Variability in Stream Erosion and Sediment Transport (Proceedings of the Canberra Symposium, December 1994). IAHS Publ. no. 224, 1994.

Sand slugs generated by catastrophic floods on the Goulburn River, New South Wales

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Abstract The Goulburn River in New South Wales is characterized by a very steep annual series flood frequency curve and hence has high flood variability. Therefore, catastrophic floods, which are defined as floods with a peak discharge at least 10 times greater than the mean annual flood, occur more frequently than in other hydrologic areas. The floods of 1955, 1971 and 1977 were the three largest events this century and had peak discharges between 12.9 and 43.4 times greater than the mean annual flood. Each of these floods produced a significant sand slug or bed load wave. These slugs resulted in up to 2.1 m of bed aggradation and were rapidly reworked over a period of a few years, returning bed levels to their pre-flood position. The source of the sand was massive erosion of in-channel benches and the high flood plain. Reworking of the sand slug by subsequent smaller events rapidly excavated a small channel in the overwide flood bed and deposited sand and finer sediment on top of a sand and gravel nucleus as a bench.

INTRODUCTION

Wolman & Miller (1960) made a clear distinction between the relative amount of work done by different sized events (for example, sediment transport) and their relative importance in forming the landscape. It is the latter aspect which is addressed here. Pickup & Warner (1976) found that the small channels to the west of Sydney, New South Wales were formed by two groups of dominant discharges. Channel capacity was related to large, floods which were competent to erode the banks and to destroy and reconstruct the flood plain. On the other hand, the bed was shaped by small floods which transported the most bed load over time. Erskine & Melville (1983) documented a divergence of river response to large and moderate floods on the Macdonald River, New South Wales. In particular, large floods caused massive bank erosion which overloaded the channel with sand, resulting in significant aggradation. Subsequent smaller floods reworked the sand temporarily stored in the bed, producing rapid degradation and hence channel recovery. Alternating bed aggradation and degradation represent a sand slug or bed load wave.

The purpose of this paper is to determine the response and recovery of the Goulburn River, New South Wales, to catastrophic floods. Erskine (1986) found that the Goulburn River is characterized by high flood variability and, therefore, catastrophic floods occur more frequently than on rivers with low flood variability, such as those investigated by Wolman & Miller (1960). McMahon *et al.* (1992) found that many Australian rivers, including the Goulburn River, had high flood variability by world standards.

STUDY AREA

The Goulburn River is a large drainage basin (8200 km^2) in the Hunter Valley, New South Wales (Fig. 1). The channel has incized through Triassic sandstones into the underlying, softer Permian sedimentary rocks, forming a relatively wide valley. However, the channel still frequently impinges against the bedrock valley walls. A series of benches are common below a high flood plain. Channel capacity at the high flood plain level corresponds to a flood return period in excess of 20 years on the annual series at most gauging stations. The present study concentrates on the sites at Coggan, Kerrabee, Sandy Hollow and Martindale (Fig. 1) where bed slopes vary between 0.78 and 1.2 m km^{-1} and where the mean bed material size varies between 37 and 0.49 mm.

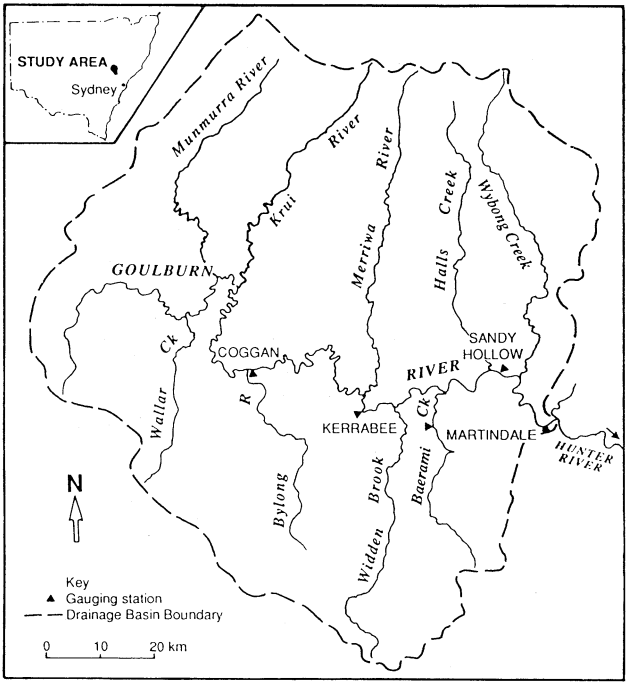

Fig. 1 Goulburn River drainage basin showing the location of the four study sites.

