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Contemporary versus long-term denudation along a passive plate margin: the role of extreme events

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Abstract

Short-term (contemporary) and long-term denudation rates were determined for the Blue Mountains Plateau in the western Sydney Basin, Australia, to explore the role of extreme events (wildfires and catastrophic floods) in landscape denudation along a passive plate margin. Contemporary denudation rates were reconstructed using 40 years of river sediment load data from the Nattai catchment in the south-west of the basin, combined with an analysis of hillslope erosion following recent wildfires. Long-term denudation rates (10 kyr–10 Myr) were determined from terrestrial cosmogenic nuclides, apatite fission track thermochronology and post-basalt flow valley incision. Contemporary denudation rates average several times lower than the long-term average (5·5 ± 4 mm kyr^{-1} versus 21·5 ± 7 mm kyr^{-1}). Erosion of sediment following wildfires accounts for only a small proportion (5%) of the contemporary rate. Most post-fire sediment is stored on the lower slopes and valley floor, with the amount transported to the river network dependent on rainfall–run-off conditions within the first few years following the fire. Historical catastrophic floods account for a much larger proportion (35%) of the contemporary erosion rate, and highlight the importance of these events in reworking stored material. Evidence for palaeofloods much larger than those experienced over the past 200 years suggests even greater sediment export potential. Mass movement on hillslopes along valleys incised into softer lithology appears to be a dominant erosion process that supplies substantial volumes of material to the valley floor. It is possible that a combination of infrequent mass movement events and high fluvial discharge could account for a significant proportion of the discrepancy between the contemporary and long-term denudation rates.

Keywords: extreme events; denudation; wildfire; cosmogenic nuclides; Sydney Basin

Introduction

Recent studies have compared long-term denudation rates (10 kyr–10 Myr) determined from cosmogenic nuclides and apatite fission track thermochronology (AFTT), with contemporary rates (1–100 yr) calculated from stream gauging, sediment rating curves and sediment trapping (see, e.g., von Blanckenburg, 2005). Whilst some studies have observed similar short-term and long-term rates of denudation indicating steady state erosion (Bierman and Caffee, 2001; Matmon *et al.*, 2003; Nichols *et al.*, 2005), many have found either elevated contemporary rates attributable to human impact and land use change (Hewawasam *et al.*, 2003; Gellis *et al.*, 2004), or lower rates thought to be explained by the absence of high-magnitude, low-frequency (extreme) events in records that span only decades (Kirchner *et al.*, 2001; Schaller *et al.*, 2001). To substantiate the former, paired catchment type investigations have been conducted using undisturbed environments to give reasonable estimates of natural contemporary rates (Brown *et al.*, 1998; von

Blanckenburg *et al.*, 2004). For the latter, determination of sediment yields from hypothetical extreme events has proved to be more problematic and, as a result, so has extrapolation of these contemporary records to long-term landscape evolution.

In a study of denudation rates from the Rocky Mountains in Idaho, USA, Kirchner *et al.* (2001) found that modern sediment yields measured over 10–84 years from stream gauging and sediment trapping were on average 17 times lower than the long-term sediment yield. They concluded that the mismatch in rates was the result of sediment delivery being dominated by extreme erosional events triggered by external forces such as severe storms and wildfires, which occur at time intervals greater than the length of the modern record. In south-eastern Australia, weather extremes including drought, floods and wildfires are a dominant characteristic of the landscape. Very low rates of contemporary denudation have been reported (Bishop, 1984; Wasson, 1994; Wasson *et al.*, 1996), despite significant increases as a result of European settlement and land use change (Wasson, 1994). However, it is possible that these short-term records have not captured extreme events. In this paper, we compare long-term denudation rates derived from terrestrial cosmogenic nuclides, AFTT and other measures with contemporary rates determined from stream gauging, to establish the denudational regime that applies to the Sydney region. We then analyse the flood and wildfire records to quantify the sediment yield arising from relatively high-magnitude erosional events that have occurred over the past few decades.

Study Area

The focus of this study is the Nattai River catchment, located on the Blue Mountains Plateau on the western margin of the Sydney Basin, south-eastern Australia (34° 13′S, 150° 20′E) (Figures 1 and 2). The Nattai River is a major tributary of the Wollondilly River, which drains into the reservoir of Lake Burragorang, Sydney's principal water supply. Consequently, the lower reaches of the Nattai River are flooded and most of the catchment (c. 70%) is protected as Water Supply Special Area, National Park or wilderness (Greater Blue Mountains World Heritage Area). Gully erosion in the catchment is negligible (Dyson, 1965). Several small rural townships and grazing properties established around the late 1800s with an estimated total current population of less than 7000 are situated on the plateau close to the catchment divide. Prior to construction of Warragamba Dam (1950s–1960), small scale pastoral activity and coal extraction occurred along the lower reaches of the Nattai River. These lands were reclaimed in the 1940s and the vegetation allowed to regenerate. Hence, the extent of human impact on contemporary sediment yield is likely to be minimal.

The Nattai River forms a steep, incised valley (catchment area, 701 km^2; maximum relief, 528 m) set within a Triassic sandstone plateau (Figure 3). The valley floor and lower slopes are cut into softer Permian shales, siltstones and sandstones, and are mantled by colluvial deposits, resulting from mass movement of sediment in the form of debris flows and landslides (Tomkins *et al.*, 2004b). The bed of the lower section of the Nattai River is filled with coarse sandy sediment resulting from reworking of colluvial material (present prior to reservoir filling). The Nattai is typical of other valleys in the Blue Mountains Plateau, which are thought to have incised in response to uplift along the Lapstone Structural Complex (LSC) following rifting of the Tasman Sea in the Late Cretaceous (Branagan and Pedram, 1990; van der Beek *et al.*, 2001).

Average annual rainfall in the Nattai catchment is around 850 mm based on data from eight rainfall gauges (Figure 2), with records commencing as early as 1902. Vegetation is dominated by open *Eucalyptus* forest, which grades into tall open forest in the moister, sheltered valleys and woodland on drier, west-facing slopes (Fisher *et al.*, 1995). The catchment has a history of severe wildfires as well as management-related controlled burns. The two most recent wildfires, which burnt over 50 per cent of the catchment, occurred in November–December 1968 and December 2001–January 2002 (Sydney Catchment Authority, unpublished data). Smaller wildfires affecting part of the plateau forming the western catchment divide occurred in February 1965 and November 1997 (Sydney Catchment Authority, unpublished data).

Determination of Long-term Denudation Rates

Terrestrial cosmogenic nuclide (TCN) data were obtained from the Blue Mountains Plateau near Lithgow (Figure 1), adjacent to where soil production rates have been inferred using TCNs (Wilkinson *et al.*, 2005). Average denudation rates from two catchments were derived from stream sediments collected from a first order tributary (Marra Creek; <1 km^2) and trunk stream (Marrangaroo Creek; 13 km^2) (Table I). Sample targets of ^{10}Be and ^{26}Al were prepared using a modified version of the standard procedures described by Child *et al.* (2000). TCN abundance was determined using

