Postwildfire hydrological response in an El Niño–Southern Oscillation–dominated environment

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[1] The rainfall-runoff events following five fires that occurred within a 40-year period in eucalypt forests of the Nattai catchment, southeastern Australia, were investigated to quantify the postwildfire hydrological response and to provide context for lower than expected erosion and sediment transport rates measured after wildfires in 2001. Daily rainfall and hourly instantaneous discharge records were used to examine rainfall-runoff events in two gauged subcatchments (>100 km^2) for up to 3 years after fire and compared with nonfire periods. Radar imagery, available from 2001, was used to determine the intensity and duration of rainfall events. Wildfires in the study catchment appear to have no detectable impact on surface runoff at the large catchment scale, regardless of fire severity, extent or time after fire. Instead, the magnitude of postfire runoff is related to the characteristics of rainfall after fire. Rainfall is highly variable in terms of annual totals and the number, size, and type of events. Rainfall events that cause substantial surface runoff are characterized by moderate-high intensity falls lasting one or more days ($\geq$1 year average recurrence interval). These are triggered by synoptic-scale weather patterns, which do not reliably occur in the postfire window and are independent of broad-scale climate dominated by the El Niño–Southern Oscillation (ENSO). This study highlights the importance of considering the characteristics of rainfall, as well as local factors, in interpreting the postfire hydrological response.

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1. Introduction

[2] The impacts of wildfires on vegetation, soils and catchment hydrology have been widely reported in Australia, USA and elsewhere [*Brown and Smith*, 2000; *Neary et al.*, 2005; *Shakesby and Doerr*, 2006; *Shakesby et al.*, 2007]. A common focus of previous studies has been postfire runoff and erosion at the plot to hillslope scales, with many finding substantially elevated rates within the first year or so after severe fires and often in response to the first rainfall events when the potential for enhanced runoff and erosion is perceived to be greatest [e.g., *Inbar et al.*, 1998; *Cannon*, 2001; *Meyer et al.*, 2001; *Moody and Martin*, 2001b; *Cannon and Gartner*, 2005; *Reneau et al.*, 2007].

[3] A few studies have focused more specifically on the hydrological response to wildfires at the catchment scale, comparing postfire streamflows to prefire or modeled flows. These have shown higher annual totals for several years after fires [*Helvey*, 1980; *Lavabre et al.*, 1993; *Loáiciga et al.*, 2001; *Kunze and Stednick*, 2006; *Lane et al.*, 2006] and enhanced discharge from individual rainfall events [*Scott*, 1993; *Moody and Martin*, 2001a; *Mayor et al.*, 2007], providing support for similar observations at smaller spatial scales. The result is a widespread perception that severe wildfires lead to increased surface runoff and erosion on hillslopes, with fire-induced, or enhanced soil water repellency, decreased infiltration through sealing of soil pores and destruction of the vegetation cover frequently cited as the primary causes [*Letey*, 2001; *Martin and Moody*, 2001; *Shakesby and Doerr*, 2006].

[4] In southeastern Australia, a number of investigations have been carried out to quantify postfire runoff and erosion rates at the plot to catchment scales, focusing on the fire-prone eucalypt forests of the Sydney region and other parts of the southeast Australian highlands. Many studies, however, have found lower than expected rates of surface runoff and erosion even after severe, widespread wildfires [*Good*, 1973; *Blong et al.*, 1982; *Zierholz et al.*, 1995; *Prosser and*

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Williams, 1998; *Shakesby et al.*, 2003, 2006]. Only two studies have recorded significant postfire effects. The first, by *Brown* [1972], showed changes in stream hydrographs for up to 4–5 years after wildfires in the Snowy Mountains, including double peaks in discharge representing runoff from burnt and unburnt parts of a 227 km^2 catchment and enhanced peak discharge from a 44 km^2 catchment that was completely burnt. The second example by *Atkinson* [1984], showed extensive flooding, erosion and sediment transport in a small catchment south of Sydney, in response to two large (10-year recurrence interval) rainfall events occurring within months of wildfires.

[5] Despite considerable efforts to measure postfire soil and vegetation conditions, including water repellency and fire severity, the reasons for the lower than expected postfire runoff and erosion rates in southeastern Australia are still unclear. Some authors have suggested the lack of rainfall in the years following the fire as a likely explanation [e.g., *Blong et al.*, 1982; *Prosser and Williams*, 1998]. Despite this, comparatively little attention has been given to rainfall events in the postfire period, presumably because storms of sufficient erosivity are assumed to occur in the years after fire and prior to any significant vegetation recovery. More recent investigations by *Lane et al.* [2006] and *Sheridan et al.* [2007] following wildfires in wet eucalypt forests of Victoria, have provided new insights into postfire runoff. Using rainfall simulation, these authors showed that any localized increases in overland flow on hillslopes were negated by areas of higher infiltration downslope. No increases in the magnitude of peak flows were observed from daily discharge data, however it is possible that enhancement of surface runoff occurring within the 24-h sampling interval may have not been recorded.

[6] In this paper we investigate the rainfall-runoff events in nonfire periods and following four wildfires and a hazard reduction burn (HRB; defined as a low-intensity fire ignited for the purpose of reducing ground fuel loads [*NSW Rural Fire Service*, 2006]) that occurred within a 40-year period in the Nattai catchment, southeastern Australia (Figure 1). Our aims were (1) to assess whether rainfall, ranging from individual events to annual or decadal trends, could provide insight into runoff in the postfire period, and (2) to characterize the postfire hydrological response in two gauged catchments to determine whether fires, of different severities and extent, have any detectable impact on surface runoff at the large catchment scale (>100 km^2). The results are presented in light of previous work on postfire geomorphic processes and erosion rates in the Nattai catchment after wildfires in 2001.

2. Study Area

[7] The Nattai River catchment (701 km^2) is located approximately 80 km southwest of Sydney (34° 13′S, 150° 20′E) (Figure 1). The Nattai River drains the southern end of the Blue Mountains Plateau, a sandstone-dominated tableland on the western margin of the Sydney Basin. This and other rivers draining the plateau form deeply incised valleys with up to 800 m relief, giving rise to rugged topography and often inaccessible terrain.

[8] The topography exerts a strong influence on soils and vegetation. Soil depth on the plateau is mostly <1 m with widespread rock outcrop [*King*, 1994; *Henderson*, 2002; *Wilkinson et al.*, 2005]. Within the incised valleys, the upper slopes are characterized by vertical cliffs, the middle to lower slopes are mantled by gravelly colluvium, while thicker sandy deposits (>3 m depth) occur on the floors of the main valleys and side tributaries [*Tomkins et al.*, 2004]. The vegetation is dominated by dry eucalypt forest which grades into tall open forest in moist sheltered valleys, woodland on drier west facing slopes and heath on thin soils on the plateau [*Fisher et al.*, 1995; *Wilkinson and Humphreys*, 2006]. Most species in the eucalypt forests have fire-adaptive traits, with very few killed by severe wildfires [*Gill*, 1981]. As a result, postfire recovery of vegetation is rapid, especially in the first year. Often a complete return of vegetation cover occurs within 5–6 years of fire, with fuel loads generally reaching between 15 and 30 t ha^{-1} [*Chafer et al.*, 2004]. Owing to the characteristics of the terrain, only small areas on the plateau have been cleared for agriculture and urban settlement. The majority (∼70%) of the Nattai catchment is protected native forest.

[9] The climate of the study region is humid to subhumid warm temperate (Köppen classification, Cf). Mean monthly minimum and maximum temperatures are 2°C (July) and 27°C (January), respectively (Bureau of Meteorology, Climatic averages for NSW and ACT sites, available at http://www.bom.gov.au/climate/averages/tables/ca_nsw_names.shtml, accessed 12 October 2006). Rainfall is uniformly distributed throughout the year with a summer maximum and occasional light snowfalls in winter at higher elevations. Annual rainfall totals range from 400 mm (in drought years) to 1800 mm, with an average of 864 mm determined from eight rainfall gauges across the catchment. Large yearly variations in rainfall across southeastern Australia have been linked to the El Niño–Southern Oscillation (ENSO) [*Chiew et al.*, 1998]. Below average rainfall and higher than average temperatures are generally associated with El Niño events, while the reverse conditions are associated with La Niña events [*Kiem et al.*, 2006].

[10] The Nattai catchment is drained by the Nattai River in the south and west and a major tributary, the Little River to the east. In this study, the Nattai River catchment is further subdivided into the upper, middle, and lower Nattai, while the Little River is divided to define its major tributary, Blue Gum Creek (Figure 1). The rationale for this is twofold: to broadly distinguish gauged from ungauged parts of the catchment and to analyze rainfall intensity and accumulation, particularly for storms with limited distributions. Flow gauges are located in the mid-Nattai subcatchment (gauged area 446 km^2 or 64% of the total catchment area) and on the Little River above the confluence with Blue Gum Creek (104 km^2 or 15% of total area). The subcatchments differ in terms of relief and drainage (Table 1) reflecting the degree of stream incision through the different units of the Sydney Basin sequence. For example, the upper Nattai shows the steepest stream gradient, highest drainage density and lowest proportion of slopes greater than 30% reflecting headwater drainage off the sandstone plateau. The middle and lower Nattai sections are characterized by a low stream gradient and a

