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The impact of bushfires on water yield from south-east Australia's ash forests

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[1] Widespread disturbance within forested catchments typically increases runoff. However, following widespread fire in 1939 throughout south-east Australia, Kuczera (1987) reported persistent reductions in runoff that were attributed to increased evapotranspiration from regenerating "ash" forests. Kuczera projected ongoing reductions of water yield for ~150 years. In 2003, widespread fire in the headwaters of the Murray-Darling Basin (MDB) again stimulated extensive regeneration of ash forests, raising the prospect of subsequent water yield reductions. To understand the potential impact of the 2003 bushfires, we re-evaluated yield reductions from three of the catchments originally studied by Kuczera using the same calibration period. We also used an expanded prefire calibration period (1908–1938) based on data not originally available to Kuczera. The trend of postfire water yield that we observed in 1939-affected catchments is qualitatively consistent with Kuczera's projections, but the quantitative details were, as expected, sensitive to the prefire calibration period used. We then used a simplified method to examine a further five ash-dominated catchments affected by the 2003 fires. We report relative reductions in mean annual stream flow in all five catchments and a statistically significant ($\alpha = 0.05$) postfire reduction in one of five catchments. Postfire yield reductions during the austral summer (October to April) were greater in relative magnitude in all five catchments and were statistically significant ($\alpha = 0.05$) in three of five catchments. We conclude that a postbushfire Kuczera-type response may be widespread in regenerating ash forests. On that basis, we anticipate postfire yield reductions in ash forests elsewhere and conclude that further reductions in stream flow are likely in the MDB for at least another decade.

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1. Introduction

[2] An extensive international literature exists on the impact of changes in forest cover on runoff and stream flow. Several detailed reviews [*Bosch and Hewlett*, 1982; *Brown et al.*, 2005; *Stednick*, 1996] of this literature have concluded that loss of forest cover typically leads to a sudden increase in runoff that is quickly followed (e.g., ~1 year) by a gradual return to predisturbance conditions (Figure 1a). Counter examples of reduced runoff following forest disturbance are not as common, but have been reported. For example, in the Hubbard Brook catchment harvesting of late-successional species and the subsequent regeneration of early successional species has been associated with stream flow declines [*Swank and Douglass*, 1974; *Hornbeck et al.*, 1997]. Reductions in stream flow following forest disturbance (e.g., fire, timber harvesting) are more common in southeast Australia.

[3] Following widespread bushfires in January 1939 that affected approximately 1.6 million ha of forested land in south-east Australia [*Ellis et al.*, 2004], declining stream flow was observed in a number of affected catchments [*Langford*, 1976]. These deficits followed short-lived (~3 years) increases in stream flow relative to predisturbance conditions (Figure 1b). Unlike the increases in stream flow, the stream flow deficits reported by Langford persisted throughout subsequent decades. Langford attributed reduced stream flow (relative to rainfall) to the regeneration of fire-affected stands of *Eucalyptus regnans* and *Eucalyptus delegatensis*. These are among a small number of *Eucalyptus* species that make up "ash" forests that are killed by severe fire and regenerate profusely from seed [*Ashton*, 1976; *Grose*, 1957].

[4] Integrating observations from eight forested catchments comprising both mixed-eucalypt and regenerated post-1939 ash stands *Kuczera* [1987] proposed a two-parameter model as a basis for estimating postbushfire flow changes (ΔF) relative to predictions derived from prefire

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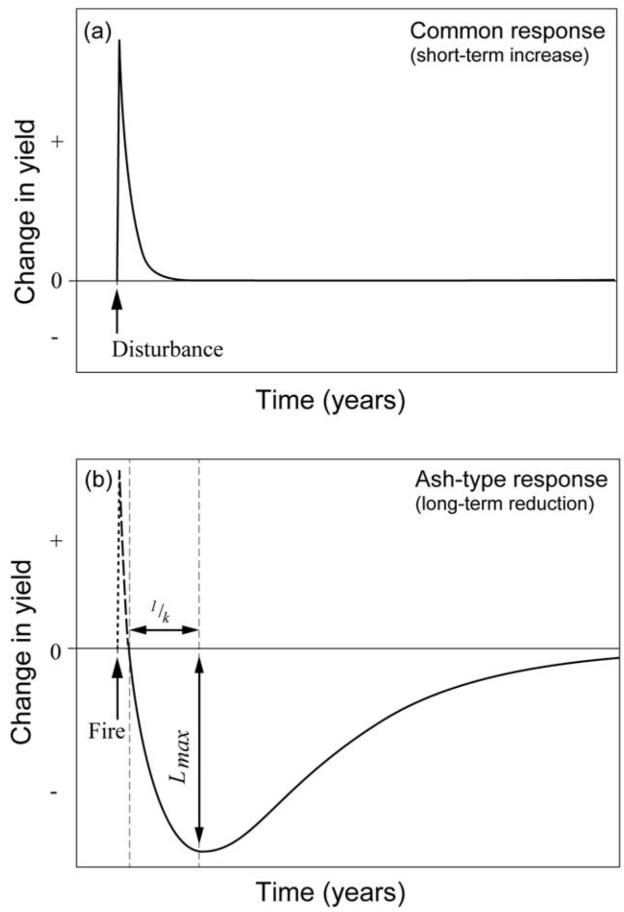