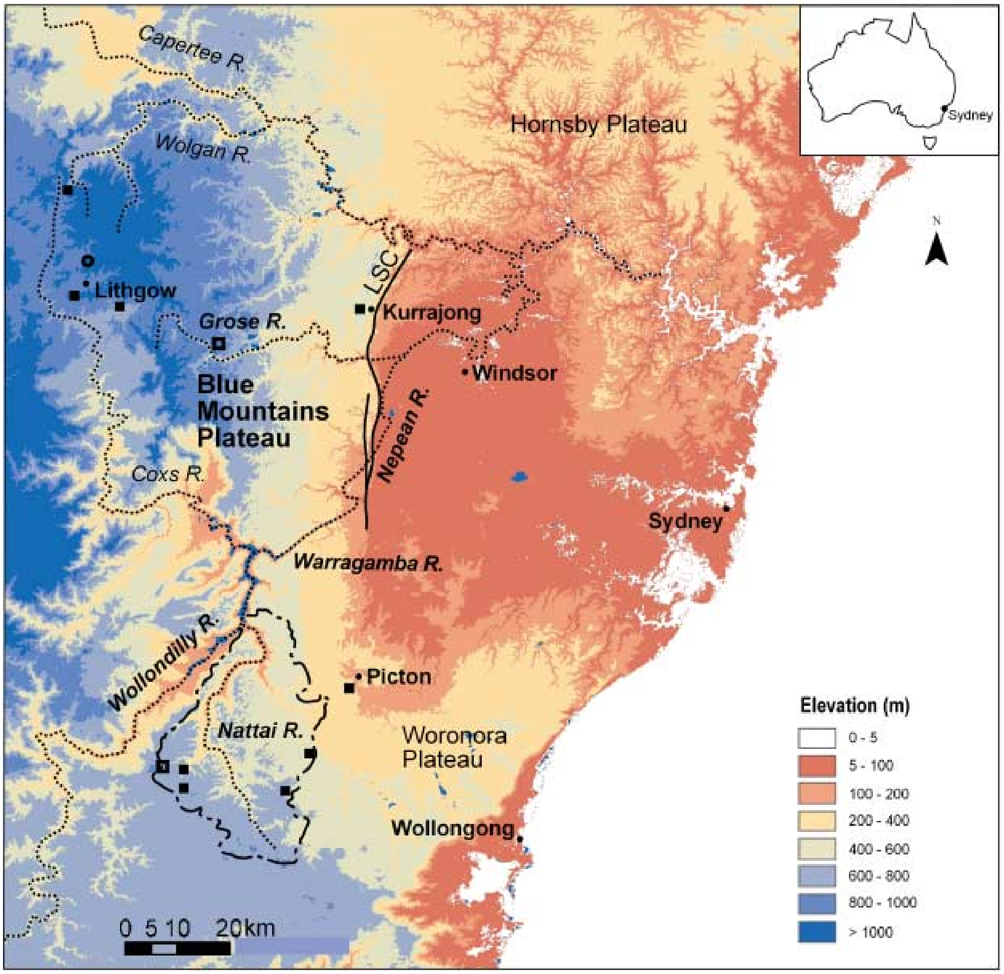

Figure 1. Incised valleys of the Blue Mountains Plateau, located on the western margin of the Sydney Basin, south-eastern Australia. The Nattai River, a tributary of the Wollondilly River, drains the southern part of the plateau. Approximate locations of AFTT (closed square), TCN (open circle) and post-basalt flow (open square) data used to determine the long-term denudation rate for the Blue Mountains Plateau are shown. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Table I. Erosion rates for the Blue Mountains Plateau calculated from terrestrial cosmogenic nuclides in stream sediment north of Lithgow

Sample	Location[a]	Alt. (m)	P_0 (atoms g^{-1} yr^{-1})	Nuclide conc. ± σ (10^6 atoms g^{-1})	Max. erosion rate ± σ (mm kyr^{-1})
BM-21	Marrangaroo Ck	1100	9·75	0·34 ± 0·01 (^{10}Be)	16·3 ± 0·7
			59·43	2·17 ± 0·24 (^{26}Al)	15·1 ± 1·9
BM-23	Marra Ck	1065	9·75	0·25 ± 0·01 (^{10}Be)	20·9 ± 0·9
			59·43	1·79 ± 0·38 (^{26}Al)	17·4 ± 4·9

[a] North of Lithgow, 33° 25′S, 150° 10′E.

the Australian National Tandem Accelerator for Applied Research (ANTARES) (Fink *et al.*, 2004). Erosion rates were calculated using the TCN production rates and scaling of Stone (2000) based on catchment altitudinal ranges of 130–190 m. Shielding by steep spur side slopes was included in calculations along with corrections for sample thickness (Nishiizumi *et al.*, 1989, 1991).

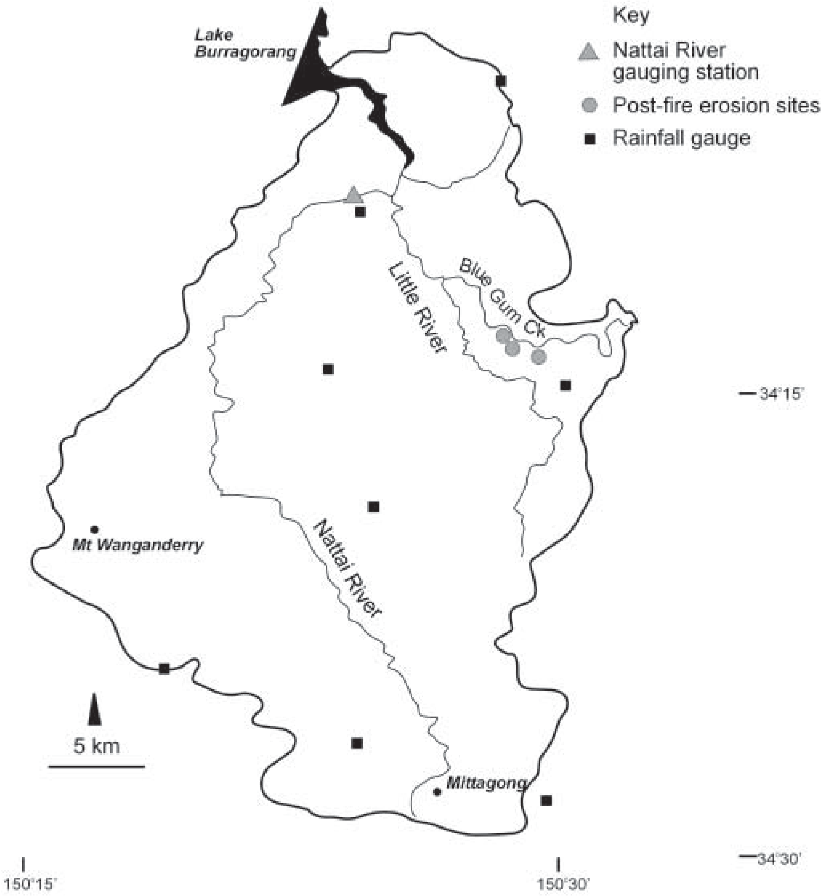

Figure 2. Nattai catchment, showing the location of flow and rainfall gauges used in this study and the location of the post-fire erosion sites at Blue Gum Creek.

Figure 3. Nattai River valley incised within the Blue Mountains Plateau, showing the steep cliff-lined rim and colluvial deposits on the lower slopes and valley floor. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Table II. Additional data used to determine the average long-term denudation rate for the Blue Mountains Plateau

Location (author)[a]	Method[b]	Timeframe/age (Ma)	Denudation (km)	Ave. denudation rate (mm kyr^{-1})
North of Lithgow (1)	AFTT	73·1	2	27·4
Nattai catchment area (2)	AFTT	74	2	27·0
Nattai catchment area (2)	AFTT	82	2	24·4
Nattai catchment area (2)	AFTT	127	1·5–2	13·8
Nattai catchment area (2)	AFTT	60	1·5–2	29·2
Picton area (2)	AFTT	107	1·5–2	16·4
Kurrajong area (2)	AFTT	88	1·5–2	19·9
East of Lithgow (2)	AFTT	100	2	20·0
Lithgow (2)	AFTT	93	2	21·5
Kurrajong Heights (3)	SVR	70	0·88	12·6
Grose R catchment (4)	P-BPL	15	<0·2	14
Grose R catchment (4)	P-BVI	15	≤0·7	40
Nattai catchment (this paper)	P-BVI	34	≤0·64	18·8

[a] Data sourced from O'Sullivan *et al.*, 1995 (1); O'Sullivan *et al.*, 1996 (2); Middleton and Schmidt, 1982 (3), and van der Beek *et al.*, 2001 (4).

[b] AFTT, apatite fission track thermochronology; SVR, surface vitrinite reflectance; P-BPL, post-basalt plateau lowering; P-BVI, post-basalt valley incision.

Apatite fission track data for the Blue Mountains Plateau were obtained from published work by O'Sullivan *et al.* (1995, 1996) (Table II). This included four samples that appear to have been collected from the Nattai catchment (O'Sullivan *et al.*, 1996) although coordinates are not provided, so we are unable to confirm this. An additional datum for the Blue Mountains Plateau was obtained from Middleton and Schmidt (1982) (Table II), who report Myr timescale denudation rates using surface vitrinite reflectance of coals.