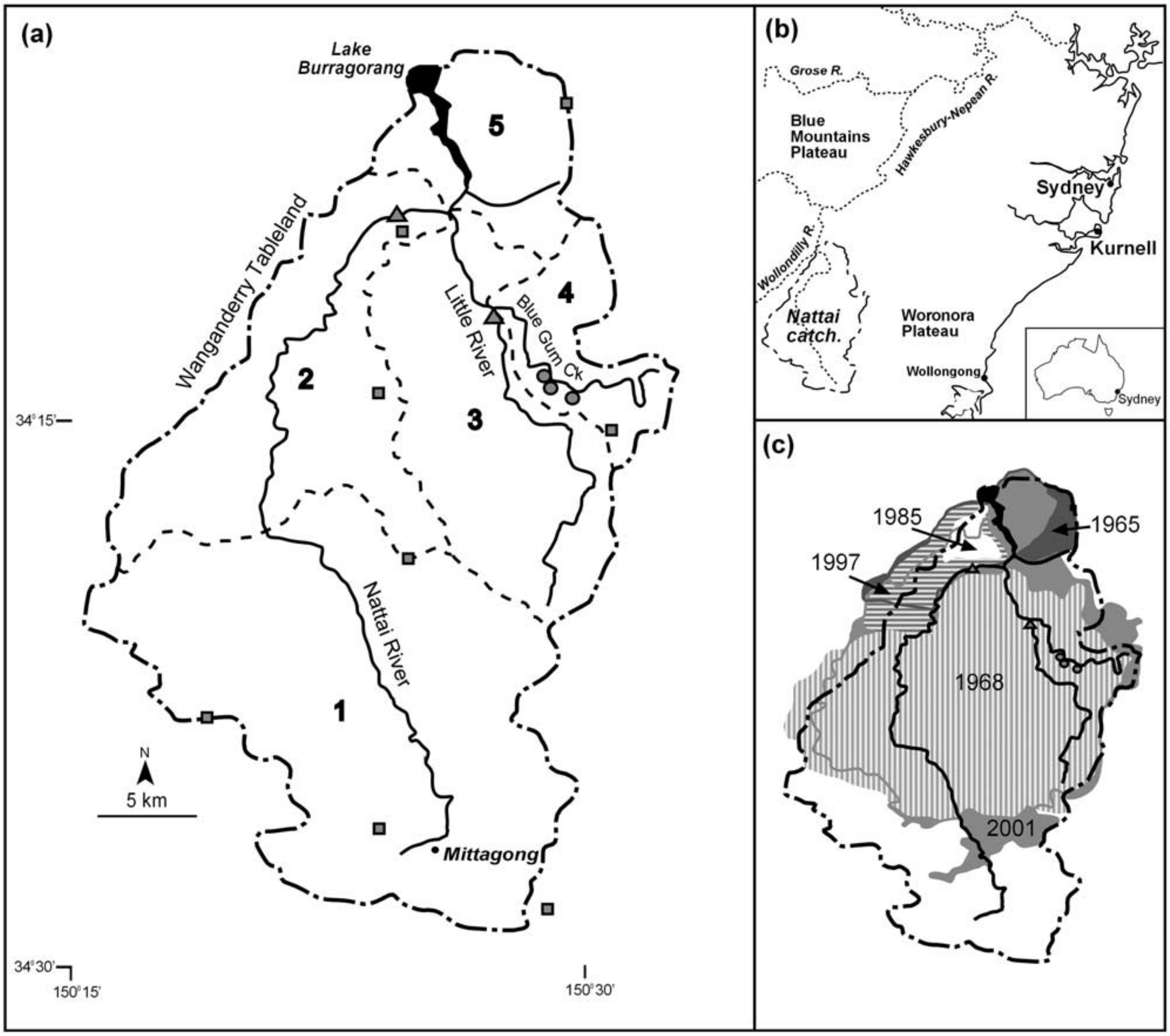

Figure 1. Nattai catchment, southeastern Australia showing (a, b) the location of rainfall gauges (square), flow gauges (triangle), Blue Gum Creek field sites (circle) and (c) extent of the 1965, 1968, 1997, and 2001 wildfires and 1985 hazard reduction burn. Subcatchments in Figure 1a are labeled as follows: 1, upper Nattai; 2, mid-Nattai; 3, Little River; 4, Blue Gum Creek; and 5, lower Nattai. The location of the Kurnell radar near Sydney is shown in Figure 1b.

greater proportion of slopes >30%, reflecting a deep valley incised into the underlying softer shale- and siltstone-dominated lithologies.

3. Wildfire History

[11] The Nattai catchment has experienced a number of wildfires since fire records commenced in 1964 (Figure 1 and Table 2). The two largest wildfires, which burnt 49–100% of the gauged catchment areas, occurred in 1968 and 2001. The 2001 wildfires were started by multiple lightning strikes across the catchment and strong westerly winds associated with a deep low-pressure system over southeastern Australia [*Winter and Watts*, 2002; Bureau of Meteorology, Summary of significant severe thunderstorm events in NSW—2001/02, available at http://www.bom.gov.au/weather/nsw/sevwx/0102summ.shtml, accessed 17 October 2006]. Very high to extreme fire severity (i.e., all green and woody vegetation <10 mm consumed including the crown) affected most of the plateau and low to very high fire severity (i.e., ground fuels and shrubs consumed) affected the valley side slopes and floor [*Chafer et al.*, 2004]. A similar situation is likely to have occurred in 1968, when lightning strike on the Wanganderry Tableland (mid-Nattai subcatchment) and strong northwest winds rapidly spread fire east across the catchment [*Cunningham*, 1984; *New South Wales National Parks and Wildlife Service*, 2002].

[12] Smaller wildfires (10–100 km^2) triggered by lightning strike occurred in 1965, 1980, 1988–1989, and 1997, burning 8% or less of the gauged catchments. Precise details regarding the severity of the smaller wildfires are unknown, but from fire service reports (NSW Rural Fire Service, Brief

Table 1. Characteristics of Subcatchments in the Nattai Catchment

	Subcatchment				
	Upper Nattai	Mid-Nattai	Lower Nattai	Little River	Blue Gum Creek
Area, km^2	300	150	65	139	48
Local relief,[a] m	666	676	533	575	359
Average stream gradient[b]	0.0186	0.0032	0.0046	0.0151	0.0098
Drainage density,[a] km km^2	2.58	2.16	1.76	1.96	2.17
Proportion >30% slope,[a] %	26	50	44	51	36
Dominant lithology	Quartz sandstone	Quartz sandstone and mudstone	Quartz sandstone and mudstone	Quartz sandstone	Quartz sandstone

[a]Determined from a digital elevation model with 25 m pixels using ArcMap and ArcHydro. Drainage density was determined using a minimum basin area of 0.125 km^2 for stream definition which captured first-order streams and higher. All catchments contain near vertical cliffs (>70°) up to 150 m high.
[b]Gradient of the Nattai River, Little River, and Blue Gum Creek (i.e., not including tributaries), determined from long profiles derived from 1:25,000 topographic maps with 10 m contour intervals.

history of bushfire, available at http://www.rfs.nsw.gov.au, accessed 17 October 2006) it is reasonable to expect similar patterns to the 2001 fires (i.e., a range of severities determined by slope and fuel loads [*Chafer et al.*, 2004]). Firefighting efforts, particularly since the 1940s, are likely to have reduced the extent of the majority of wildfires compared with natural conditions.

[13] In the cooler, winter months and during wetter years, hazard reduction burns (HRB) are carried out on the urban fringes or in strategic locations to reduce ground fuel loads. These fires are generally small (<2 km^2) and of low severity, burning only the leaf litter, grasses and shrubs. Two larger HRBs undertaken in the Nattai catchment since 1964 were carried out in September 1985 and August 1993, affecting an area of the divide between the middle and lower Nattai subcatchments, and the Blue Gum Creek valley, respectively.

4. Previous Work on Postfire Impacts in the Nattai Catchment

[14] After the 2001 wildfires, initial research was directed at three sites along Blue Gum Creek to investigate the postfire erosion (Figure 1). The sites showed evidence of extensive rain splash and overland flow on hillslopes. Despite this, postfire sediment transport was largely confined to the transfer of fine sediment, ash, charcoal and organics to the stream network, with only localized redistribution of the sandy minerogenic sediment, suggesting that limited surface runoff from hillslopes had occurred [*Shakesby et al.*, 2003, 2006; *Wallbrink et al.*, 2005; *Blake et al.*, 2006].

[15] Investigation of prefire and postfire controls on runoff revealed several important factors. Soil water repellency, naturally present at high background levels in the surface and subsurface layers, was destroyed at high temperatures during fires [*Doerr et al.*, 2006]. This resulted in patchy water repellency in the surface, with wettable areas able to absorb and store rainfall until reaching saturation or eroded by rain splash and overland flow [*Doerr et al.*, 2006]. Measurement of the rates of bioturbation by ants, small mammals and other invertebrates in the postfire period showed a rapid turnover of the upper meter of soil particularly on the middle and lower slopes, providing infiltration pathways between any water-repellent layers and deeper soil [*Shakesby et al.*, 2006]. Other hillslope features that provided sinks for overland flow were also present, including litter dams formed on low angled slopes and depressions from tree fall [*Shakesby et al.*, 2007]. There was no evidence of postfire surface sealing. Instead the surface consisted of a thin (<7 cm), loose layer of charcoal, organics and soil aggregates, overlying a colluvial mantle composed of thick, uniform sandy-gravelly units [*Tomkins et al.*, 2004]. The sandy, well drained soil implies that antecedent soil moisture is a relatively minor control on nonfire and postfire surface runoff on hillslopes, except perhaps under prolonged very wet conditions.