FLOOD HISTORY

The three longest running gauging stations in the Goulburn River basin are listed in Table 1 along with the three largest recorded floods. The February 1955 flood is the largest since European settlement and the 1971 and 1977 floods are the second and third largest floods, respectively since at least 1913. The return period of each flood at each station was determined by fitting a log Pearson Type III distribution to the annual maximum flood series. Figure 2 shows the flood frequency curves for each station and demonstrates that a log Pearson type III distribution is a good fit to the observed data. The confidence limits were not extended below a return period of 5 years because this study is concerned solely with large floods.

Table 1 Selected hydrological characteristics of the 1955, 1971 and 1977 floods at the three longest running gauging stations on the Goulburn River.

	1955 Flood			1971 Flood			1977 Flood		
Gauging Station	Peak Instantaneous Discharge (m^3s^{-1})	Return Period (years on the annual series)	Peak Discharge Mean Annual Flood	Peak Instantaneous Discharge (m^3s^{-1})	Return Period (years on the annual series)	Peak Discharge/ Mean Annual Flood	Peak Instantaneous Discharge (m^3s^{-1})	Return Period (years on the annual series)	Peak Discharge/ Mean Annual Flood
Goulburn River at Coggan	3970	53	39.8	2558	31	25.6	1759	19	17.6
Goulburn River at Kerrabee	6713	130	43.4	3414	36	22.1	3032	17	12.9
Goulburn River at Sandy Hollow	6343	40	33.2	3542	20	18.5	2801	15	14.7

Return periods of the 1955, 1971 and 1977 floods at each station as well as the ratio of the peak flood discharge to the mean annual flood are also listed in Table 1. Although the three floods are rare events (return periods vary between 15 and 130 years), they are certainly not outliers (outliers are data points which depart significantly from the trend of the balance of the data). Despite this, all events are very large relative to the mean annual flood. As noted by Baker (1977), such events often produce a catastrophic channel response because they greatly exceed the usual flood experience of the river (see Erskine (1993) also). Abrahams & Cull (1979) noted that, for geomorphic purposes, a catastrophic flood should be defined solely in terms of magnitude. They suggested that a catastrophic flood could be arbitrarily defined as one with a peak discharge equal to or greater than four times the discharge of the mean annual flood. However, other studies have found that a ratio of at least 10 is more appropriate (Erskine, 1993; 1994). Even if the higher ratio of 10 is adopted, catastrophic floods have been recorded relatively frequently in the Goulburn River basin. Rivers with a high Flash Flood Magnitude Index (Baker, 1977) exhibit steep flood frequency curves and, therefore, have a greater probability of experiencing catastrophic floods than rivers with relatively flat flood frequency curves. As the Goulburn River has a high Flash Flood Magnitude Index (>0.7), catastrophic floods should be important for channel development.

SAND SLUGS GENERATED BY CATASTROPHIC FLOODS

The impact of large floods on the Goulburn River has been assessed from vertical air photographs, survey plans, gauging records, field surveys and bench stratigraphy. A detailed record of bed level changes has been obtained for the Sandy Hollow gauging station from variations over time in cease-to-flow height or bed level (Fig. 3(c)). Kerrabee and Coggan could not be used for this analysis because of either numerous and poorly documented changes in gauge locations or missing records. Figure 3(a), (b) and (c) illustrates the temporal correlation between large floods and substantial aggradation. However, the aggradation was short-lived because of subsequent rapid degradation.