Rates of plateau lowering and valley incision below valley-filling basalt flows preserved on the Blue Mountains Plateau were also included to provide additional age control on long-term denudation (Table II). Data were obtained from van der Beek *et al.* (2001), who calculated maximum rates of plateau lowering and valley incision below Miocene basalts in the Grose River valley, 53 km north of the Nattai catchment (Figure 1). An additional datum point was calculated using river incision below a previously dated (Wellman and McDougall, 1974) Oligocene basalt (Mt Wanganderry) located on the plateau forming the drainage divide between the Wollondilly and Nattai Rivers (see Figure 2).

The averages of the long-term (10^4–10^8 years) denudation rates derived from the AFTT, TCN and post-basalt flow data are shown in Figure 4. All three are in agreement within one sigma, suggesting that over the kyr–Myr timescales surface landscape erosion and lowering are occurring at similar rates. Hence, we conclude that a reasonable estimate of the long-term denudation rate for the Blue Mountains Plateau on the western margin of the Sydney Basin is 21·5 ± 7 mm kyr^{-1}.

Calculation of Contemporary Denudation Rates

Contemporary denudation rates were determined from sediment load data calculated using suspended sediment concentration (SSC), turbidity and hourly instantaneous discharge recorded at a gauging station in the lower part of the Nattai River (catchment area, 446 km^2), but above any influence of flooding by Lake Burragorang (Figure 2). The discharge record commenced in July 1965, giving 40 years of record, following construction of the water supply reservoir, and has very few data gaps owing to the importance of this information to local water authorities. Turbidity and SSC records commenced in January 1961 and 1991 respectively, but the sampling interval for both is uneven, ranging from hourly to monthly (automated and grab samples), which hindered attempts to calculate the total sediment load. Additionally, the time of sampling for some grab samples was not specified. This information is especially important at high discharge, as the Nattai River typically peaks and falls within hours. Therefore, only those SSC and turbidity data with the exact time of sampling were used to establish a correlation with the hourly discharge.

To estimate suspended sediment load, sediment rating curves were constructed from least squares regressions of SSC and discharge using a number of different fitting procedures (see Table III and Figure 5), then applied to the 40-year discharge record. Longer SSC data sets were derived by examining the relationship between turbidity and SSC via both a linear conversion of turbidity based on a standard concentration (1 NTU = 0.606 mg L^{-1}) (Gippel,

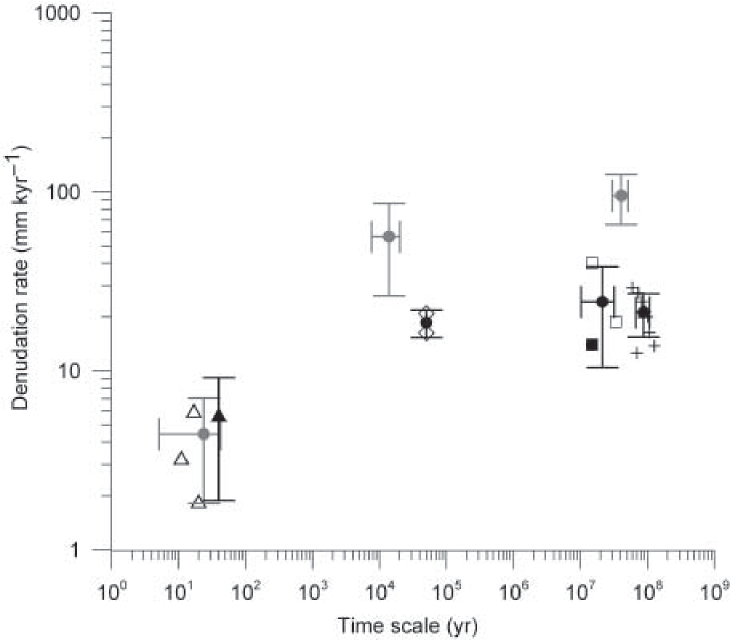

Figure 4. Discrepancy in contemporary and long-term denudation rates from the Blue Mountains Plateau, western Sydney Basin. Symbols indicate the following: open triangle, contemporary rates from south-west Sydney Basin; closed triangle, contemporary rate from Nattai catchment and standard error ($\pm 1\sigma$); diamond, terrestrial cosmogenic nuclide data; open square, post-basalt valley incision data; closed square, post-basalt plateau lowering datum; cross, AFTT data; closed black circle, averages and standard error ($\pm 1\sigma$). Averages and standard error ($\pm 1\sigma$) from Idaho, USA (Sweetkind and Blackwell, 1989; Kirchner *et al.*, 2001) are indicated as closed grey circles to show the similarity in contemporary rates with the Nattai catchment despite differences in lithology, relief and tectonic setting.

Table III. Methods used to develop sediment rating curves for the Nattai River from suspended sediment concentration (SSC) data plotted against discharge

Curve no.[a]	**Data and fitting procedure**
	Linear least squares regression
1.	Log-transformed SSC and discharge with normal correction factor (CF1) (Ferguson, 1986a, 1987)
2.	Log-transformed SSC and discharge with non-parametric correction factor (CF2) (Walling and Webb, 1988)
3.	Log-transformed mean SSC and discharge (Jansson, 1985)
	Non-linear least squares regression (power function)
4.	SSC and discharge
5.	Turbidity derived SSC (formazine standard) and discharge (Gippel, 1989)
6.	Turbidity derived SSC (linear scaling) and discharge
7.	Turbidity derived SCC (square root scaling) and discharge (Lewis, 1996)
8.	Pre- and post-fire SSC and discharge (plotted as two regressions: a, b)
	Other
9.	Discharge-weighted mean SSC

[a] Consistent with numbering shown in Figure 5.

1989) and least squares regression of SSC and turbidity data on linear and square root scaled axes (Lewis, 1996). Further analysis of the SSC and turbidity data revealed that a number of points with elevated values at low discharge were collected after the 1968 and 2001–02 wildfires (Figure 6). Hence an additional data set of pre-fire (or non-fire-impacted) and post-fire SSC was used to derive two regressions, which were applied to the discharge record accordingly.