Table 2. Major Wildfires and Hazard Reduction Burns (>10 km^2) in the Nattai Catchment Since 1964

Date of Fire	Location, Subcatchment[a]	Type of Fire (Cause[b])	Total Catchment Area Burnt,[c] km^2	Proportion of Gauged Catchment Area Burnt[d]	
				Nattai R, %	Little R, %
9 Feb 1965	MN, LN	Wildfire (lightning)	97	4.1	0
28 Nov to 2 Dec 1968	UN, MN, LR, BGC	Wildfire (lightning)	423	49	100
9 Sep 1980	LN	Wildfire (unknown)	12	0	0
5 Sep 1985	MN, LN	Hazard reduction burn	14	0.9	0
1988/1989	UN, LR	Wildfire (unknown)	23	3.2	8
24 Aug 1993	BGC	Hazard reduction burn	12	0	1
26 Nov to 18 Dec 1997	MN, LN	Wildfire (lightning)	63	6	0
3 Dec 2001 to 14 Jan 2002	UN, MN, LN, LR, BGC	Wildfire (lightning)	530	58	99

[a]UN, upper Nattai; MN, mid-Nattai; LN, lower Nattai; LR, Little River; BGC, Blue Gum Creek.
[b]Unknown cause can include lightning strike, arson, and fires associated with power lines.
[c]Calculated using unpublished GIS data obtained from the Sydney Catchment Authority and descriptions from *Winter and Watts* [2002].
[d]Gauged catchment areas are Nattai River, 446 km^2; and Little River, 104 km^2.

Table 3. Details of Rainfall and Flow Gauges in the Nattai Catchment

Rainfall Gauge	Period of Record	Average Annual Rainfall, mm	1 Year ARI Rainfall, mm d^{-1}
Mittagong Kia Ora[a]	1902–1910; 1944–2003	912	79.2
Mittagong Leicester Park[b]	1946–2006	874	65.0
Mittagong High Range[a]	1945–2003	887	64.5
Hilltop Starlights Track[b]	1981–2006	883	73.5
Buxton Amaroo[a]	1967–2004	849	70.2
Hilltop Nattai Tableland[b]	1990–2006	800	62.5
Nattai Causeway[b]	1981–2006	832	71.0
Oakdale Cooyong Park[a]	1963–2004	876	82.6
Flow Gauge (Gauged Area)[b]	**Period of Record**	**Average Annual Discharge (ML)**	**1 Year ARI Flood,[c] ML d^{-1}**
Nattai River at the Causeway (446 km^2)	1965–2004	41 500	5246
Little River at Fire Road W41 (104 km^2)	1990–2004	6638[d]	1195[d]

[a]Published records from the *Bureau of Meteorology* [2004].
[b]Unpublished records obtained from the Sydney Catchment Authority.
[c]Determined from flow duration curves constructed from the data.
[d]Figures presented are likely to be minimum values due to long periods of missing data within the short period of record.

[16] Examination of flood hydrographs from the Nattai River, including a major flood in April 1969, five months after the 1968 fires, showed a very flashy regime in response to rainfall [*Tomkins et al.*, 2007]. Numerous small hillslope channels, combined with an absence of saturated zones along streams, indicate that the majority of runoff in the catchment results from infiltration-excess overland flow, with only minor contributions of subsurface flow.

5. Methods

[17] The 1965, 1968, 1997, and 2001 wildfires and 1985 HRB were selected for detailed investigation of postfire rainfall and hydrological response. The fires were chosen for several reasons, including location within the gauged catchment areas and differences in fire severity and extent. The first year after fire was the major focus, as this immediate postfire period is when the impact of fire on runoff is expected to be greatest, attenuating over 5–6 years as the vegetation recovers. Given several unknowns in postfire vegetation recovery rates, such as whether these vary with species, burn severity and extent, years two to six after fire were excluded from most of the analysis [cf. *Brown*, 1972]. Only the first 3 years following the largest wildfires in 1968 and 2001 were examined with respect to changes with time after fire. Nonfire periods were defined as the years between fires, excluding the first 6 years after wildfire and the first year after the 1985 HRB to be certain of a complete postfire recovery and return to "normal" conditions.

[18] Analysis of daily rainfall data from eight gauges across the catchment (Figure 1 and Table 3) was carried out to identify rainfall events in the years following the fires and during nonfire periods. An event was defined as having a minimum of 10 mm d^{-1} of rainfall recorded at one or more gauges, which captured both widespread rainfall events as well as localized storms. Data from each rainfall gauge were used to determine the average annual rainfall for the period of record and average recurrence intervals (ARI) of daily rainfall (Figure 2). The annual and daily data from each gauge were averaged to determine rainfall at the catchment scale. Catchment average values are used for all rainfall analysis unless otherwise indicated. The number of rainfall events and peak rainfall for each event during postfire and nonfire periods were identified. The magnitude and frequency of rainfall events (based on peak rainfall) in the first year postfire were compared to nonfire years to determine whether the size and number of events varied. A similar analysis was undertaken to compare the rainfall events following each fire and for the 3 years after the 1968 and 2001 fires.

[19] Radar reflectivity data available since 2001 were obtained from the Australian Bureau of Meteorology (BoM) Doppler radar facility at Kurnell, south of Sydney (Figure 1). The data were used to analyze the characteristics

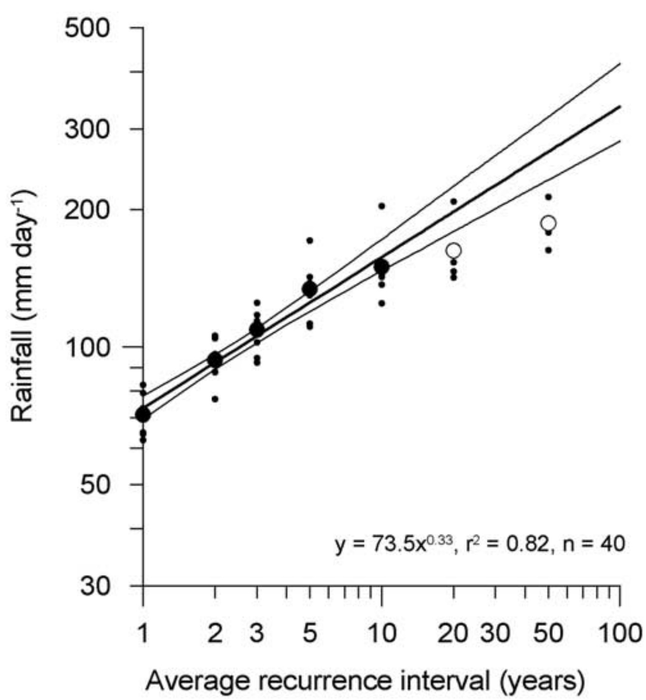

Figure 2. Average recurrence intervals (ARI) of rainfall in the Nattai catchment. Small circles indicate data from each rainfall gauge. Large closed circles indicate mean values. Large open circles indicate minimum mean values due to small sample sizes from a limited number of gauges at high ARIs. Trend (thick line) and 95% confidence limits are shown.

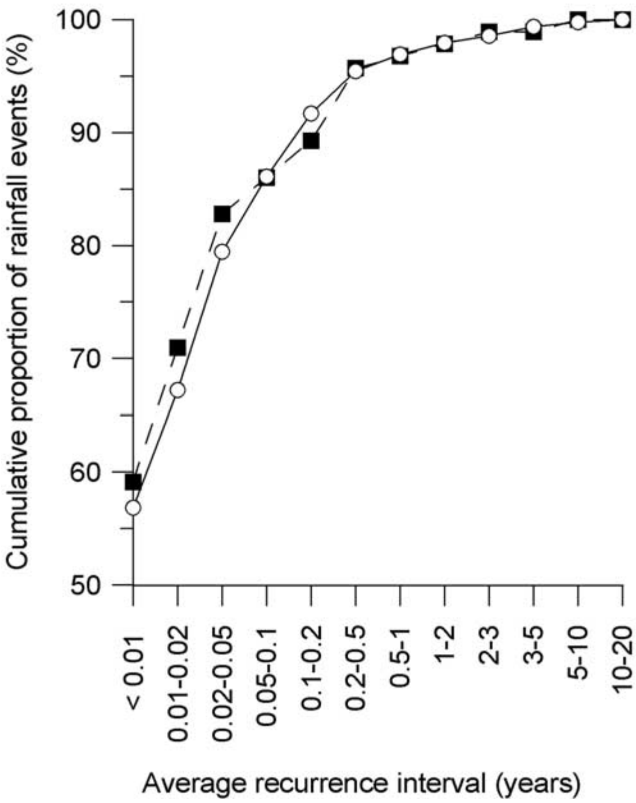

Figure 3. Magnitude of rainfall events in the first year after fire (square) and in nonfire periods (circle); $n_{postfire}$ = 93; $n_{nonfire}$ = 482.

of each rainfall event following the 2001 fires, including rainfall intensity, accumulation, distribution and type (i.e., drizzle, showers or storms). The reflectivity data, measured at 5-min intervals, were processed and calibrated with rain gauge observations by the Sydney Water Corporation and BoM to derive 15-min rainfall intensity data (in mm h^{-1}) (A. Seed, personal communication, 2006). The rainfall intensity images were examined for the period covering each event. Storm events were identified using the definition of *Matthews and Geerts* [1995]: storm cells with 15-min rainfall intensities (I_{15}) greater than 35 mm h^{-1} occurring over a continuous period with a maximum 30-min gap between cells. A GIS layer of the five subcatchments was used to export 15-min rainfall accumulation (A_{15}) data for each subcatchment, from which maximum 60-min cumulative rainfall amounts (A_{60}) were derived.

[20] Hourly instantaneous discharge data were obtained from the flow gauges in the Nattai River and Little River, with records commencing in 1965 and 1990, respectively (Figure 1 and Table 3). The data were used to calculate annual totals, average annual discharge and the mean annual flood (Nattai River, 5246 ML d^{-1} or 61 m^3 s^{-1}; Little River, 1195 ML d^{-1} or 14 m^3 s^{-1}). For each rainfall event during the nonfire and postfire periods, the corresponding peak discharge was identified and used to infer runoff at the large catchment scale. In this study, storm flow duration was not directly considered, since our purpose was to evaluate runoff magnitude and the number of peaks in discharge with respect to the fires. The data (peak rainfall and peak discharge) from the first year after the largest wildfires (1968 and 2001) were compared to nonfire data to determine any increases in runoff as a result of the fires. Comparisons of data between the five fires were carried out to determine whether runoff varied with respect to fire severity and extent (as a proportion of the gauged catchment area). The first 3 years after the 1968 and 2001 fires were compared to determine whether runoff decreased with time after fire. Examination of hydrograph shapes for each rainfall-runoff event in the first year after the fires was also undertaken to identify any double peaks in discharge.

