitude because flood frequency varies systematically with flood variability. Empirical results (Stevens *et al.*, 1975, 1977; Erskine, 1993, 1994, 1996) indicate that floods with a peak discharge at least ten times greater than the mean annual flood totally destroy the pre-flood channel whereas smaller floods do **not** cause such extensive, long-term geomorphic changes.

Brunsden & Thornes (1979) proposed that catastrophic floods are the major cause of channel changes when the flood-induced effects persist for time periods roughly equivalent to the frequency of occurrence of the event. This can be expressed by their transient form ratio (TFR) which is:

$$\text{TFR} = \text{mean relaxation time/return period} \qquad (1)$$

where mean relaxation time is the time period required for a channel to re-establish its equilibrium form following flood damage (i.e. recovery period), and return period is the average interval of time between floods of at least the specified magnitude as an annual maximum.

When TFR is greater than or equal to 1, the channel is unstable because it is constantly responding to, or recovering from, flood damage. When the TFR is much less than 1, then a steady state condition (Nanson & Erskine, 1988) will exist for most of the time with only local instabilities occurring. Rivers with large Flash Flood Magnitude Indices exhibit TFRs of about 1 (Erskine, 1996).

While many studies have reported the occurrence of catastrophic floods in southeastern Australia and commented on the erosional and depositional flood effects, the significance of such events to long term sediment yields has not been hitherto investigated. Erskine & Saynor (1995) reviewed the available evidence on rates of channel erosion in southeastern Australia and concluded that catastrophic floods were important initiators of channel enlargement and incision at rates which approximately equalled the sediment yield from the whole drainage basin. The purpose of this paper is to examine the effects of catastrophic floods on sediment yields in southeastern

Australia. Sufficient detail exists on the floods of 17-18 June 1949 on Wollombi Brook, 4-6 February 1971 on Genoa River and 3-4 October 1993 on Black Range Creek (Table 2) to address the following three issues:

(a) the amount of sediment generated solely by channel erosion during catastrophic floods;
(b) the ratio of the flood-generated channel erosion to the mean annual sediment yield for the whole basin; and
(c) the TFRs of the three rivers subjected to the above catastrophic floods.

Selected flood and drainage basin characteristics of the three study sites are shown in Table 2.

WOLLOMBI BROOK

Wollombi Brook has a total drainage basin area of 2000 km^2 and is a tributary of the Hunter River in central eastern New South Wales. Flood variability on Wollombi Brook is very high (Table 2). Of all of the Flash Flood Magnitude Indices for individual gauging stations cited by McMahon *et al.* (1992), Wollombi Brook at Warkworth had the highest value. The storm of 17-18 June 1949 produced maximum 24 h rainfalls of between 158 and 508 mm over the basin (Erskine, 1996). Either the flood peak height exceeded the gauge range or the flood totally destroyed the gauges. This is to be expected as floating trees were timed at 5 m s^{-1} at one gauge after the flood had dropped 1 m below the peak (Erskine, 1996). The flood peak discharge in Table 2 was estimated by flood routing and was substantially larger than the mean annual flood. It is the largest flood on Wollombi Brook since European settlement.

The 1949 flood widened the channel by about 100% for 83 continuous km of river where bedrock and cemented terrace sediments laterally confined the channel (Erskine, 1996). From detailed cross sections surveyed before and after the flood combined with photogrammetric analysis of 1940, 1949, 1951 and 1952 vertical air photographs for various reaches of river, it was estimated that 8.28 Mm^3 of sediment were eroded by channel enlargement in the 83 km long reach. Assuming a bulk density of 1.6 t m^{-3}, the eroded volume produces a mass of 13.25 Mt for the whole drainage basin. However, about 4 m of bed aggradation was also recorded on the lower 50 km of river during the 1949 flood. The deposited sediment volume is approximately equal to the eroded sediment volume but the former has a much lower bulk density than the latter.