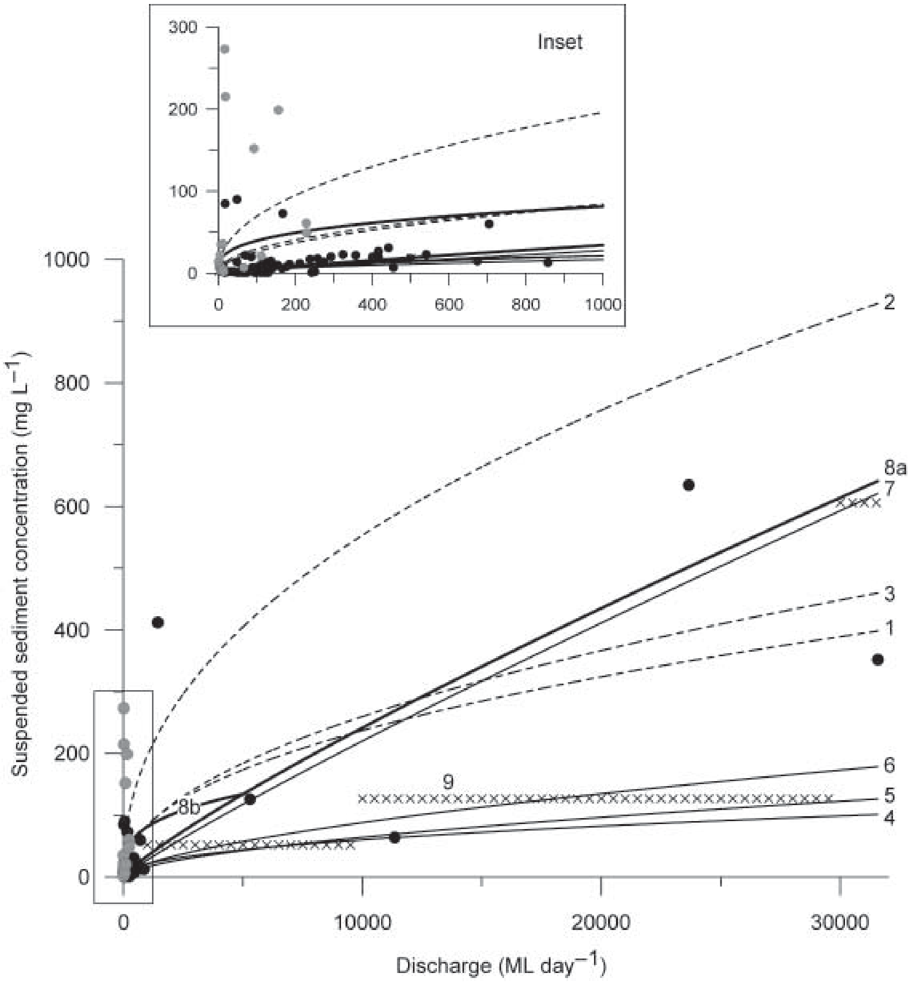

Figure 5. Sediment rating curves derived from suspended sediment concentration and discharge data from the Nattai catchment. Details of curves are provided in Table III. Closed grey circles indicate post-fire data.

A major problem with all of the curves was the lack of SSC and turbidity data at high discharge, so maximum and minimum predictions of SSC differed by almost an order of magnitude. In contrast with several other studies (e.g. Jansson, 1985; Ferguson, 1987; Asselman, 2000; Horowitz, 2003), we were unable to compare the loads predicted by the curves with the true sediment load to determine under- and over-prediction. Instead, statistical analyses of the data and residuals were conducted along with a visual assessment of the curves to determine which resulted in the best fit with the available SSC data (Jansson, 1985).

The results showed that the curves derived from log-transformed data with bias correction factors and the log-transformed mean fitted the higher scatter values at low discharge, suggesting over-prediction (Figure 5, inset). Furthermore, the logged data and the residuals of the logged data were found to have a bimodal peak rather than a normal distribution, indicating that bias corrected log transformation was not valid (Koch and Smillie, 1986; Ferguson, 1986a, 1986b). On this basis, the rating curves derived from log-transformed data were rejected.

The non-linear curves resulted in a good fit of the data at low discharge (Figure 5, inset), but deviated somewhat at high discharge. In the absence of any further SSC data, we used these curves to define a range of likely estimates of suspended sediment load for the Nattai River. To correct for bedload, an additional 10 per cent was included in calculations following suggestions by Walling and Webb (1987) and Summerfield and Hulton (1994). Dissolved load was estimated using figures quoted by Summerfield and Hulton (1994) for the Murray River, Australia, in which the ratio of mechanical to chemical denudation is 5·5:1. A bulk density of 2.2 g cm^{-3}, applicable to sandstone- and shale-dominated lithology, was used to convert sediment yield to denudation rates.

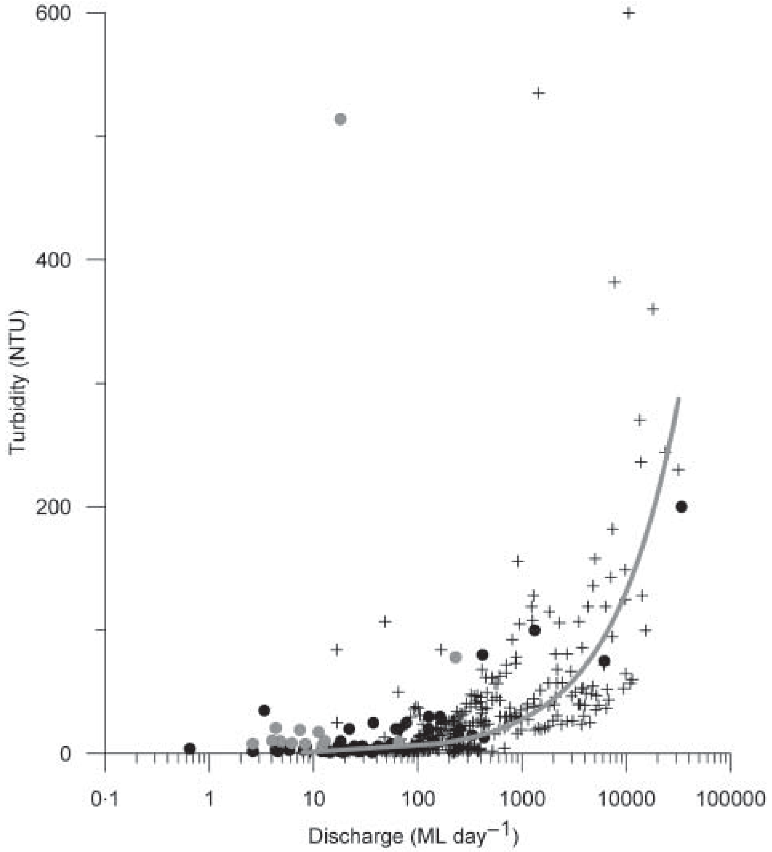

Figure 6. Turbidity data from the Nattai catchment separated as post-fire and pre- (non-) fire. Closed black circles indicate data collected after the 1968 wildfire (to 1974); closed grey circles indicate data collected after the 2001–02 wildfire (to 2003); crosses and thick grey line indicate pre-fire data and trend. For scaling purposes, three pre-fire values of >600 NTU are not shown, including one datum collected during the 1978 flood (>1000 NTU). Note that post-fire values are elevated above the trend at low discharge but within the range of scatter, and show no difference from pre-fire values at higher discharge (>5000 ML day^{-1}).

This results in an average contemporary (40-year) denudation rate for the Nattai River of 5·5 ± 4 mm kyr^{-1} (1σ) (Figure 4), with a minimum of 2·2 mm kyr^{-1} estimated using the SSC data (curve 4) and a maximum of 10·4 mm kyr^{-1} estimated using the SSC data separated into pre- (or non-) and post-fire (curves 8a, b). Throughout this paper we use the maximum estimate and other calculations derived from the pre- and post-fire curves in order to adopt a conservative approach given the uncertainties with SSC at high discharge.

Additional data on sediment yields from other catchments in the south-west Sydney Basin were compared to gauge the representativeness of the Nattai data (Figure 4). A similar rate of 5·8 mm kyr^{-1} is reported for the Warragamba River (Bishop, 1984), which also cuts through the Sydney Basin geology. Lower rates of 3·2 and 1·8 mm kyr^{-1} were reported from the upper Wollondilly River and Southern Tablelands, respectively (Wasson, 1994; Armstrong and Mackenzie, 2002), but these include other lithologies (Palaeozoic metasediments). The overall similarity in rates across the south-west Sydney Basin provides a clear regional picture, with our estimates for the Nattai River, obtained through rigorous analysis of data, suggesting higher rather than lower values.

Analysis of the Contribution of Catastrophic Floods to Denudation

The flood record for the Nattai River was determined using the hourly instantaneous discharge data from the Nattai gauge. A flow duration curve was constructed and used to calculate average recurrence intervals (ARIs) by applying a natural log correction. The mean annual flood (1 year ARI) was calculated as 5246 ML day^{-1} (61 cumecs). Catastrophic floods were identified using the definition of Erskine and Saynor (1996)—events with a flood peak discharge