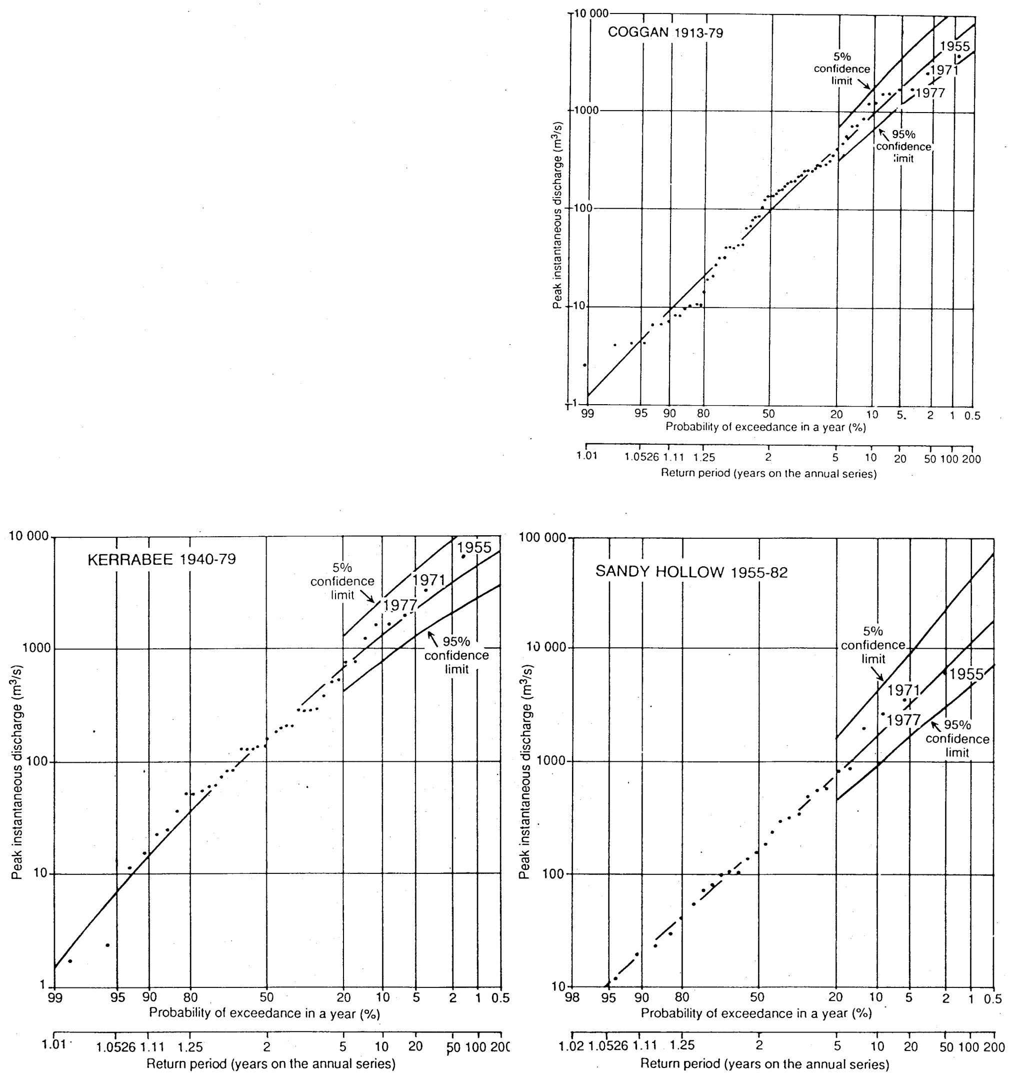

Fig. 2 Annual series flood frequency curves at the three longest running gauging stations on the Goulburn River.

These rapid increases in bed level followed by slower decreases, produce a sand slug or bed load wave. The residence time of the sand is an order of magnitude shorter than the frequency of the causative event because sand supply is an episodic process dependent on catastrophic floods and because the Goulburn River is an efficient transporter of sand (Erskine *et al.*, 1985).

A series of cross sections surveyed at three sites on the Goulburn River not only support the above changes in bed level but also provide evidence of other channel changes (Fig. 3(a), (b) and (d)). The 1955 flood widened the channel at the old Sandy Hollow bridge site by destroying the benches on the right bank. Aggradation has been caused by the overloading of the channel with sand derived from channel enlargement. Continued aggradation occurred for at least 8 months after the 1955 flood. By 1980