6. Trends in Nonfire and Postfire Rainfall

6.1. Frequency-Magnitude of Rainfall Events in Nonfire and Postfire Periods

[21] The magnitude of rainfall events in nonfire periods compared with those in the first year postfire showed no significant difference (chi-square test, p value = 0.74) (Figure 3). In both, 98% of events were <1 year ARI (73.5 mm d^{-1}) and ~58% were <0.01 year ARI (16.1 mm d^{-1}). There were similar proportions of events with 1–10 year ARIs, but only one rainfall event had a return period of >10 years, which occurred during the (longer) nonfire period.

[22] The frequency of rainfall events (separated into <1 year ARI and ≥1 year ARI) showed some differences in the first year postfire compared with nonfire periods (Figure 4). More than 50% of nonfire years experienced between 20 and 30 rainfall events of <1 year ARI, whereas the majority of postfire years experienced fewer (10–20) rainfall events. A similar pattern is revealed for rainfall of ≥1 year ARI. The results suggest that nonfire periods tend to be wetter than the first year after fire, although this may

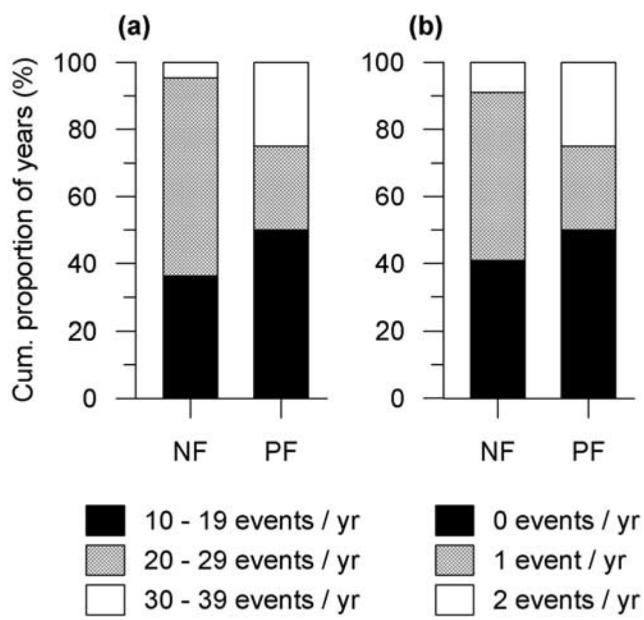

Figure 4. Frequency of rainfall events (a) <1 year ARI and (b) ≥1 year ARI in the first year after fire (PF) and in nonfire periods (NF); $n_{postfire}$ = 4 years; $n_{nonfire}$ = 22 years. There were no years with <10 rainfall events of <1 year ARI.

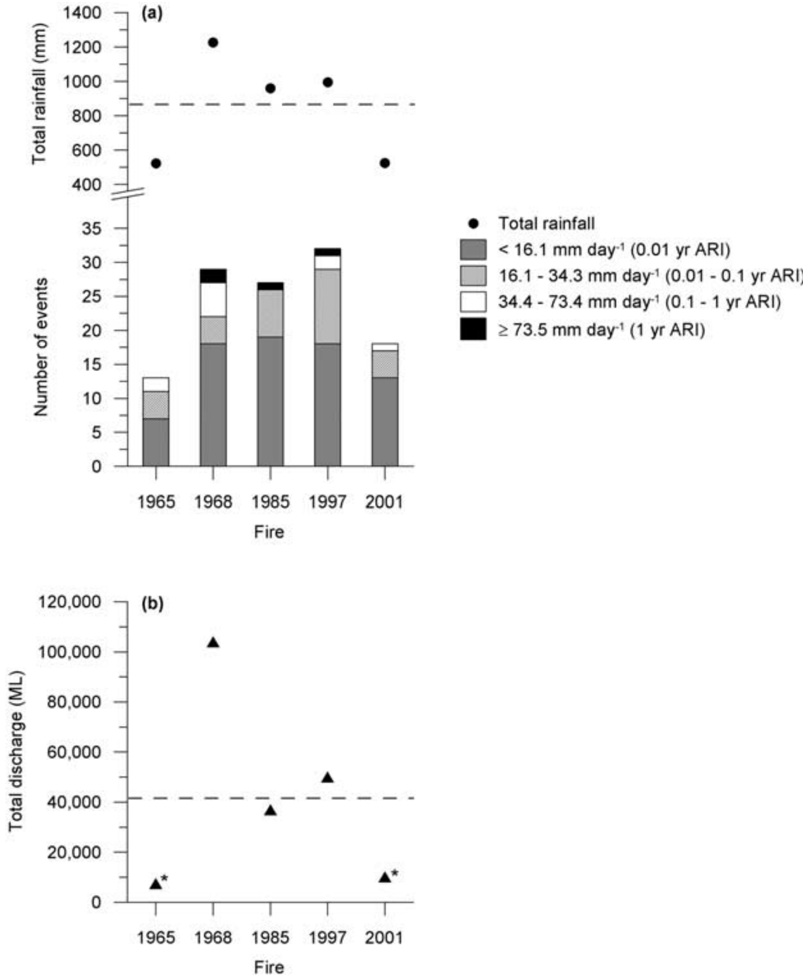

Figure 5. Summary of (a) rainfall and (b) discharge in the Nattai River in the first year after the 1965, 1968, 1997, and 2001 wildfires and 1985 hazard reduction burn. Horizontal dashed lines indicate average annual rainfall and average annual discharge. Asterisk in Figure 5b indicates minimum values (44% of the 1965 record is missing; 21% of the 2001 record is missing).

be an artifact of the small sample sizes for postfire data (n = 4 years). Years with ≥30 rainfall events of <1 year ARI and years with two events of ≥1 year ARI occur in both nonfire and postfire periods and, at least 40% of years experienced no large magnitude rainfall events.

6.2. Frequency-Magnitude of Rainfall Events After Each Fire

[23] Rainfall events in the first year after each fire, including the 1985 HRB (Figure 5a), and for the first 3 years after the 1968 and 2001 fires (Figure 6a) show greater variability than was evident in the earlier analysis of nonfire and postfire data. Annual rainfall totals and the total number and size of events differ substantially between the years investigated, with no clear pattern or common trend. For example, total rainfall across the catchment after the 1968, 1985, and 1997 fires was above to well above average (by a factor of 1.11 to 1.42), contrasting with well below average conditions following the 1965 and 2001 fires (0.60 to 0.61x). There were more, larger rainfall events after the 1968, 1985, and 1997 fires, compared with fewer events following the 1965 and 2001 fires. There were two ≥1 year ARI rainfall events in the first year after the 1968 fires compared with one each following the 1997 and 1985 fires and none in the years after the 1965 and 2001 fires. In the second year after the 1968 fires there were more mostly smaller events and total rainfall was substantially below average. Although data is not presented here for nonfire periods, similar interannual variability was observed.

[24] Variability in the number and size of rainfall events and total rainfall each year is strongly reflected in total discharge (Figures 5b and 6b). For example, the first year after the 1968 fires, with well above average rainfall and a greater number of larger events, had well above average discharge (2.5x). Around 27% of the total annual flow (1969 flood) resulted from the largest rainfall event (peak 126 mm d^{-1}). In comparison, the first 3 years after the 2001 fires with few, smaller rainfall events and no events ≥1 year ARI, experienced well below average discharge each year (<0.3x, adjusted for the missing record).

6.3. Rainfall Events After the 2001 Fires

[25] Analysis of the radar imagery for each rainfall event following the 2001 fires revealed two main rainfall types (Table 4 and Figure 7). Type 1 is characterized by stratiform rainfall (showers and drizzle) lasting one to several days,

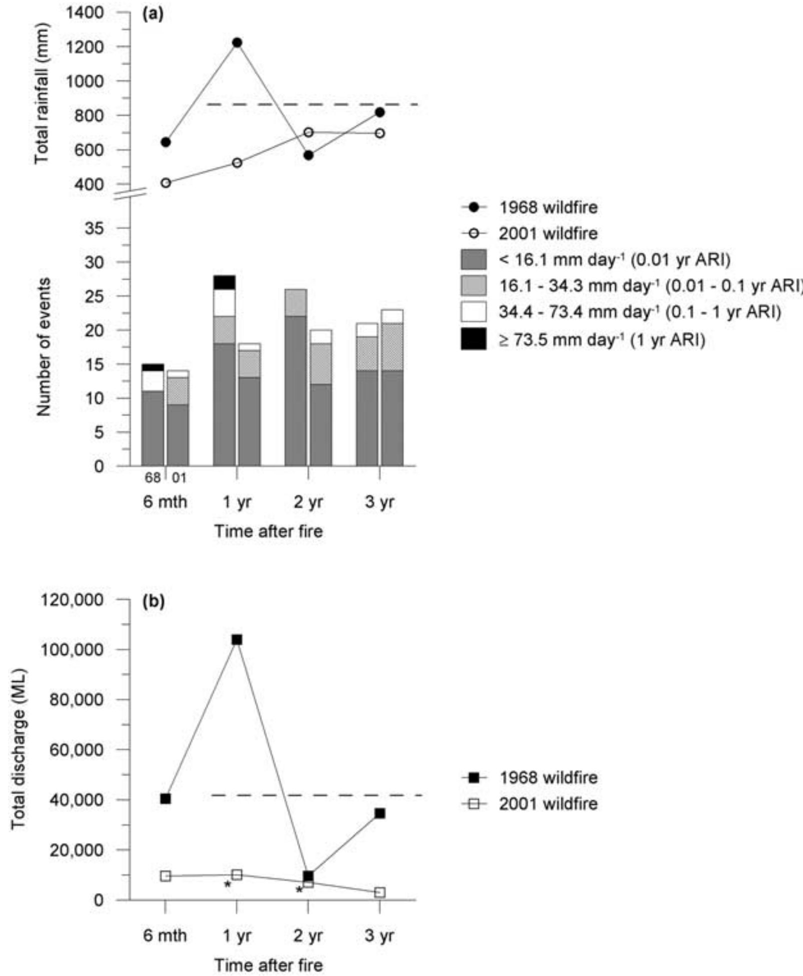

Figure 6. Summary of (a) rainfall and (b) discharge in the Nattai River in the first 3 years after the 1968 and 2001 wildfires. Horizontal dashed lines indicate average annual rainfall and average annual discharge. Asterisk in Figure 6b indicates minimum values (20–25% of the 2001 record is missing).