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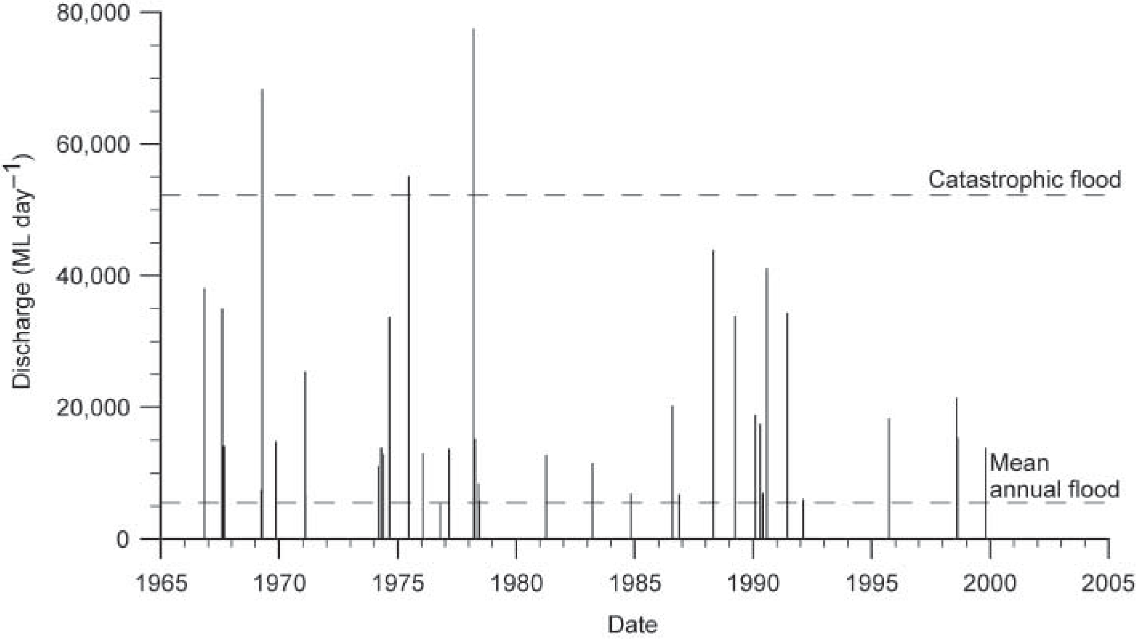

Figure 7. Flood record from the Nattai River since 1965, showing three quasi-catastrophic floods (1969, 1975 and 1978). Catastrophic floods were identified using the definition of Erskine and Saynor (1996): flood peak 10 times greater than the mean annual flood.

at least 10 times greater than the mean annual flood. To distinguish between floods that only just exceed this threshold (quasi-catastrophic) and larger catastrophic events (>100 year ARI), we use the terms class 1 (C1) and class 2 (C2), respectively. Using this criterion, there have been three C1 catastrophic flood events in the Nattai River since 1965 (Figure 7, Table IV): April 1969 (five months after the 1968 wildfire), June 1975 and the maximum recorded flood (50 year ARI) in March 1978, which had a peak discharge of 77 500 ML day^{-1} (897 cumecs). Since 1978, flood magnitude and frequency has declined, particularly after 1992, which may be a reflection of repeated drought conditions across south-eastern Australia.

Table IV. Catastrophic floods in the Nattai River since 1965 and estimate of the 1867 flood

Date of flood	Peak discharge (ML day^{-1})	Peak discharge (cumecs)	Average return interval (years)	No. of times greater than mean annual flood
15–22 April 1969	68 269	790	>20	13
21 June–2 July 1975	55 106	638	>20	10·5
18–30 March 1978	77 500	897	50	14·8
June 1867[b]	215 136	2490	200	41

Date of flood	Total sediment yield[a] (t km^{-2})	No. of times greater than mean annual sediment yield	Denudation rate (mm per event)
15–22 April 1969	48·0	2·1	0·0218
21 June–2 July 1975	74·9	3·3	0·0340
18–30 March 1978	178·6	7·8	0·0812
June 1867[b]	1180·3	51·8	0·5365

[a] Calculated using the maximum estimate of suspended sediment concentration based on the pre- and post-fire sediment rating curves.
[b] Estimate based on extrapolation of data using the 1978 flood hydrograph.

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The largest flood on record since settlement of the catchment (1799) was recorded in the Warragamba and Nepean Rivers (downstream of the Nattai River) in June 1867, with an estimated return interval exceeding 100 years (Bracewell and McDermott, 1985a, 1985b). Extrapolation of the 1867 flood to the Nattai River was undertaken to obtain an estimate of the maximum likely discharge for an event of this magnitude. This was achieved by comparing the 1978 flood discharge from a gauge on the Warragamba River with the 1978 flood discharge in the Nattai River to determine the relative contribution of flow. Assuming a linear relationship, the 1867 flood discharge recorded at the Warragamba gauge (Bracewell and McDermott, 1985a) yields a maximum peak discharge of around 215 000 ML day^{-1} (2490 cumecs) in the Nattai River. On this basis, the 1867 flood was equivalent to 41 times the mean annual flood in the Nattai River and from calculated flood recurrence intervals would represent a 1 in 200 year event (C2 catastrophic flood). This is consistent with data presented by Riley (1980) for the Hawkesbury–Nepean River at Windsor, which has a flood record extending back to 1799.

A hydrograph of each recorded catastrophic flood in the Nattai River is shown in Figure 8. For all three events, it is clear that the Nattai River experiences flashy flows, with peaks occurring within hours of the commencement of the flood and recession of the majority of flood water within 4–6 days thereafter. The 1969 flood produced a very sharp, single peak in discharge followed by a rapid decline, compared with the 1975 and 1978 floods, which showed one or more secondary peaks. There may be some link to the 1968 wildfires (five months earlier) through enhanced run-off volume and velocity from the hillslopes. Alternatively, the flood peak may simply reflect the 5–20 year return interval rainfall event, which fell over two days across the catchment. The 1975 and 1978 floods occurred several years after fire, when the vegetation cover was intact and, therefore, appear to be solely a response to large-magnitude rainfall events in the catchment.

Catastrophic floods in south-eastern Australia have been found to generate 11–283 times the mean annual sediment yield (Erskine and Saynor, 1996). Sediment yields were calculated for the three C1 floods in the Nattai River to analyse the importance of these events with respect to contemporary erosion rates (Table IV). In just six days, the 1978 flood peak had generated 21 per cent of the total sediment yield produced over 40 years, whilst the three floods combined produced 35 per cent of total sediment yield. The 1975 flood resulted in a greater sediment yield than the 1969 flood, which is inconsistent with flood peak magnitude, but may reflect the enhanced flood duration. Flood duration (i.e. short and flashy) may also explain why the three floods generated sediment yields of less than 11 times the mean annual sediment yield, as reported by Erksine and Saynor (1996). Alternatively, it is possible that we have underestimated sediment yields from these events, given the uncertainties with the rating curves. Nonetheless, the three C1 events generated a significant proportion of total sediment yield over the 40-year record. On this basis, the 1867 flood (C2) may be expected to have generated the equivalent of 55 years of sediment yield in a single event.

Denudation rates were calculated to determine the contribution of catastrophic floods to contemporary and long-term rates. Based on the 40-year Nattai record, the three C1 floods account for 3·6 mm kyr^{-1} of the maximum 10·4 mm kyr^{-1} contemporary rate (35%). This calculation, however, does not include the larger C2 events which occurred outside the 40-year record, such as the 1867 flood, and is therefore an underestimate of the true contribution of catastrophic floods over the longer timescale. Hence, the rates were recalculated using recurrence intervals indicated by the longer flood record from the Hawkesbury–Nepean River at Windsor (Riley, 1980). The Windsor record (measured as flood height) showed that the 1867 flood was by far the largest since 1799 and the 1975 and 1978 floods were the largest since 1965 (up to the end of record in June 1978). Thirty-three floods of greater magnitude than the 1975 flood have occurred in the last 180 years (1799–1978), but the record can be extended to the present (207 years) using our knowledge of floods in the Nattai River. A height–duration curve was constructed to show that 23 floods reached heights between the 1975 and 1978 levels, and nine were up to 1 m higher than the 1978 level. The 1867 flood clearly exceeded the 1978 flood by 5 m. Since the Windsor record is in stream height, we were unable to extrapolate the record directly to the Nattai River. Instead, an average of the sediment yield arising from the 1975 and 1978 floods in the Nattai River was used to give a reasonable (although minimum) estimate of the yield arising from the 32 C1 flood events over 200 years. Sediment yield for the 1867 flood was estimated using the pre-fire rating curve and extrapolated discharge as outlined above. Using the 200-year flood record, we estimate that the denudation rate in the Nattai catchment from catastrophic floods is a maximum of 11·9 mm kyr^{-1} or 55 per cent of the long-term denudation rate (Table V).