Figure 1. Catchment-level response of water yield to large-scale forest disturbance. (a) Typically, the removal of forest cover results in a short-lived increase in water yield immediately after disturbance. (b) In ash-type eucalypt stands short-term water yield increases (short-dashed line) are followed by a prolonged decline and gradual return of yield to the prefire mean (long-dashed and solid lines). *Kuczera*'s [1987] model of post-disturbance water yield incorporates two parameters—$L_{\max}$ (maximum yield reduction) and $1/k$ (timing of $L_{\max}$ relative to t_o), where t_n is the calendar year for which the change in flow is to be estimated and t_o is the year before flow deficits are assumed to commence. Kuczera's model estimates elevated yield relative to mean prefire conditions when $(t_o - t_n) < 0$ (long-dashed line) and yield deficits (solid line) when $(t_o - t_n) > 0$. Kuczera only applied the model to estimate yield deficits (i.e., when $(t_o - t_n) > 0$). *Kuczera* [1987] reported that yield deficits are evident from catchments comprising regenerating *E. regnans* stands 3 years after bushfires.

calibrated stream-flow regression models (Figure 1b). Kuczera's two-parameter model may be expressed as

$$\Delta F(t_n) = -L_{\max} k (t_n - t_0) e^{1-k(t_n - t_0)} \tag{1}$$

where $L_{\max}$ is the maximum effect of disturbance on flow, k is a rate constant and the inverse of the time in years in which the maximum effect is expressed (see Figure 1b), t_n is the calendar year for which the reduction in flow is to be estimated, t_o is the calendar year before flow reduction is assumed to commence. Yield deficits are projected when $(t_n - t_o) > 0$. Both *Langford* [1976] and *Kuczera* [1985] reported that deficits commenced 3 years after disturbance.

[5] Kuczera related the magnitude of yield reductions to the proportion of each catchment that comprised postfire ash regeneration. For a pure ash (*E. regnans*) overstorey, Kuczera estimated a maximum annual water yield reduction of 580 mm a^{-1} (48%) in a catchment yielding $\sim$1200 mm a^{-1} prior to disturbance. Kuczera projected that the maximum reduction in flow ($L_{\max}$) occurs in 27 year old stands and that the return to prefire flow may take up to 150 years. Since ash stands are widespread in southeast Australia, the magnitude of the above-noted effect identified by Kuczera is of immense hydrological importance in terms of water yields and subsequent inflows to dams.

[6] Like *Langford* [1976], *Kuczera* [1987] attributed postfire reductions in water yield to high water use (transpiration) by regenerating ash stands. Subsequent studies of age-dependent trends in hydraulic and structural characteristics of *E. regnans* stands appear to at least partly support this attribution [e.g., *Vertessy et al*., 2001]. Observations of age-dependent stand-structural trends in seed-regenerated eucalypt forests elsewhere [*MacFarlane et al*., 2010; *Roberts et al*., 2001] suggest that age-dependent trends in water yield may be widespread in eucalypt forests. Recently, *Buckley et al*. [2012] reported that water use by 70 year old stands of *E. delegatensis* ($\sim$390 mm yr^{-1}) was less than half that of 5 year old stands ($\sim$860 mm yr^{-1}). This observation may have significant implications for water yield from the high-elevation forested catchments that generate the majority of runoff within Australia's largest drainage basin, the Murray-Darling (MDB).

[7] During extensive bushfires in 2003, large tracts of ash forests were killed [*Benyon and Lane*, 2012; *SKM*, 2009] within the very high to extremely high yield zones that deliver around 30% of the MDB's water yield [*Donohue et al*., 2011]. The subsequent decade has seen a wave of seedling regeneration throughout fire-affected ash forests. The observations of *Buckley et al*. [2012] suggest that runoff may have substantially declined from ash-dominated catchments incorporating these regenerating forests.