predominantly of low intensity (<10 mm h^{-1}) but increasing to moderate intensity (10–30 mm h^{-1}) at times, with peak falls of up to 70 mm d^{-1}. These are further divided into subsets 1a and 1b, representing continuous, widespread falls and intermittent, patchy falls, respectively, with the amount of runoff a function of rainfall duration and distribution. Type 2 is characterized by localized, convective rainfall (thunderstorms) predominantly occurring during the summer months with well defined, short-lived high-intensity cells (I_{15} > 75 mm h^{-1}) and peak rainfall of up to 45 mm d^{-1} in the path of the storm. These produced well defined short-lived peaks in discharge in the catchment depending on cell location, size, speed, and direction. Although no events of ≥1 year ARI (≥73.5 mm d^{-1}) occurred after the 2001 wildfires, it is likely that these were characterized by widespread, continuous stratiform rainfall (i.e., type 1) with extended periods of moderate to high-intensity falls to accumulate large daily totals and generate substantial surface runoff.

[26] The greatest number of rainfall events in the first year after the 2001 fires were type 1b (61%; Table 5) indicating that patchy, low-intensity rainfall prevailed throughout the year. Most of the remaining events were type 2 especially in the first months after the fire, with storm cells tracking across the Nattai catchment concentrating rainfall in the mid-Nattai, Little River and Blue Gum Creek subcatchments. Only one type 1a event occurred less than a month after the fires producing widespread, low-intensity rainfall over several days. Similar trends in the number and type of rainfall events continued for the 3 years thereafter. There were also a number of unclassifiable events within the record because of missing radar data. Daily rainfall totals alone were inconclusive, especially for those events with low totals over 1–2 days, which could result from either of the rainfall types.

7. Trends in Nonfire and Postfire Hydrological Response

7.1. Rainfall-Runoff Events in Nonfire and Postfire Periods

[27] In the Nattai River, 91% of rainfall-runoff events in the first year after the 1968 and 2001 wildfires (49–58% of the gauged catchment area burnt) fall within the range of expected values defined by 95% pointwise prediction limits determined from the nonfire data (Figure 8a). Only two

Table 4. Summary of Rainfall Types Following the 2001 Fires Determined From Radar Reflectivity Data

	Value
	Type 1a[a]
Maximum I_{15}	10 mm h^{-1}
Maximum A_{15}[b]	<3 mm
Maximum A_{60}[b]	<10 mm
Total rainfall accumulation[c]	>300 mm
Duration of event	4 d
Maximum rainfall recorded at a gauge	40–70 mm d^{-1}
Peak rainfall[d]	30–50 mm d^{-1}
Synoptic conditions[e]	Often associated with slow moving high-pressure systems (predominantly northeasterly or northwesterly winds)
	Type 1b[f]
Maximum I_{15}	30 mm h^{-1}
Maximum A_{15}[b]	1–5 mm
Maximum A_{60}[b]	2–15 mm
Total rainfall accumulation[c]	50–200 mm
Duration of event	1–3 d
Maximum rainfall recorded at a gauge	10–80 mm d^{-1}
Peak rainfall[d]	10–70 mm d^{-1}, often 20–50 mm d^{-1}
Synoptic conditions[e]	Often associated with moist onshore winds, offshore high-pressure systems or low-pressure systems (predominantly northeasterly or southeasterly winds)
	Type 2[g]
Maximum I_{15}	>75 mm h^{-1}
Maximum A_{15}[b]	5–20 mm
Maximum A_{60}[b]	15–40 mm
Total rainfall accumulation[c]	50–250 mm
Duration of event	2–15 h, often 6–8 h
Maximum rainfall recorded at a gauge	20–50 mm d^{-1}
Peak rainfall[d]	10–45 mm d^{-1}
Synoptic conditions[e]	Often associated with inland or prefrontal troughs (predominantly northwesterly or southwesterly winds)

[a]Widespread low-intensity stratiform rainfall over >70 h with large rainfall accumulation resulting in a gradual increase in river discharge.

[b]Maximum 15- and 60-min rainfall accumulation determined for each subcatchment.

[c]Sum of total rainfall accumulation determined for each subcatchment.

[d]Averaged across eight rainfall gauges in the Nattai catchment.

[e]Determined from daily mean sea level pressure charts obtained from the Bureau of Meteorology (Australian Regional MSLP Analysis Chart Archives, available at http://www.bom.gov.au/nmoc/MSL/index.shtml, date accessed 26 September 2006).

[f]Low-moderate intensity stratiform rainfall over 10–40 h with no or only a very small increase in river discharge depending on rainfall distribution (patchiness) and totals.

[g]Short-duration, intense convective rainfall with well-defined storm cells during summer (November–February) resulting in a significant but short-lived increase in river discharge. Rainfall and discharge are heavily dependent on storm cell location, size, speed, and direction.

relatively small postfire events after the 1968 fires are above the upper prediction limit but these are consistent with the upper range of nonfire data for similar rainfall values, indicating that runoff after severe, widespread wildfires was no greater or more enhanced than runoff under nonfire conditions. The majority of runoff events after the 1968 fires generally group toward the upper prediction limit, but these are probably a reflection of the much wetter conditions during the year rather than impacts of fire. There are also a few rainfall events falling below the lower prediction limit that produced no or very little runoff. These events occurred in nonfire periods and immediately after the 1968 and 2001 wildfires (i.e., the first postfire rainfall-runoff events). The most extreme datum following the 1968 fires was preceded by a prolonged period of no flow in the Nattai River, suggesting either minimal runoff from hillslopes in response to rainfall or total absorption of runoff within the dry river bed.

[28] In the Little River, 6 out of 10 rainfall-runoff events in the first year after the 2001 wildfires (99% of the gauged catchment area burnt) fall within the 95% prediction limits determined from the nonfire data, and eight out of ten events occur within the nonfire range (Figure 8b). The data suggest an upward shift in runoff which is inconsistent with rainfall (below average in 2002), but given the small number of events no conclusions can be made with any certainty. Of the two events with relatively high runoff, one (April 2002; three months postfire) is clearly more extreme than the nonfire data, suggesting that runoff from some smaller events (e.g., storms) may be enhanced by fire. However, it is possible that this point is an artifact of our analysis since the event was the result of a very small thunderstorm that tracked eastward across the mid-Nattai, Little River, and Blue Gum Creek catchments. The storm produced localized very high intensity falls in these catchments with a gauged maximum of 25 mm d^{-1} that was averaged in the analysis to 9 mm d^{-1}.

7.2. Rainfall-Runoff Events After Each Fire

[29] Comparisons of rainfall-runoff events in the Nattai River in the first year after the 1965, 1968, 1997, and 2001 wildfires and 1985 HRB show no clear pattern of increasing runoff with respect to fire severity or extent (Figure 9). Trend lines constructed from the data for each fire show that events following the 2001 wildfires, which burnt the largest area of the gauged catchment, fall within a similar range to the much smaller 1965 and 1997 wildfires and low-severity 1985 HRB. Only runoff events in the much wetter year after 1968 wildfires were comparably higher indicated by an upward shift in the line intercept.

[30] Comparisons of rainfall-runoff events in each of the 3 years after the 1968 and 2001 fires show no clear pattern of decreasing runoff with time after fire (Figure 10). Instead, the trends in the Nattai River after the 1968 fires (Figure 10a) suggest that there may be a correlation between the magnitude of rainfall-runoff events and total annual rainfall (year 1, 1225; year 2, 570; year 3, 819 mm a^{-1}), but this is not consistent in the data for the 3 years after the 2001 fires (year 1, 525; year 2, 702; year 3, 697 mm a^{-1}). Alternatively, the similar trends in the magnitude of rainfall-runoff events in the 3 years after the 2001 fires may be a reflection of the relatively similar proportions of the different rainfall types (Table 5).