Analysis of the Contribution of Wildfires to Denudation

The December 2001–January 2002 wildfire burnt a substantial proportion of the Nattai catchment. The fire was followed by a small–moderate rainfall event, which occurred three weeks later. Rainfall was widespread across the catchment with an average of 117·9m recorded at eight gauges over four days and a maximum of 63 mm day^{-1}. The Nattai River showed a small peak of 874 ML day^{-1} (10 cumecs) in response. Subsequent rainfall events across the

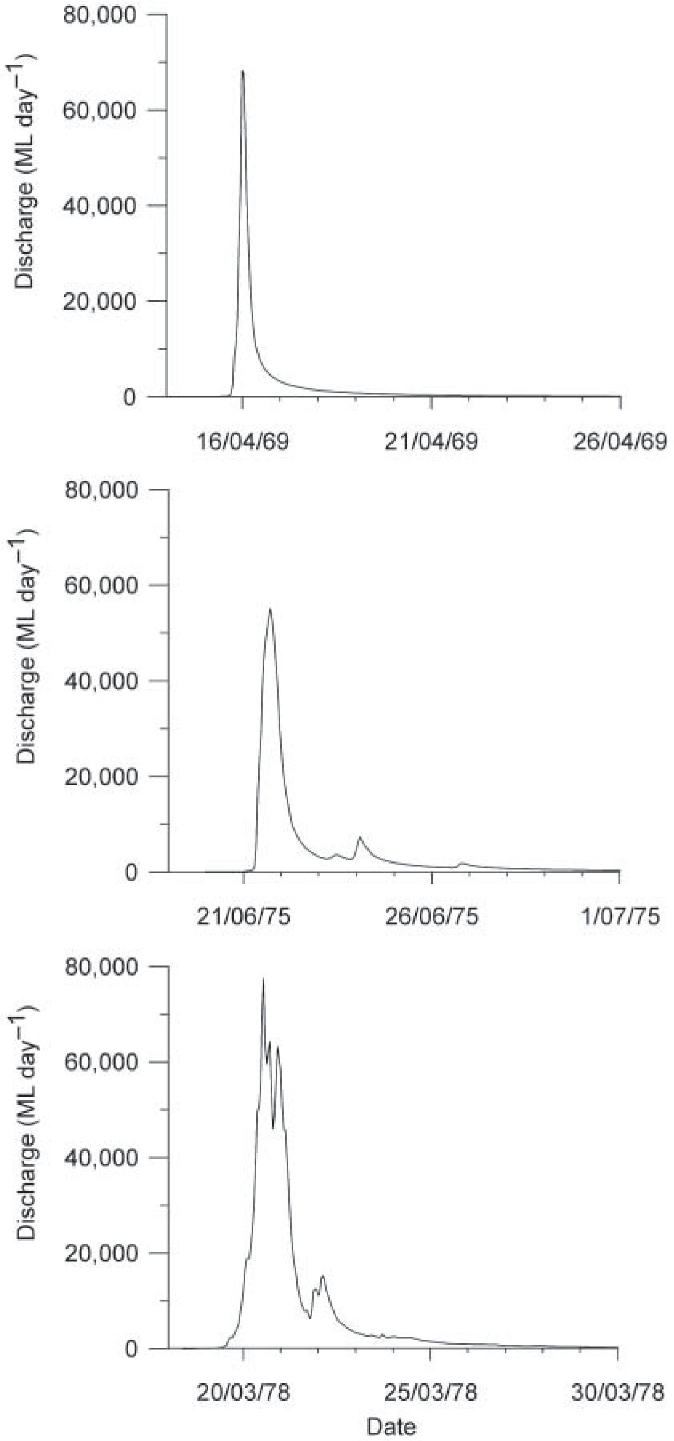

Figure 8. Hydrographs of the 1969, 1975 and 1978 floods. Note the rapid, uniform increase and decline of the 1969 flood, which occurred five months after the 1968 wildfires. The 1969 flood recorded a much lower peak in the Nepean River downstream, suggesting enhanced post-fire run-off from within the burnt Nattai catchment.

Table V. Prediction of maximum sediment yields and denudation rates from catastrophic floods in the Nattai catchment using recurrence intervals determined from the longer Windsor flood record

Flood	Equivalent no. of floods over 200 (1000) years	Sediment yield ($t\ km^{-2}\ kyr^{-1}$)	Denudation rate ($mm\ kyr^{-1}$)
1975/1978	32 (160)	20 279	9·2
1867	1 (5)	5 901	2·7
Total	33 (165)	26 180	11·9

catchment were of a lesser magnitude, although higher daily totals were recorded at some of the upper catchment gauges. Overall, rainfall and discharge between 2002 and 2005 were well below average (Figure 9).

Data on post-fire erosion from hillslopes were obtained from three sites within the Nattai catchment burnt during the 2001–02 wildfires. The sites are located along Blue Gum Creek (Figure 2) and were chosen using a satellite-image based classification of burn intensity (low, moderate and extreme fire severity) supported by ground observations (Chafer *et al.*, 2004). At two sites (low–moderate severity and moderate–extreme severity), data on ground surface changes were collected at intervals of 5, 12, 13 and 25 months after the fire from the plateau top, slopes (upper, mid, lower, foot) and valley floor using the methods outlined by Shakesby *et al.* (2003, 2006). The result is an estimated soil loss of 50–100 and 7–70 t ha^{-1} in the first and second years after the fire, respectively, with little effect due to variation in fire severity (Shakesby *et al.*, 2006). These estimates are consistent with data presented by Paton *et al.* (1995, Figure 4.6). At the third (moderate severity) site, sediment budgets were constructed from radionuclide tracers (^{210}Pb, ^{7}Be, ^{137}Cs) to indicate gross sediment loss or gain from each landscape unit (Wallbrink *et al.*, 2005).

A problem with the measurement of ground surface change is that it does not take into account localized sediment redistribution, i.e. sediment that has only been moved short distances or trapped in micro-terraces on slope (Mitchell and Humphreys, 1987). This was confirmed through field observations after the fire, which suggested that most of the

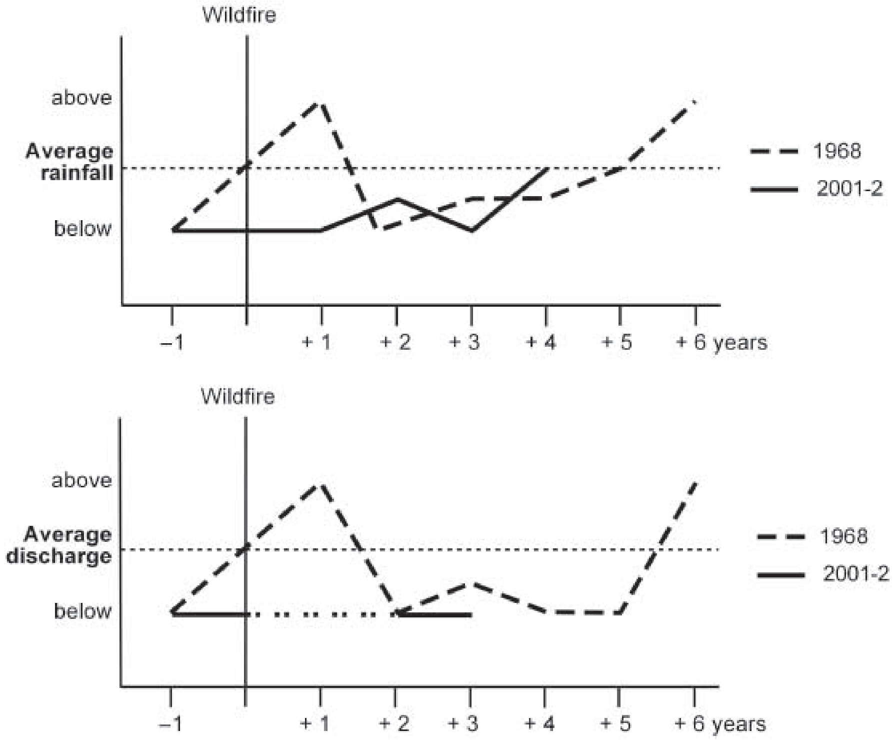

Figure 9. Comparison of average rainfall and discharge for one year prior to and six years after the 1968 and 2001–02 fires. The scale on the *y*-axis is indicative rather than quantitative and missing data are indicated by a dotted line. Rainfall conditions following the 2001–02 fires were below average, compared with above average conditions in the first year after the 1968 fires.