[8] There has been speculation that post-2003 regeneration may already be impacting stream flow in the MDB [*Roderick and Farquhar*, 2011]. Whilst the southern parts of the MDB experienced rainfall during 1997–2009 that was similar to the lowest on record, associated stream flows were by far the lowest in the instrumental record [*Potter et al*., 2008]. Several mechanisms, including changes in the seasonality of rainfall [*Kiem and Verdon-Kidd*, 2010; *Potter and Chiew*, 2011; *Verdon-Kidd and Kiem*, 2009], increased evaporation associated with higher averaged mean and maximum temperatures [*Cai and Cowan*, 2008; *Nicholls*, 2004; *Timbal et al*., 2010], and reduction in interannual variability [*Timbal et al*., 2010] have been proposed as reasons for the greater reduction in stream flow during 1997–2009 in comparison to historical droughts. The possibility that postfire regrowth [*Buckley et al*., 2012] may be playing a role has yet to be considered.

[9] In this paper, we examine the impact of bushfire on water yield in south-east Australia. *Kuczera's* [1987] original analysis of the response to the 1939 bushfires was based

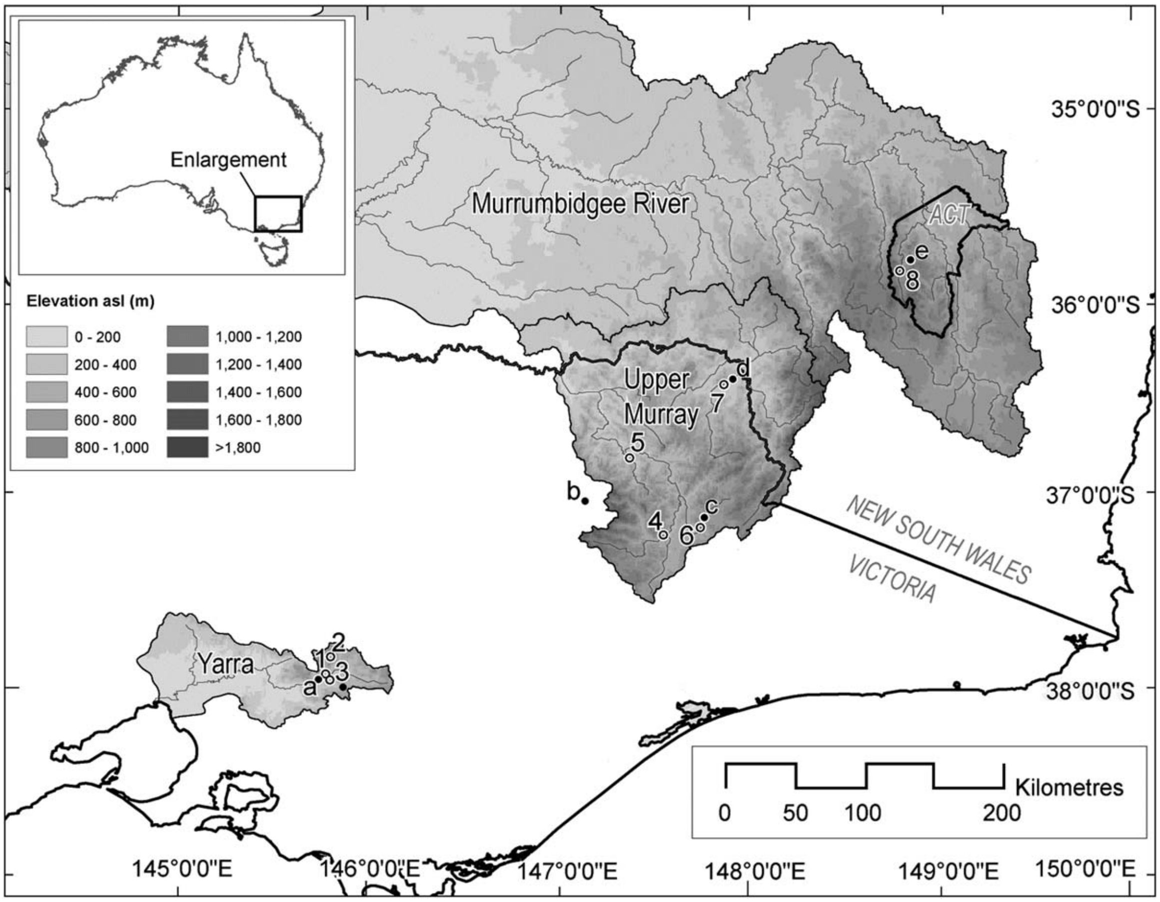

Figure 2. Study area and catchment locations. Numbered circles correspond with the gauged flow stations in the Yarra (1, Watts River; 2, Graceburn; 3, Donnellys), Upper Murray (4, Big River; 5, Snowy Creek; 6, Gibbo River; 7, Nariel River), and Murrumbidgee (8, Cotter River) catchments. Letters denote the closest meteorological stations ((a) Maroondah Reservoir; (b) Tawonga; (c) Uplands; (d) Nariel Valley; (e) Sawpit Creek). Elevation is shown within catchments. Spatial data were obtained from *GeoScience Australia* [2012].

on data available at that time and used a relatively short prefire calibration period (1926–1938) with projections made to 1981 (1942–1981). With data now extending to 2011, we can re-examine the accuracy of these projections. Hence, we first reanalyze flow data in the catchments originally studied by Kuczera. In addition, we also examine water yield in other ash-dominated catchments that were burnt during the 2003 bushfires to establish whether the effect on stream flow is widespread. Too little time has elapsed since the 2003 bushfires to analyze the multidecadal effect of postfire regeneration on stream flow and we restrict that analysis to a simple comparison of prefire to postfire stream flow relative to precipitation.

2. Materials and Methods

2.1. Data

2.1.1. Yarra River Catchments