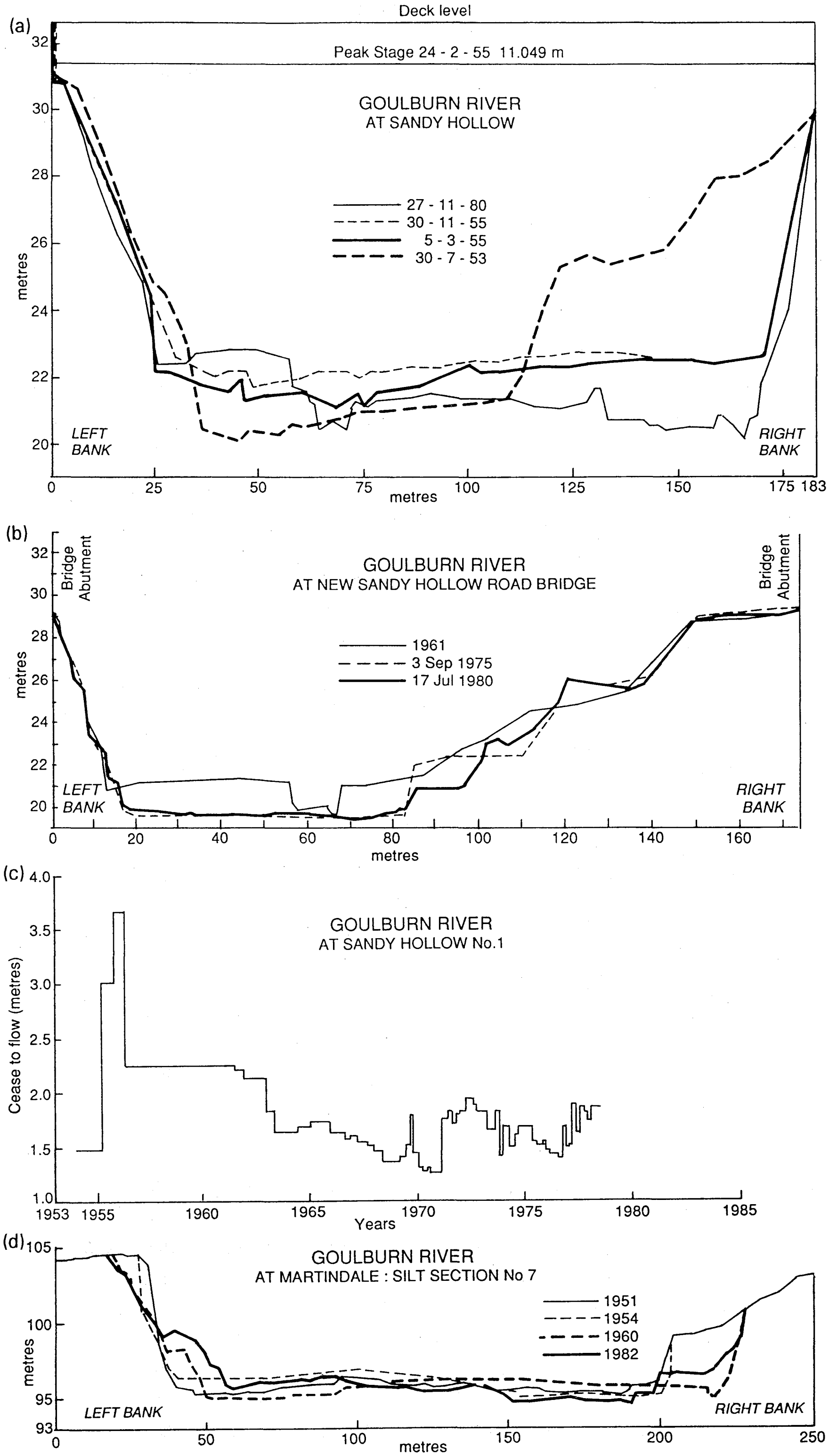

Fig. 3 (a) Cross-sectional changes at Sandy Hollow Gauge No. 1; (b) cross-sectional changes at New Sandy Hollow Road Bridge; (c) bed level changes at Sandy Hollow Gauge No. 1; and (d) cross-sectional changes at Martindale.

substantial degradation had taken place and a low bench had been constructed on the left bank. At the new Sandy Hollow bridge site, over 1 m of degradation occurred between 1961 and 1975 but no further degradation was recorded up to 1980. At least one tributary, Baerami Creek behaved in-phase with the Goulburn River. The Goulburn River at Martindale was extensively widened by bank erosion and bench destruction during the 1955 flood. Channel recovery by bench construction at the base of the high banks is now well advanced (Fig. 3(d)). Surprisingly, the channel at Martindale did not aggrade during the 1955 flood, despite being substantially enlarged.