mineral soil component was only locally redistributed, whereas the low-density material including charcoal, leaves and clay were exported to the river system (Shakesby *et al.*, 2003, 2006). Sediment tracer budgets confirmed this interpretation, showing that 28–35 per cent of topsoil and organic matter was lost from the catchment (using ^{210}Pb and ^{7}Be results) whereas only 4 per cent of subsoil (using ^{137}Cs results) was lost (Wallbrink *et al.*, 2005). To resolve this, the soil loss data predicted from ground surface changes were combined with the results from the sediment tracer budgets to determine the total amount of soil material actually exported. The result is an estimated sediment yield from the hillslopes and plateaux of 1976 and 495 t km^{-2} yr^{-1} for the first and second years after the 2001–02 fire, respectively (Table VI). The yields are assumed to be representative of post-fire erosion within the broader Nattai catchment, given the similar geology and vegetation, and widespread post-fire rainfall.

Sediment yields in the Nattai River were calculated for the years following the 2001–02 fires with available discharge data (using the post-fire sediment rating curve, 8b) to compare with the hillslope results (Table VI). Since most of the Nattai catchment was burnt during the fires, the river load is assumed to be a reflection of net post-fire erosion. The first year following the fire (2002) showed a maximum river sediment yield of just 1·71 t km^{-2} yr^{-1}, which is two to three orders of magnitude less than the rates from the hillslope data. The second and third years (2003–04) showed decreased river yields of 1·09 and 0·27 t km^{-2} yr^{-1}, respectively, also several orders of magnitude less than those from the hillslopes. The sediment yields measured in the Nattai River suggest that less than 1 per cent of the predicted material eroded from the hillslopes actually reached the main river system in the first few years after the 2001–02 fires, and most of this material consisted of clay, burnt organics and charcoal (Blake *et al.*, 2004). It appears that movement of coarse sediment after the 2001–02 fires was primarily confined to the plateaux and slopes (Blake *et al.*, 2004; Wallbrink *et al.*, 2005), with considerable storage on the foot slopes and valley floor. These lower slope units in the valley would seem to provide an effective buffer between the eroding hillslopes and the channel, especially during light to moderate rainfall events.

Like the 2001–02 wildfire, the fire in 1968 also burnt a significant proportion of the Nattai catchment. This fire was followed by a substantial rainfall event, which occurred five months later, resulting in the 1969 flood. An average of 162·4 mm of rainfall fell across the catchment in two days, including a maximum of 165·1 mm day^{-1} (10 year ARI). A total of 200·7 mm rainfall was recorded at the Buxton gauge close to the Blue Gum Creek sites. Overall in the six years after the 1968 fire, rainfall and discharge were below average, with the exception of 1969 and 1974, when more than 1000 mm rainfall fell across the catchment and discharge was more than double mean annual discharge (Figure 9). The difference between the discharge in the years following the 1968 fire and the 2001–02 fire appears to reflect the prevailing rainfall–run-off conditions rather than any fire severity differences.

Sediment yields in the Nattai River were calculated for up to six years after the 1968 fire (to 1973) using the relationship of Paton *et al.* (1995, Fig 4.6) and based on the assumptions that all sediment load was related to post-fire erosion, and reworking of fluvial and non-fire-related colluvial sediments was negligible during the 1969 flood. The first year after the fire (1969) shows a maximum sediment yield of 74 t km^{-2} yr^{-1} (Table VI), which is far greater than any other year, including the years after the 2001–02 fires. Unfortunately, no data exists on hillslope sediment loss, so the 2001–02 rates were used as a proxy to show <5 per cent total export of sediment off the hillslopes into the river system (Table VI). Given the greater rainfall in 1969, even higher rates of erosion would have been expected on the hillslopes, hence use of the 2001–02 soil loss rates is probably an under-estimate.

Table VI. Comparison of estimated sediment yields and denudation rates from the Nattai catchment for up to three years following the 2001–02 and 1968 wildfires

	Average sediment yield (t km^{-2} yr^{-1})			Denudation rate (mm yr^{-1})		
	Year 1	**Year 2**	**Year 3**	**Year 1**	**Year 2**	**Year 3**
2001–02 wildfire						
Post-fire erosion on hillslopes	1976	495	na	0·898	0·225	na
Nattai River[a]	1·71	1·09	0·27	0·0008	0·0005	0·0001
Export from hillslopes to river	0·09%	0·22%	na			
1968 wildfire						
Nattai River[a]	74·0	1·14	10·63	0·0336	0·0005	0·0048
Export from hillslopes to river[b]	3·7%	0·23%	na			

[a] Maximum estimates from sediment rating curves.

[b] Assuming the same rates of post-fire erosion on hillslopes as those calculated following the 2001–02 wildfires.

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Table VII. Prediction of post-fire sediment yields and denudation rates from the Nattai catchment following the 2001–02 and 1968 wildfires (1969 flood excluded) using a wildfire recurrence interval of 33 years

Wildfire	Sediment yield[a] (t km^{-2} kyr^{-1})	Denudation rate[a] (mm kyr^{-1})
2001–02	100·1	0·045
1968	1288·5	0·59
Average	694·3	0·32

[a] Calculation based on data shown in Table VI, with additional data to estimate sediment yields for 4–6 years after the 2001–02 fires from Paton *et al.* (1995, Fig 4.6).

Denudation rates were calculated to assess the contribution of wildfires to the contemporary and long-term denudation rates. The rates can be considered maxima, as we have assumed that all sediment load in the river is related to fire. In reality this is probably not the case, and at least a small proportion would represent the background sediment yield generated regardless of fire. The 2001–02 fire, including the three years thereafter with available data, accounts for 0·03 mm kyr^{-1} of the contemporary rate (0·3%). The 1968 fire and up to six years thereafter, including the 1969 flood, accounts for 1·1 mm kyr^{-1} (10·5%). If the 1969 flood is not included, the rate falls to 0·51 mm kyr^{-1} (5%). The yields from the 2001–02 and 1968 wildfires (1969 flood excluded) were extrapolated over 1000 years using an estimated wildfire recurrence interval of 33 years and then averaged to give an estimated denudation rate from wildfires of 0·32 mm kyr^{-1} or 2 per cent of the long-term rate (Table VII).

Discussion

Contemporary versus long-term denudation

Our analysis of data from the Blue Mountains Plateau in the western Sydney Basin shows that the average contemporary denudation rate of 5·5 ± 4 mm kyr^{-1} determined from the Nattai River is considerably less than the long-term average rate of 21·5 ± 7 mm kyr^{-1} determined from AFTT, TCN and post-basalt flow data. The difference of 16 mm kyr^{-1} is not as great as that found in the study by Kirchner *et al*. (2001) in Idaho, USA (Figure 4), although it is interesting to note that the contemporary averages from the Nattai River and Idaho (4·4 ± 3 mm kyr^{-1}) are very similar, despite differences in lithology, relief and tectonic setting. Similar contemporary and long-term denudation rates have also been reported from Europe from the Meuse, Regen and Loire Rivers (Schaller *et al*., 2001).

The long-term average denudation rate from the Blue Mountains Plateau is consistent with rates reported previously for the highlands of south-eastern Australia using cosmogenic nuclides and AFTT (see, e.g., Fabel and Finlayson, 1992; Heimsath *et al*., 2001; Wilkinson *et al*., 2005) and is therefore considered to be reliable. The rate also fits within a common global range of ~5–50 mm kyr^{-1}, which includes data from landscapes with different lithologies, climate and tectonic settings (Bierman, 1994; von Blanckenburg, 2005; Wilkinson and Humphreys, 2005). Somewhat lower long-term denudation rates for south-eastern Australia have been reported by others (e.g. Bishop, 1985; Gale, 1992). These differences may be affected by method of calculation such as averaging of removal of material over longer timescales (Mesozoic and Cenozoic) and inclusion of data marginal to the highlands. Alternatively, the differences may reflect relief and degree of terrain dissection, which can vary at sub-regional scales depending on uplift history and geological structure.