The total sediment load was estimated for the post-flood period from depth integrated suspended sediment concentrations and from Colby's (1957) method for estimating the unmeasured sediment discharge transported in the zone near the bed below the intake to the suspended sediment sampler. Rating curves were calculated and combined with the flow duration curve using Piest's (1964) method. The calculated specific sediment yield (Table 2) is high by Australian standards (Olive & Rieger, 1986) but expected given the large volume of flood-deposited sand stored in the river bed. The flood-eroded sediment is equivalent to 14 years of mean annual sediment yield.

Despite the overloading of the channel with sand by the 1949 flood, the bed load transport capacity after the flood (calculated using a bed load function) was approximately halved in comparison to the pre-flood condition. Therefore, the channel could not quickly remove the aggraded sand. In the 40 years after the flood, about half of the

Table 2 Selected hydrological and geomorphic characteristics of the three catastrophic floods which have been recorded in southeastern Australia.

River	Drainage basin area (km^2)	Flood	Maximum 24-h rainfall (mm)	Specific peak instantaneous discharge ($m^3\ s^{-1}\ km^{-2}$)	Return period[a] (years on the annual series)	Flood peak discharge/ mean annual flood[a]	Flash Flood Magnitude Index[b]	Specific sediment yield ($t\ km^{-2}\ year^{-1}$)	Channel erosion by specified flood ($t\ km^{-2}$)	Transient form ratio[c]
Wollombi Brook, Hunter Valley, NSW	1848	17-18 June 1949	508	2.51[d]	87	26.9	0.90	299	6624	1.0
Genoa River, East Gippsland, Victoria	837	4-6 February 1971	290	3.15[e]	>100	12.4	0.74	324	>3500	0.5
Black Range Creek, northeastern Victoria	54.4	3-4 October 1993	238.4	6.71	>1000	45.0	0.38	26.0	>7360	0.02

[a]Determined by fitting a log Pearson type-III distribution to the annual maximum flood series by the method of moments after Pilgrim and Doran (1987).
[b]This is the standard deviation of the $\log s_{10}$ of the annual maximum flood series (Baker, 1977).
[c]Brunsden & Thornes (1979) define this as the ratio of the channel recovery time from flood damage to the frequency of occurrence of the causative flood.
[d]At an upstream gauging station, the specific peak instantaneous discharge was 4.14 $m^3\ s^{-1}\ km^{-2}$.
[e]At an upstream gauging station, the specific peak instantaneous discharge was 5.00 $m^3\ s^{-1}\ km^{-2}$.

aggraded sand has been evacuated by bed load transport. This suggests that the residence time of the flood aggraded sand is comparable to the return period of the catastrophic flood. Therefore, the TFR of Wollombi Brook is approximately 1 and the channel is rarely stable or in a steady state condition (Nanson & Erskine, 1988) because it is always responding to, or recovering from, the damage caused by catastrophic floods.

GENOA RIVER

Genoa River has a total drainage basin area of 1950 km^2 and flows into the Pacific Ocean near the New South Wales/Victorian border. This study is confined to the upper 900 km^2 of the basin. Flood variability in East Gippsland is much higher than elsewhere in Victoria (Tables 1 and 2). The storm of 4-6 February 1971 followed a period of wet weather and produced a maximum 72 h rainfall of 363 mm within the basin (Erskine, 1993). The resultant flood was the largest since European settlement and had a peak discharge over ten times greater than the mean annual flood (Table 2). However, the February 1919 flood had only a slightly lower peak height (Erskine, 1993). Nevertheless, the return period of the 1971 flood is in excess of 1:100 years according to the fitted log Pearson type-III distribution (Table 2).

Massive channel widening and flood plain destruction occurred on the Genoa River where there were spatially disjunct pockets of alluvium. At just one of these pockets, Erskine (1993) found that 2.13 Mt of sediment were eroded. From the information contained in Erskine (1992), it has been estimated that the 1971 flood eroded at least 2.93 Mt of channel and flood plain sediment. No information was collected for some tributaries, so the real value is likely to be higher. Furthermore, Erskine (1992, 1993) emphasized that much of the Genoa River is a bedrock gorge which also exhibited localized but unmeasured erosion. About 1.3 Mm^3 of sand was stored in the bed where the channel debouches from a bedrock gorge onto a coastal flood plain (Erskine, 1993).