SEDIMENT SOURCES

The cross-sectional evidence suggests that bank erosion and bench destruction are the dominant sediment source of the sand slug. This hypothesis was investigated by comparing a number of channel reaches before and after catastrophic floods. Figure 4(d) shows the massive widening of the Goulburn River at Martindale by the 1955 flood. In 1946, the sand-bed channel was very narrow and was flanked by continuous, vegetated benches. These benches were entirely destroyed in February 1955 and replaced by a large sand-floored trench. Furthermore, the banks up to the high flood plain were also subjected to massive but localized erosion. Figure 4(c) shows the location of the concave bank of the Goulburn River at Dunroven, near Sandy Hollow in 1930 and 1980. Approximately 1.8 million m^3 of sediment were eroded, resulting in the re-routing of the original railway line. Information supplied by the State Rail Authority and Department of Water Resources indicates that most of this erosion occurred during the 1955 flood. Department of Water Resources, in an unpublished study of 15 km of the Goulburn River between Wybong Creek and Martindale (Fig. 1), found that the benchfull channel was widened from 60 m to up to 300 m by the 1955 flood. Approximately 1.1 million m^3 of sediment were eroded from benches and a further 4.3 million m^3 of sediment were eroded from the high flood plain. If it is assumed that none of this sediment was transported out of the reach then the channel bed would have aggraded by 3.5 m (calculated using the post-1955 mean channel width of 100 m). This value is only 33% greater than the observed increase in bed levels at Sandy Hollow (Fig. 3(a) and (c)). The discrepancy between the two values can be accounted for by the transportation of some of the eroded sediment out of the reach and by the presence of some channel sections which are wider than 100 m.

Channel enlargement by bench destruction during the 1955 flood was not restricted to just the lower Goulburn River. Figure 4(a) and (b) shows that the middle reaches at Coggan and Kerrabee were also widened but not to the same extent as at Sandy Hollow and Martindale. River gauging data indicate that the river bed at Coggan and Kerrabee frequently alternates between sand and gravel. The gravel appears to form a relatively stable substrate which is episodically buried by sand slugs after catastrophic floods. Department of Water Resources' photographs show that the 1977 flood at Kerrabee converted the channel to a sand bed stream. By 1980, this sand had been entirely transported past the gauge, re-exposing the underlying gravel.

Floods exceeding the high flood plain of the Goulburn River are very large events which mobilize the channel boundary sediments and remove all obstructions, thus maintaining a large capacity channel. During these events, in-channel benches are destroyed and the high flood plain is subjected to large scale but localized erosion. The