7.3. Hydrological Response of Individual Rainfall-Runoff Events in the First Year After Fire

[31] Analysis of the impacts of fire on stream hydrographs was limited to the few events producing an increase in discharge to >500 ML d^{-1} (Figure 11). Of these, the

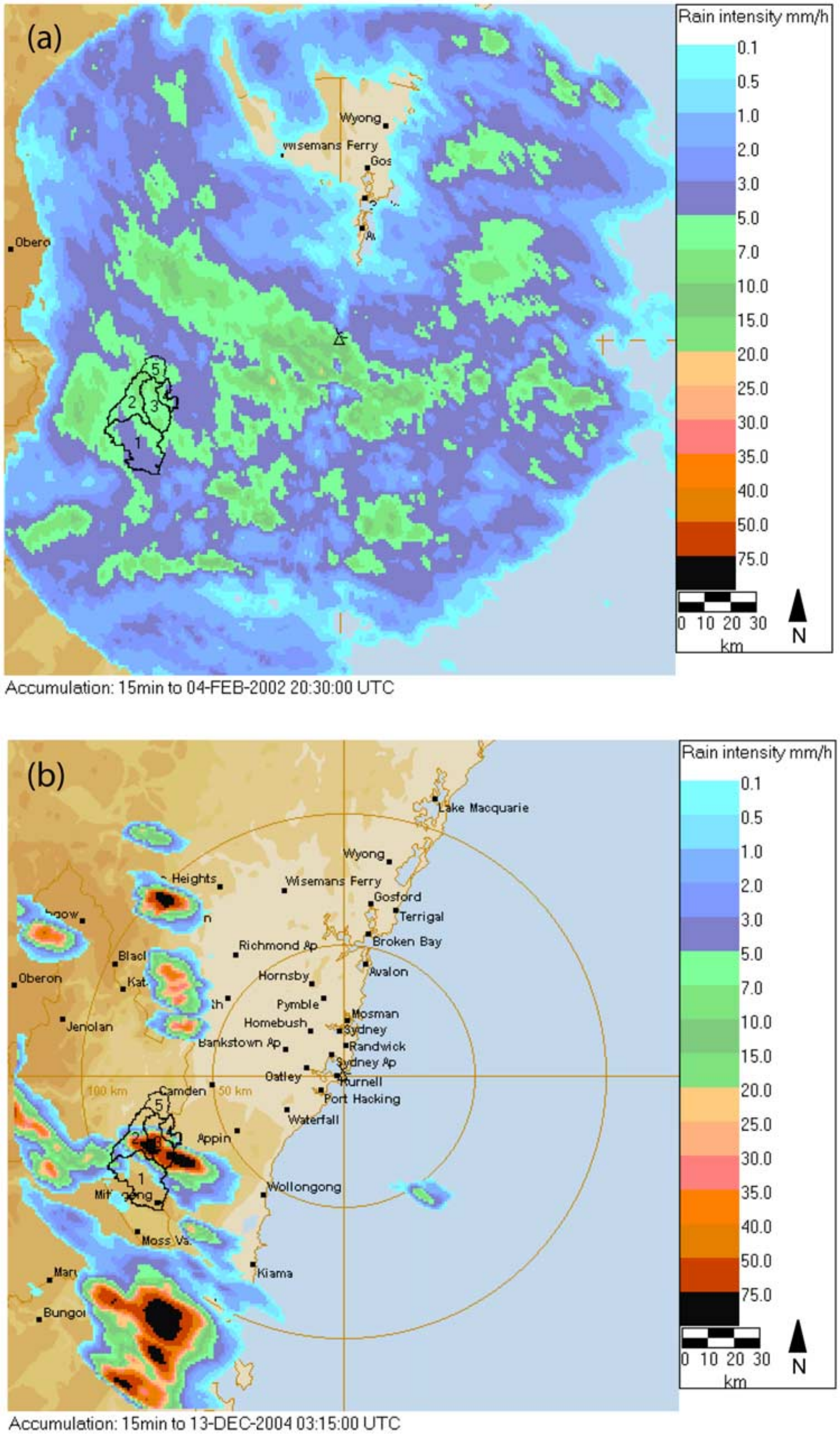

Figure 7. Examples of (a) type 1, low-intensity stratiform rainfall and (b) type 2, short-duration, high-intensity convective thunderstorms determined from radar data.

Table 5. Number of Rainfall Events by Type Recorded After the 2001 Fires

Year	Rainfall Type[a] 1a	1b	2	unknown[b]
2002	1	11	6	0
2003	1	9	9	2
2004	0	10	11	6
Total	2	30	26	17

[a]Details shown in Table 4.
[b]Radar data not available.

majority show single peaks with a rapid rise and fall especially during the flood events in August 1986, April 1969, and 8 August 1998 and in response to the thunderstorm in the Little River catchment in April 2002. Only two of the events, in March 1969 and 18 August 1998, show significant multiple peaks in discharge, and another two in October 1965 and February 2002, show double peaks. For the 18 August 1998 event, the similarity in both the number and magnitude of the peaks in the Nattai River (6% gauged catchment area burnt) and Little River (unburnt) indicates that these are a response to variations in rainfall intensity and/or duration not evident from the daily rainfall totals, rather than differences in hydrological response from burnt and unburnt areas. The 1965 and 1969 events show differences in daily rainfall totals coinciding with the discharge peaks, supporting this interpretation. The radar imagery for February 2002 provides more conclusive evidence showing two distinct rainfall episodes which correlate with the discharge pattern. Hence multiple peaks in discharge in

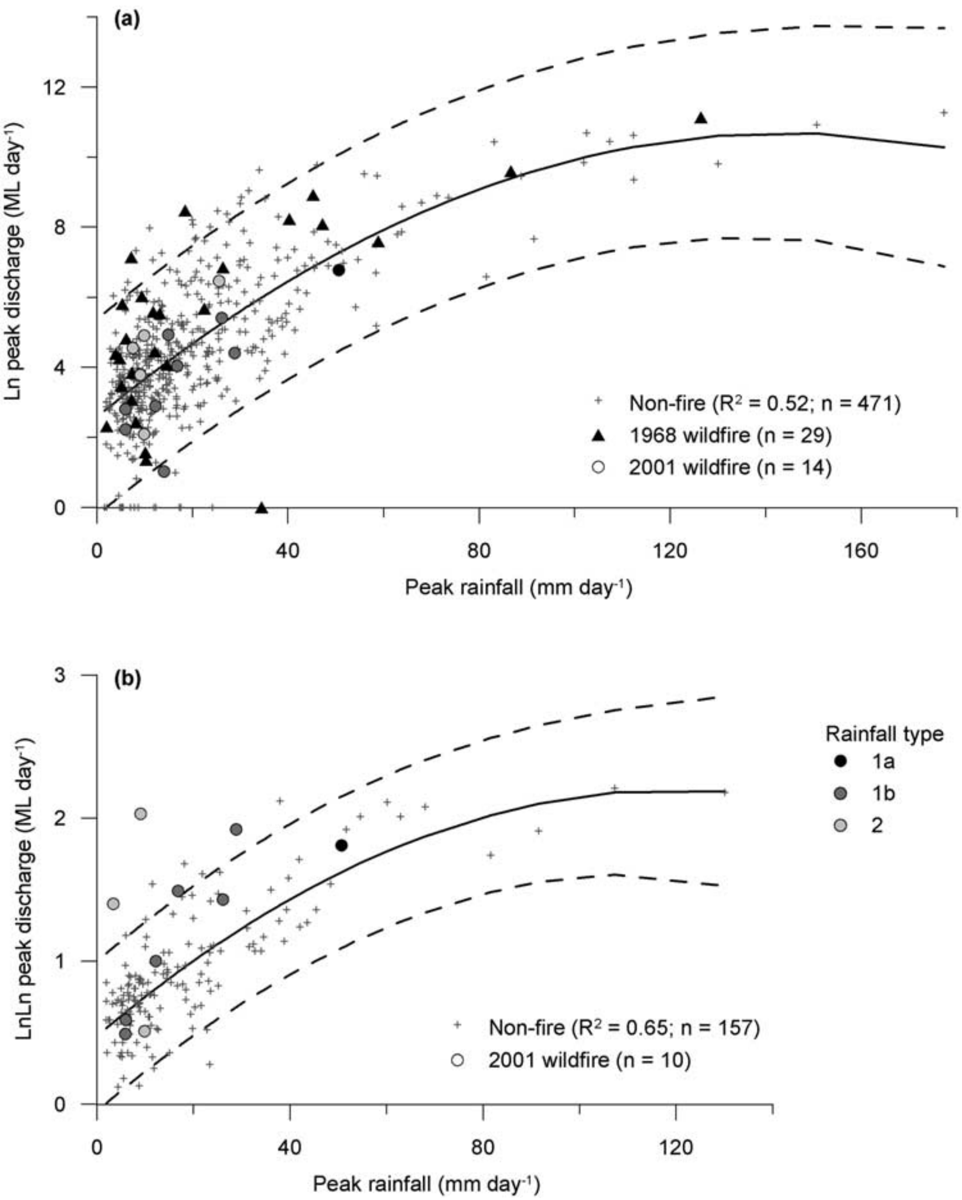

Figure 8. Rainfall-runoff events in the (a) Nattai River and (b) Little River in the first year after severe wildfires in 1968 and 2001 and in nonfire periods. Solid lines indicate quadratic functions fitted to the nonfire data. Dashed lines indicate 95% pointwise prediction limits for the nonfire data determined using SPSS.

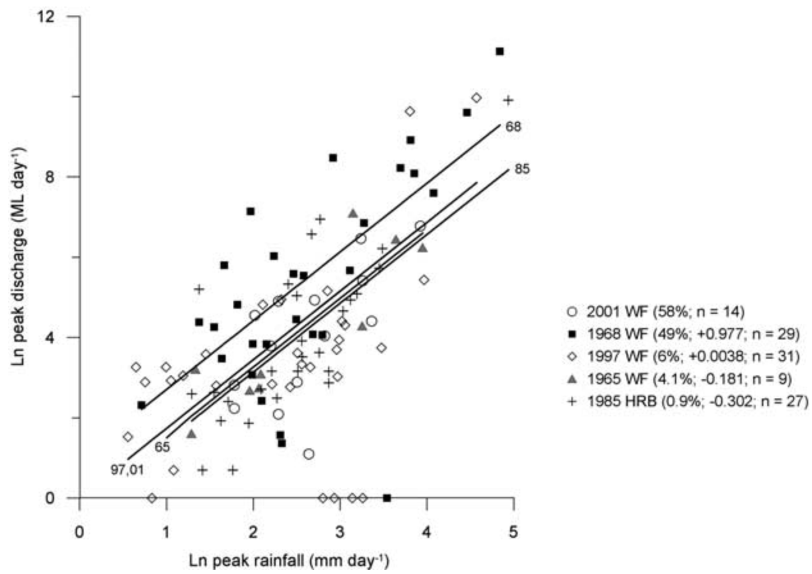

Figure 9. Rainfall-runoff events in the Nattai River in the first year after the 1965, 1968, 1997, and 2001 wildfires and 1985 hazard reduction burn. Trend lines were determined using the general linear model function in Minitab and an F test of the difference in variance between the residuals (zero values were excluded to achieve normality). Numbers in parentheses indicate the proportion of gauged catchment area burnt, the difference in the intercept relative to the 2001 trend and sample sizes.

the Nattai catchment appear to be a response to rainfall characteristics rather than impacts of fire.