Chessman (1986), from gulp samples of suspended sediment collected in 1978, 1979 and 1983, determined a suspended sediment yield of 219 000 t $year^{-1}$ or 292 t km^{-2} $year^{-1}$. This sediment yield was estimated by rating curves for a short period of record and has been increased by 11% to allow for the unmeasured sediment load (Table 2). The conversion factor of 11% was calculated for Wollombi Brook above and has been applied here because the Genoa River is also an active sand-bed stream. Table 2 shows that the estimated specific sediment load is high by Australian standards (Olive & Rieger, 1986) but expected given the extensive wildfires which had occurred in the basin (Chessman, 1986). The flood-eroded sediment is equivalent to 11 years of mean annual sediment yield.

Detailed historical photographs and cross section surveys of the Genoa River show that the bed aggrades by up to 4.0 m during catastrophic floods such as 1919 and 1971 and then slowly degrades over the next 50 or so years (Erskine, 1992, 1993). This suggests that the residence time of the flood-aggraded sand is about half the return period of the causative catastrophic flood. Therefore, the TFR of Genoa River is approximately 0.5 and the channel is stable or in a steady state condition (Nanson & Erskine, 1988) for about the same time period as it is responding to, or recovering from, the damage caused by catastrophic floods.

BLACK RANGE CREEK

Black Range Creek has a total drainage basin area of 94 km^2 and is a tributary of the King River in northeastern Victoria. Flood variability in this area is much lower than at the other study sites (Tables 1 and 2). The storm of 3-4 October 1993 produced maximum 24 h rainfalls of between 198 and 238.4 mm over the basin. The maximum rainfall intensity occurred between 2200 h on 3 October 1993 and 0075 h on 4 October 1993 when 78 mm (28.4 mm h^{-1}) were recorded. Return periods for both 12 and 24 h durations greatly exceed 1:100 years. The flood peak discharge at the Edi Upper gauging station was estimated by the slope-area method because the peak height (4.53 m) greatly exceeded both the maximum gauged flow (1.215 m) and the previous maximum recorded flow (2.23 m). Flood frequency analysis was performed on the annual maximum series which **excluded** the 1993 flood because the station had been discontinued 10 years before the flood. The estimated return period is in excess of 1:1000 years; the October 1993 flood is truly an outlier, having a peak discharge an order of magnitude larger than the 1:100 year flood.

The channel responded to the 1993 flood by widening substantially. Comparison of cross sections surveyed in September and October 1991 and February 1994 revealed an increase in bankfull width of between 100 and 500%. The volume of sediment generated by flood erosion was estimated at more than 432 000 m^3. Assuming a bulk density of 1.6 t m^{-3}, the eroded sediment equals 691 200 t. This is a minimum mass because some tributaries were not included in the above calculations due to lack of data. Furthermore, no allowance has been made for any of the debris flows which also occurred in many drainage lines during this flood (Rutherfurd *et al.*, 1994). However, their contribution to the total sediment yield generated by the flood was insignificant (Rutherfurd *et al.*, 1994). The channel erosion estimate in Table 2 has been calculated on a unit area basis for the whole basin but the greatest channel erosion occurred in the upper two-thirds of the basin. Furthermore, some of the eroded sediment was deposited as overbank sediments on sections of the flood plain which were not eroded by the flood. In valley expansions, mean depths of overbank sands across complete flood plain cross sections ranged from 236 to 275 mm but in valley constrictions, mean depths ranged from only 114 to 145 mm. Clearly, a significant proportion of the flood-eroded sediment has gone immediately into storage. On the other hand, post-flood channel bed levels were often similar to pre-flood levels, except where there were significant backwater effects during the flood.

The specific sediment yield in Table 2 was estimated by Wasson's (1994) regression equation which relates mean annual sediment yield to basin area for the Southern Uplands of Australia. The flood-eroded sediment is equivalent to 283 years of mean annual sediment yield.