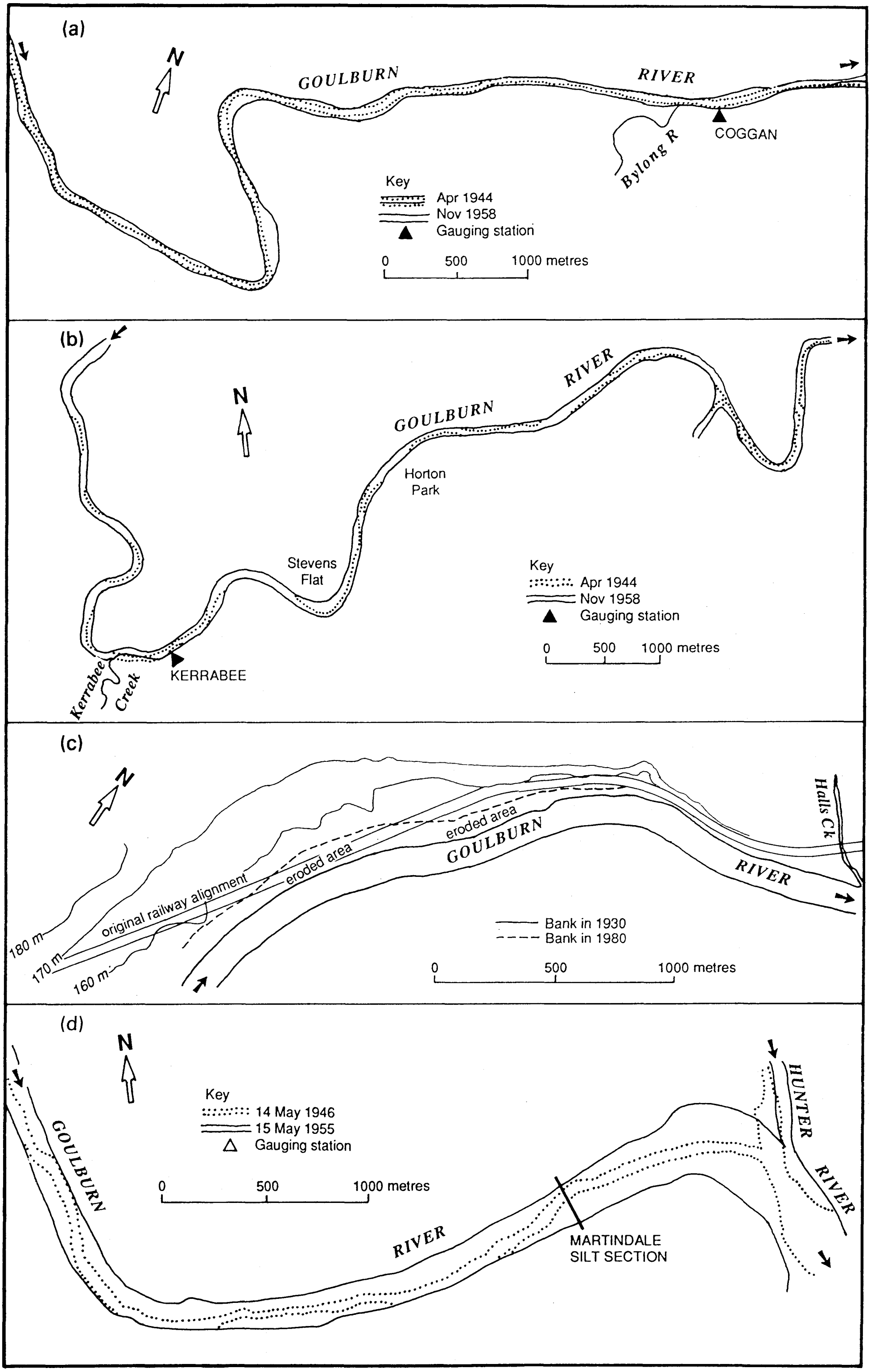

Fig. 4 Channel widening caused by the 1955 flood at: (a) Coggan, (b) Kerrabee, (c) Sandy Hollow, and (d) Martindale.

river becomes overloaded with sand, resulting in aggradation and the formation of a bed load wave. Sand is only supplied to the Goulburn River in appreciable quantities during large "bankfull" floods because these are the only events to exceed the resistance threshold of the channel boundary. Small to moderate floods after the large event are not high enough to modify the high flood plain but transport the flood-deposited sediment. Rapid degradation occurs because bed-material supply is an episodic process contingent upon infrequent "bankfull" floods and eventually produces either an armoured bed or a narrow post-flood sand-bed channel. This degradation only affects a relatively small part of the enlarged flood channel bed, leaving the higher sections as potential nuclei for later bench formation. As continued incision produces a better defined low flow channel, progressive deposition on the higher stranded sections of the flood channel bed leads to bench development.

BENCH STRATIGRAPHY

The stratigraphy of in-channel bench sediments at Coggan, Kerrabee and Sandy Hollow shows two distinct facies. The coarse facies is composed of sand and gravel strata similar in grain size to the bed material in the adjoining channel, whereas the fine facies is composed of fine sand, sandy loam and, in the higher benches, finer-textured sediments up to clay loam. The former corresponds to the bench nucleus whereas the latter corresponds to in-channel deposition by small to moderate floods after the catastrophic event. Although Woodyer (1968) maintained that benches are stable, comparison of individual bench levels at the Kerrabee gauge since 1966 shows variations of up to 2.4 m in 8 years. This is *not* indicative of a stable landform and represents episodic bench destruction and reformation.

CHANNEL-FORMING DISCHARGES

Two ranges of flow are effective in determining different aspects of channel form on the Goulburn River. Catastrophic events are mainly destructive agents, demolishing benches and eroding the banks of the high flood plain, thus maintaining an enlarged channel. Subsequent small and moderate floods are both constructional and destructional agents. Continuous degradation after the catastrophic flood, partly removes the flood-deposited sediment and in-channel deposition on the remnants of the flood-channel bed leads to bench formation. In short, channel capacity is determined by catastrophic floods whereas the form of the bed of the enlarged flood channel is controlled by smaller events. Pickup & Warner (1976) came to essentially the same conclusion from different evidence for small gravel bed streams near Sydney.

The effectiveness of catastrophic floods on the Goulburn River to maintain a large capacity channel suggests that they should be called "superfloods" (Schick, 1974). These superfloods destroy in-channel benches in the same way that Schick (1974) proposed that their arid counterparts would destroy terraces. Benches are recovery landforms constructed by small to moderate floods within the enlarged channel cleaned out by the superflood.

Acknowledgements For their assistance with various aspects of this work, sincere thanks are extended to Dr M. D. Melville, Dr R. J. Loughran, D. O. Erskine, B. Smart, M. Eather, D. Yeates, E. Hatfield, G. Adamson, J. Gardiner, D. Carcary, P. Collins and R. Hilder.

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