8. Discussion

[32] For the wildfires examined, our results show that fire has no detectable effect on runoff at the large catchment scale, although some individual storm events in the smaller, more extensively burnt Little River catchment may have been fire affected. Instead the magnitude and extent of runoff after wildfires appears to be related to the number and characteristics of rainfall events in the postfire period. These findings are consistent with previous postwildfire studies from southeastern Australia which range from small to large spatial scales: in years with low total rainfall and/or low-intensity rainfall events, little or no postfire runoff (and erosion) was observed, irrespective of fire extent and severity [e.g., *Vertessy*, 1984; *Prosser and Williams*, 1998]. In other postfire years, significant runoff and sediment transport resulted from one or two very large magnitude rainfall events [e.g., *Atkinson*, 1984].

8.1. Controls on Rainfall and the Timing of Wildfires in Southeastern Australia

[33] There is a suggested link between ENSO, or more specifically rainfall deficits associated with El Niño events (or a negative Southern Oscillation Index, SOI), and the onset or increased activity of wildfires during the spring-summer (October–~March) fire season [*Vines*, 1974; *Skidmore*, 1987; *Williams and Karoly*, 1999]. This relationship is demonstrated by *Cunningham* [1984], who reconstructed the fire history in the Blue Mountains since 1804, showing a clear pattern of below average rainfall in the prefire October and November months during the years that had outbreaks of wildfires. In the Nattai catchment, similar trends of well below average October–November rainfall precede the 1968, 1997, and 2001 wildfires, corresponding to a neutral or negative SOI. The February 1965 fires were preceded by much wetter October–November months, but a very dry December–January, confirming a link between consecutive months of rainfall deficits and the timing of major wildfires.

[34] ENSO has been shown to be a major control on climate variability across southeastern Australia, influencing the total numbers and intensity of rainfall events on interannual timescales [*Nicholls and Kariko*, 1993]. The influence of ENSO on rainfall in some years after fire is evident, however, in other years the relationship is less clear. For example, Cunningham's Blue Mountains record showed that six wildfire events were followed by a negative SOI, but four of these experienced above average rainfall in the first year postfire (i.e., the opposite to what is expected). The Nattai fires revealed similar results, with both the strength of the SOI and the impact on rainfall varying between fires, but not in any predictable manner (Figure 12). For example, in 1969 and 2002 the SOI was weakly negative, but in 1969 the impact on rainfall was weak (above average), whereas in 2002 the impact on rainfall was very strong causing widespread drought (Bureau of Meteorology, El Niño—Detailed Australian analysis, available at http://www.bom.gov.au/climate/enso/australia_detail.shtml, accessed 8 November 2006). Hence in some years after fires, other factors likely to be caused by atmosphere-land surface interactions appear to be influencing annual rainfall trends.

[35] The major controls on the timing and type of individual rainfall events are weather patterns governed by atmospheric circulation. In southeastern Australia, weather patterns producing large magnitude rainfall events appear to be the most critical since these events generate substantial surface runoff and sediment transport [*Tomkins et al.*, 2007].

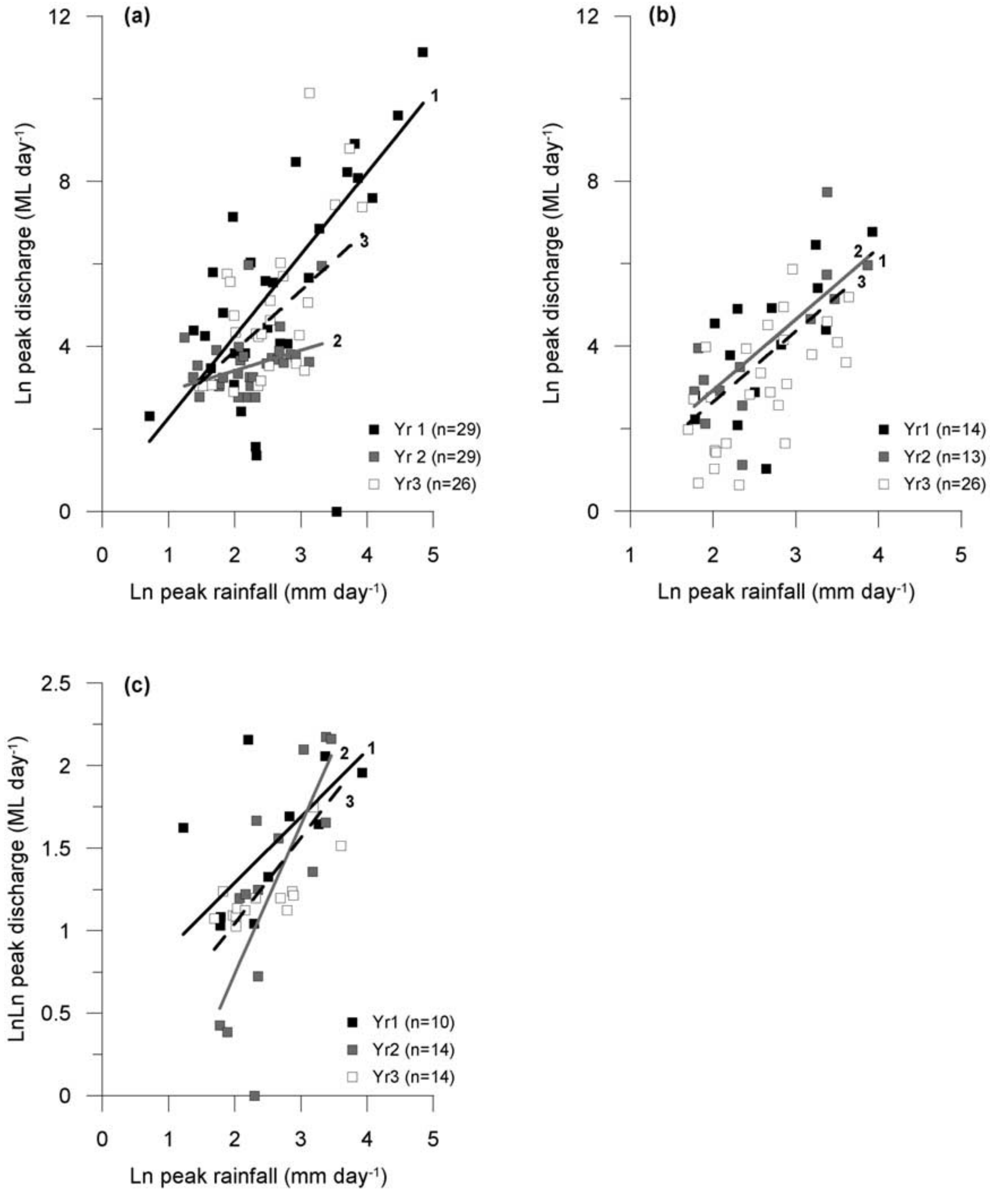

Figure 10. Rainfall-runoff events in the (a, b) Nattai River and (c) Little River in the first 3 years after the 1968 (Figure 10a) and 2001 wildfires (Figures 10b and 10c). Trend lines were determined using the general linear model function in Minitab and an *F* test of the difference in variance between the residuals.

Large rainfall events can also significantly raise annual totals, which may explain the poorer correlation between ENSO and rainfall in the years when these events occurred (e.g., 1969). The April 1969 flood was triggered by a tropical cyclone which moved southeasterly into the higher latitudes (Australian Severe Weather, Listing of all tropical cyclones from Bureau of Meteorology data, available at http://www.australiansevereweather.com/cylcones/bomsumm.htm, accessed 30 January 2007; National Institute of Informatics, Kitamoto Laboratory, Digital Typhoon Project, available at http://angora.ex.nii.ac.jp/digital-typhoon, accessed 30 January 2007). Other large magnitude rainfall events including those in August 1986 and 1998 were caused by severe east coast low-pressure systems (ECL) which formed offshore near Sydney. [*Holland et al.*, 1987; *Lynch*, 1987].