The 1993 flood destroyed the gravel riffle-sand pool bedforms, replacing them with a flat, featureless sand bed. Immediately after the flood, the channel was often flowing supercritical with plane bed, standing wave and antidune bedforms. Within 12 months of the flood, much of the sand had been evacuated and gravel had started to be spatially segregated into patches often spaced at about five channel widths. This is interpreted as the initiation of pool-riffle development. Channel recovery is much more rapid here than on the other rivers. Extrapolation of post-flood rates of pool-riffle development yields a flood recovery time of about 20 years. If this is correct then the TFR is about 0.02.

Therefore, while the erosional effects of the 1993 flood were truly catastrophic, it appears that the channel will recover rapidly. While such outliers of the flood distribution will always substantially erode the channel, recovery is so rapid that, in the long-term, the channel will exhibit a steady state condition (Nanson & Erskine, 1988) with only occasional instabilities.

DISCUSSION AND CONCLUSIONS

The Flash Flood Magnitude Indices of the three rivers investigated in southeastern Australia vary directly with drainage basin area. For this limited sample, large flood variability is **not** confined to small drainage basins, a result which is also consistent with that of Erskine (1986) for the area near Sydney, Australia and with that of McMahon *et al.* (1992) for Australia as a whole.

The specific sediment yields listed in Table 2 have been calculated by different methods, for different time periods and for different basin areas. As a result, they are not directly comparable. Furthermore, the use of rating curves on Wollombi Brook and Genoa River is known to be inaccurate but generally underestimates sediment loads (Olive & Rieger, 1987). Given the relatively large basin areas of Wollombi Brook and Genoa River, it is likely that the error calculations of Olive & Rieger (1987) do not apply here, despite their study sites being located within the Genoa River basin.

The three catastrophic floods investigated in southeastern Australia had peak discharges between 2.51 and 6.71 $m^3\ s^{-1}\ km^{-2}$ which were between 12.4 and 45.0 times greater than the mean annual flood. Channel response to these floods always included massive widening which supplied between 3500 and 7360 t km^{-2} of sediment. These flood-generated in-channel sediment yields varied between 11 and 283 times greater than the mean annual sediment yields. However, much of the eroded sediment was temporarily stored in the river bed and/or on the flood plain. Where the river bed was a significant store (i.e. Wollombi Brook and Genoa River), the residence time of the flood-aggraded sand was much longer than the above ratios of flood-eroded sediment to the mean annual sediment yield because of upstream sediment supply. Where the flood plain was a significant store (i.e. Black Range Creek), the residence time was much shorter than the ratio of flood-eroded sediment to the mean annual sediment yield. The time needed to evacuate the flood-deposited sediment varies in relation to the frequency of the catastrophic flood. On rivers with high flood variability (i.e. Flash Flood Magnitude Indices > 0.6), catastrophic floods occur so frequently that the channel is rarely stable. The TFR of rivers with high flood variability is greater than or equal to 0.5 whereas the TFR of rivers with low flood variability is less than 0.1. Catastrophic floods are only important to **long term** sediment yields on flood variable rivers. However in the short term, catastrophic floods can generate **all** of the sediment yield by the massive reworking of channel and flood plain sediment stores.

Acknowledgements This work was supported by the Australian Research Council, the Department of Conservation and Natural Resources, Victoria and the East Gippsland River Management Board. For their assistance with various aspects of this work, we thank J. J. Sherrard, M. D. Melville, J. W. Tilleard, C. Peacock, C. Wassink, J.

Bridle, I. N. Drummond, W. Thomas, N. Rankin, J. Mulligan, J. Oates, R. Allen, R. Candy, I. Stringer and A. Piesley.

REFERENCES

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

Brunsden, D. & Thornes, J. B. (1979) Landscape sensitivity and change. *Trans. Inst. Brit. Geogr.* New Series **4**, 463-484.

Chessman, B. C. (1986) Impact of the 1983 wildfires on river water quality in East Gippsland, Victoria. *Austral. J. Mar. Freshwat. Res.* **37**, 399-420.