The reliability of the contemporary denudation rate is much less certain. It is possible that the 40-year Nattai record is far too short to be representative of catchment-scale processes or to capture events that occur less frequently such as the 1867 flood. The record may also inadequately represent climatic cycles greater than 30 years such as the 30–50 year alternating flood- and drought-dominated fluvial regimes postulated for eastern Australia (Erskine and Warner, 1988). Alternatively, it may be possible that the rate calculated for the Nattai catchment (and other areas in the south-west Sydney Basin) reflects true contemporary denudation processes and that climatic change over timescales of 10^3–10^5 years provides the missing link with the long-term rate. In a recent study, Nanson *et al*. (2003) provides a chronology of units forming the upstream section of the Hawkesbury–Nepean floodplain. They describe basal gravels deposited under a braided river system during the last interglacial (dated between 75 and 110 ka) and later reworking of units during interstadials (40–50 ka). This suggests that at times spanning tens of thousands of years the Hawkesbury–Nepean system has had greater river competence, greater discharge, a more abundant supply of coarser sediment and presumably higher denudation rates than at present. Similar findings of episodes of higher fluvial discharge during interglacial and interstadial periods in the Shoalhaven River (south of the Nattai catchment) are reported by Nott *et al*. (2002).

Denudation through extreme events

In both the European and Idaho studies, extreme events such as floods and wildfires were identified as the most likely cause of the mismatch in contemporary and long-term denudation rates. We set out to test this using the Nattai catchment, which has experienced two major wildfires and three quasi-catastrophic floods over a 40-year period. Analysis of the breakdown of the contemporary rate (using the maximum indicated from the rating curves) shows that the three C1 floods account for 35 per cent, the 2001–02 and 1968 wildfires (not including the 1969 flood) account for 5 per cent and a balance of 60 per cent formed the background, which includes small to medium floods, low flows and other erosional events not considered in this study such as mass movement (Table VIII).

Extrapolation of the rates to 1000 years using the longer (200-year) Windsor flood record and an estimate of wildfire recurrence changes the proportions substantially (Table VIII). The importance of catastrophic floods increases to account for over half of the long-term denudation rate, primarily through a greater frequency of floods than is represented in the 40-year Nattai record. It is possible that this proportion could increase further through larger magnitude (extreme) floods with recurrence intervals of greater than 200 years. For example, slack-water deposits from at least one palaeoflood in the Nepean River up to 8 m higher than the 1867 flood have been found and dated to around 3750 years BP (Saynor and Erskine, 1993), providing evidence that extreme events have occurred within at least the last few thousand years and probably during the Holocene under similar climatic conditions. However, to achieve a higher denudation rate there must also be a ready supply of sediment, an argument that also applies to both an increase in magnitude and/or frequency of floods and/or an increase in the sediment load of each flood.

Over the longer timeframe, denudation resulting from wildfires declines to a smaller proportion through adjustment to a 33-year wildfire return interval (Table VIII). This suggests that over decadal timescales and longer the erosional impact of fire at the catchment scale (701 km^2) is modest, an assessment which is in contrast to that normally portrayed for south-eastern Australia (see, e.g., Brown, 1972; Prosser and Williams, 1998), especially from studies where post-fire erosion is determined at the hillslope or first order catchment scale. Instead, the role of wildfires appears to be largely confined to localized reworking of sediment on hillslopes, with the bulk of sediment generated being deposited and stored on the lower slopes and valley floor. A similar finding is reported by Moody and Martin (2001), who investigated post-wildfire erosion in Colorado, USA. Minor to catastrophic floods then play a role in remobilizing stored material and ultimately exporting it from the catchment. In view of this, the connectivity between hillslopes and the river system is important (Fryirs and Brierley, 1999; Fryirs *et al.*, 2006), as is the time involved in mobilizing sediment between different sediment stores (e.g. alluvial fans, floodplains and within-channel bars). The amount of post-fire erosion appears to be highly dependent on the rainfall–run-off conditions in the years following the fire. Significantly higher rates of erosion might be possible if an extreme rainfall event occurred within the first

Table VIII. Calculation of sediment yield and denudation rates from catastrophic floods and wildfires, compared with contemporary and long-term denudation rates

Rates based on 40-yr Nattai record (maximum prediction from rating curve)

	Sediment yield/ event (t km^{-2})	Denudation rate (mm kyr^{-1})	% contemp. denudation
Denudation from floods	302	3·6	35
Denudation from wildfires[a]	46	0·54	5
Background denudation[b]	–	6·2	60
Total		10·4	100

Rates extrapolated over 1000 years using Windsor flood record and wildfire ARI

	Sediment yield (t km^{-2} kyr^{-1})	Denudation rate (mm kyr^{-1})	% long-term denudation
Denudation from floods	26 180	11·9	55
Denudation from wildfires[a]	694	0·32	2
Background denudation[b]	13 685	6·2	29
Total	40 559	18·4	86

[a] 1969 flood excluded (due to inclusion in calculations for catastrophic floods).

[b] Rate also includes other erosion events such as small to medium floods and mass movement on hillslopes.

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12 months of an extreme wildfire event, resulting in the complete removal and export of hillslope material (stripping). However, the likelihood of this occurring is low and becomes much less with increasing time after fire, as the vegetation recovers.

Other extreme erosional events

Other erosional events such as mass movement of sediment on hillslopes have not been considered thus far but are recognized as an important source of sediment yield. The presence of mass movement features such as landslides and debris flows appear to be characteristic of the Nattai catchment, and indeed the rest of the Blue Mountains Plateau, especially where the valley has incised into the softer, underlying Permian strata (McElroy and Relph, 1958; Macris, 2002; Tomkins *et al*., 2004a). At the Blue Gum Creek sites, lobes of talus forming steep fans lie directly adjacent to shallow but incised drainage lines on slopes of up to 35°. Preliminary radiocarbon dates indicate late Holocene ages, though older than 200 years (Tomkins *et al*., 2004a). The talus is mainly composed of Hawkesbury sandstone, sourced from the cliff line above. Additionally, large-scale rotational slumping within the Permian bedrock is inferred along the lower Nattai River (Taylor, 2005). The slumping is thought to have triggered a rock avalanche with an estimated volume of $1{\cdot}5\ \mathrm{Mm}^3$. Based on the spatial distribution of mass movement features within the catchment and the thickness of colluvial material stored on the lower slopes, it is highly plausible that mass movement events triggered by prolonged rainfall during wetter periods, or by earthquakes (Tomkins *et al*., in press), may well be the provider of copious sediment to the river system. Quantification of these extreme events may elevate the contemporary denudation rate further towards the long-term rate.

Conclusions

Denudation rates from the Blue Mountains Plateau, located on the western margin of the Sydney Basin, were examined to assess the likelihood of extreme erosion events. Contemporary rates, determined from river sediment yield, flood and fire records over 40 years in the Nattai catchment were found to account for an average of $5{\cdot}5 \pm 4\ \mathrm{mm\ kyr^{-1}}$ of landscape denudation. The contemporary rates are much lower than the longer term average rate of $21{\cdot}5 \pm 7\ \mathrm{mm\ kyr^{-1}}$, determined from apatite fission track thermochronology, post-basalt flow incision and terrestrial cosmogenic nuclides, suggesting that high-magnitude, low-frequency extreme events might account for the discrepancy. Wildfires appear to have a modest impact on denudation, largely resulting in reworking of sediment on hillslopes, with the extent of sediment transport to the river system being highly dependent on rainfall conditions in the first few years following the fire. Catastrophic floods appear to play an important role in remobilizing large volumes of sediment stored on the lower slopes and valley floor, with much larger floods detected outside the contemporary record indicating an even greater sediment export potential. Where valleys have incised into softer Permian strata, mass movement events on hillslopes may prove to be the dominant source of sediment to the river system.

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