[36] Severe ECLs (also termed east coast cyclones) are common on the east coast of Australia in the midlatitudes, occurring around once per year usually in the autumn and winter months [*Holland et al.*, 1987; *Hopkins and Holland*, 1997]. Some authors have suggested a link between the frequency of ECLs and ENSO [*Hopkins and Holland*,

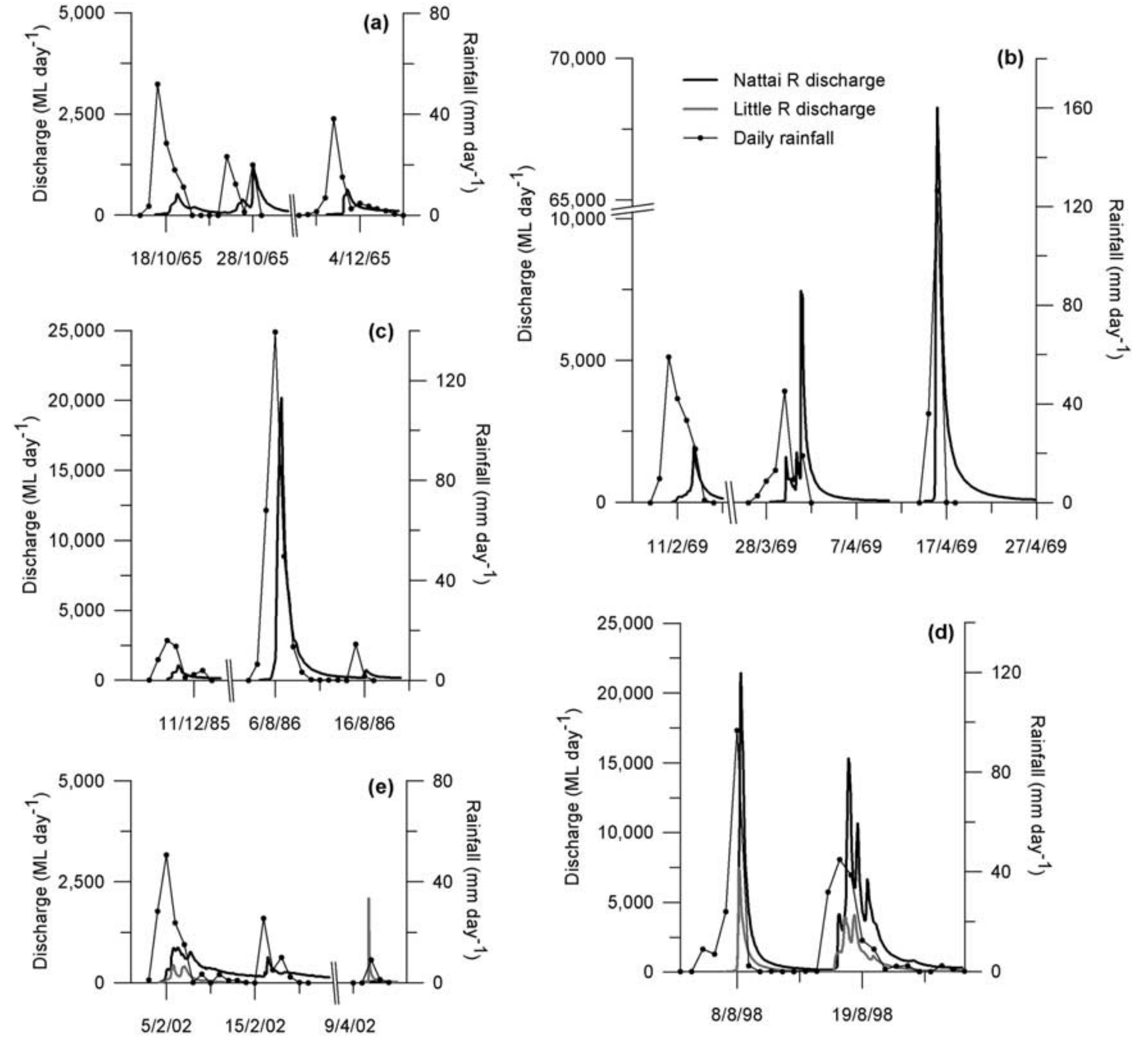

Figure 11. Hydrological response of rainfall-runoff events with >500 ML d^{-1} discharge in the first year after the (a) 1965, (b) 1968, (d) 1997, and (e) 2001 wildfires and (c) 1985 hazard reduction burn showing single and multiple peaks in discharge in response to rainfall.

1997] although others have found that the overall numbers are relatively unaffected [*Allen and Callaghan*, 1999]. Conversely, the link between tropical cyclone frequency and ENSO is well established with more cyclones tending to form during La Niña years [*Solow and Nicholls*, 1990]. From the existing records, the frequency of large rainfall events is typically about one per year, with most triggered by ECLs. There is considerable variation affecting both

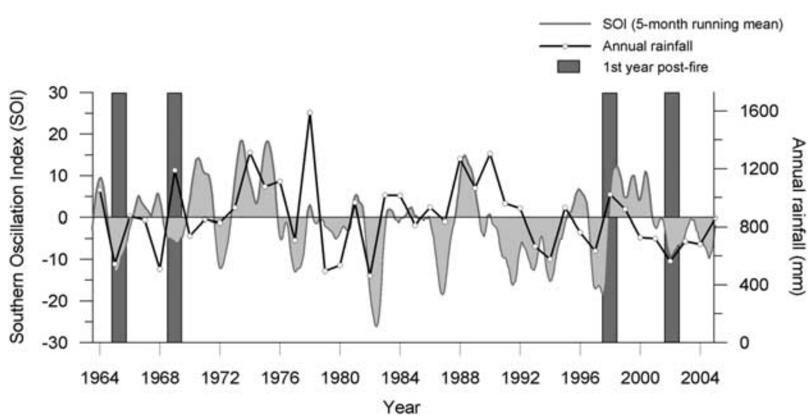

Figure 12. Timing of wildfires in the Nattai catchment showing differences in total annual rainfall compared to the Southern Oscillation Index in the first year postfire.

nonfire and postfire periods, ranging from two or more events per year, to at least 40% of years when no large rainfall events occurred.

8.2. Controls on Postfire Hydrological Response

[37] The limited impact of wildfires on runoff in the Nattai catchment suggests that large-scale hillslope hydrological processes after fires are relatively unchanged in the eucalypt forests, despite widespread destruction of the vegetation and litter decreasing interception of rainfall and exposing the soil surface. It is possible that small-scale processes are affected by fire with significant localized impacts. However, these appear to be mitigated at the larger scale. This general conclusion appears to be well supported by results from earlier work at the Blue Gum Creek sites and elsewhere in southeastern Australia, detailed below.

[38] The persistence of strong water repellency in the soil before and after fires [*Doerr et al.*, 2006; *Sheridan et al.*, 2007] and absence of surface sealing with ash, indicates that the effects on infiltration and runoff are similar in nonfire and postfire periods. The only apparent changes to the soil as a result of severe wildfires may be localized destruction of water repellency in the surface, forming a patchy, wettable layer overlying a strongly repellent subsurface soil, which can reduce or delay runoff from initial postfire rainfall [*Doerr et al.*, 2006]. This is in contrast to the more commonly reported scenario after severe wildfires of fire-induced or enhanced water repellency in the soil leading to decreased infiltration and significantly increased runoff, until repellency weakens to prefire levels [*DeBano*, 2000; *Letey*, 2001].

[39] The limited runoff from most rainfall events highlights the importance of bioturbation in aiding infiltration into the water repellent soil, either directly through tunnels or indirectly through disrupting the surface layers. High rates of ant mounding and mammal scrapes were observed at the Blue Gum Creek sites in the initial 2001 postfire period [*Shakesby et al.*, 2006] and in the 6 years thereafter with only seasonal fluctuations being evident during this time (G. S. Humphreys, unpublished data, 2007). Bioturbation is likely to be one of the major factors limiting nonfire and postfire runoff from low-medium intensity rainfall events (type 1). This is supported by the findings of *Burch et al.* [1989], who showed that infiltration rates of up to 55 mm h^{-1} or 82% of runoff were facilitated by bioturbation in forested, hydrophobic soils. Outside of southeastern Australia, the hydrological effects of bioturbation have rarely been reported in postfire studies (a notable exception is that by *Booker et al.* [1993]), presumably because fauna are less active or other factors impacting on runoff in the postfire landscape like soil water repellency are relatively more important.

[40] The rapid rate of postfire vegetation recovery in the eucalypt forests (with the exception of the wet sclerophyll Mountain Ash forests in Victoria and Tasmania which may be killed by high severity fires [*Vertessy et al.*, 1998]) is also likely to be a major factor in limiting the hydrological response after wildfires. Return of large percentages of the vegetation cover through regeneration of grasses and ferns and resprouting of several species, including the eucalypts, through epicormic buds and lignotubers have been recorded within weeks to months of wildfires [*Gill*, 1981; *Blong et al.*, 1982; *Zierholz et al.*, 1995]. Vegetation recovery quickly narrows the postfire window placing increasing importance on the timing and characteristics of rainfall events initially after fire. This contrasts with the much slower regrowth of the coniferous and broadleaf forests and woodlands of the Northern Hemisphere following high severity stand replacing fires [*Pausas*, 1999; *Brown and Smith*, 2000]. Here, the window of postfire disturbance is much longer (years to decades) meaning that there is a greater likelihood of effective rainfall occurring when the vegetation cover is low [*Meyer et al.*, 2001].

9. Conclusions

[41] Previous work on the hydrological impacts of wildfires has tended to place importance on variables relating to ground conditions including fire severity and soil water repellency, leading to expectations of enhanced postfire runoff from initial rainfall events. In the eucalypt forests of southeastern Australia, wildfires appear to have no detectable impact on runoff at the large catchment scale. Instead, it is the timing and type of rainfall events, governed by weather patterns that are the major determinants of the magnitude of runoff in the postfire window.

[42] Rainfall across southeastern Australia shows pronounced variability ranging from annual to event timescales, largely influenced by the El Niño-Southern Oscillation. Severe, widespread wildfires tend to occur following several months of significant ENSO-related rainfall deficits during the spring-summer fire season. Substantial runoff after fires and in nonfire periods results from large magnitude rainfall events ($\geq$1 year ARI) characterized by moderate to high-intensity (heavy) falls lasting one or more days. These events are triggered by the formation of east coast lows and other synoptic-scale weather systems, which do not occur reliably each year including the first year after severe wildfires when the vegetation cover is reduced.

[43] Rainfall variability, the persistence of soil water repellency, bioturbation and the rapid recovery of vegetation in the eucalypt forests, appear to be major factors limiting the impact of fires on runoff. These findings highlight the importance of understanding local controls on runoff including changes to soil and vegetation as a result of fire, as well as external controls such as rainfall, in interpreting the postfire hydrological and geomorphological response.

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