Colby, B. R. (1957) Relationship of unmeasured sediment discharge to mean velocity. *Trans. AGU* **38**, 708-717.

Erskine, W. D. (1986) River metamorphosis and environmental change in the Macdonald Valley, New South Wales since 1949. *Austral. Geogr. Studies* **24**, 88-107.

Erskine, W. D. (1992) *An Investigation of Sediment Sources in the Genoa River Catchment.* East Gippsland River Management Board, Mallacoota.

Erskine, W. D. (1993) Erosion and deposition produced by a catastrophic flood on the Genoa River, Victoria. *Austral. J. Soil Wat. Conserv.* **6**(4), 35-43.

Erskine, W. D. (1994) Sand slugs generated by catastrophic floods on the Goulburn River, New South Wales. In: *Variability in Stream Erosion and Sediment Transport* (ed. by L. J. Olive, R. J. Loughran & J. A. Kesby) (Proc. Canberra Symp., December 1994), 143-151. IAHS Publ. no. 224.

Erskine, W. D. (1996) Response and recovery of a sand-bed stream to a catastrophic flood. *Z. Geomorphol.* in press.

Erskine, W. D. & Saynor, M. J. (1995) *The Influence of Waterway Management on Water Quality with Particular Reference to Suspended Solids, Phosphorus and Nitrogen.* Dept of Conservation and Natural Resources, Victoria, East Melbourne.

McMahon, T. A., Finlayson, B. L., Haines, A. T. & Srikanthan, R. (1992) *Global Runoff.* Catena Paperback.

Nanson, G. C. & Erskine, W. D. (1988) Episodic changes of channels and floodplains on coastal rivers in New South Wales. In: *Fluvial Geomorphology of Australia* (ed. by R. F. Warner), 201-221. Academic Press, Sydney.

Olive, L. J. & Rieger, W. A. (1986) Low Australian sediment yields – a question of inefficient sediment delivery? In: *Drainage Basin Sediment Delivery* (ed. by R. F. Hadley) (Proc. Albuquerque Symp., August 1986), 477-482. IAHS Publ. no. 159.

Olive, L. J. & Rieger, W. A. (1987) *Eden Catchment Project: Sediment Transport and Catchment Disturbance 1977-1983.* Monograph Series no. 1, Dept of Geography & Oceanography, Univ. College, Univ. of NSW, Austral. Defence Force Academy, Canberra.

Piest, R. F. (1964) Long term sediment yields from small watersheds. In: *Land Erosion, Precipitations, Hydrometry, Soil Moisture* (Proc. Berkeley Symp., August 1963), 121-140. IASH Publ. no. 65.

Pilgrim, D. H. & Doran, D. G. (1987) Flood frequency analysis. In: *Australian Rainfall and Runoff* (ed. by D. H. Pilgrim), vol. 1, 195-236. Inst. Engrs Austral., Barton.

Rutherfurd, I. D., Bishop, P. & Loffler, T. (1994) Debris flows in northeastern Victoria, Australia: occurrence and effects on the fluvial system. In: *Variability in Stream Erosion and Sediment Transport* (ed. by L. J. Olive, R. J. Loughran & J. A. Kesby) (Proc. Canberra Symp., December 1994), 359-369. IAHS Publ. no. 224.

Stevens, M. A., Simons, D. B. & Richardson, E. V. (1975) Nonequilibrium river form. *J. Hydraul. Div. ASCE* **101**, 557-566.

Stevens, M. A., Simons, D. B. & Richardson, E. V. (1977) Closure – nonequilibrium river form. *J. Hydraul. Div. ASCE* **103**, 197-198.

Wasson, R. (1994) Annual and decadal variation of sediment yield in Australia, and some global comparisons. In: *Variability in Stream Erosion and Sediment Transport* (ed. by L. J. Olive, R. J. Loughran & J. A. Kesby) (Proc. Canberra Symp., December 1994), 269-279. IAHS Publ. no. 224.