[10] To re-examine *Kuczera's* [1987] observations, we obtained hydrological data from gauges within three Yarra River catchments (Figure 2) from the catchment management agency, Melbourne Water. The Yarra River catchments examined here are the Watts, Graceburn, and Donnellys catchments (Table 1) previously investigated by *Kuczera* [1987]. The overstory of these catchments comprises both mixed- and pure-species eucalypt stands. As described by *Kuczera* [1987], forests within the Yarra River catchments were burnt during January 1939 leading to the establishment of seedling *E. regnans* stands. No large-scale disturbances (e.g., new dams, stand-replacing bushfires) affected these catchments until bushfires in 2009. Although the 2009 bushfires affected approximately 75% of the Yarra River catchments, these fires did not have significant impacts upon the overstory in the study catchments.

[11] Data sets for each of the Yarra River catchments comprised an unbroken record of total monthly stream-gauged flow in megalitres per month (ML/month) and were typically of the order of gigalitres (GL) per month. The flow was converted to depth using the same catchment areas used by Kuczera.

[12] *Kuczera* [1987] used the then available precipitation and flow records (1926–1938) to represent pre-fire conditions and then made projections of flow to 1981 based on precipitation data from the nearby Bureau of Meteorology

Table 1. Summary of Catchment Attributes[a]

Catchment/ Gauge	Location (Latitude, Longitude)	Area (km^2)	Yield ($GL\ a^{-1}$)	Fire Year	Q/P; (Prefire, Postfire)	BoM Station (Latitude, Longitude)
Yarra River						
Watts	(145.57° E, 37.62° S)	100.9	93.6	1939	0.64, 0.52	Maroondah Reservoir (145.55° E, 37.64° S)
Graceburn	(145.55° E, 37.65° S)	25.0	20.1	1939	0.56, 0.42	
Donnellys	(145.53° E, 37.62° S)	14.3	6.4	1939	0.31, 0.26	
Upper Murray						
Big River	147.47°E, 36.93°S	356.0	219.3	2003	0.52, 0.46	Tawonga (147.13° E, 36.66° S)
Snowy Creek	147.41°E, 36.57°S	407.0	203.0	2003	0.42, 0.29	
Gibbo River	147.71°E, 36.76°S	389.0	115.0	2003	0.27, 0.19	Uplands (147.71° E, 36.86° S)
Nariel River	147.83°E, 36.45°S	252.0	135.5	2003	0.51, 0.37	Nariel Valley (147.80° E, 36.33° S)
Murrumbidgee River						
Cotter River	148.82°E, 35.59°S	148.0	45.5	2003	0.33, 0.20	Sawpit Creek (149.95°E, 35.60°S)

[a]Location, size, and annual average flow for sub-catchments of the Yarra River (1908–1938), Upper Murray (1972–2011), and Murrumbidgee River (1973–2011) and the year in which each sub-catchment was affected by bushfire is shown. Ratios of annual flow to precipitation (Q/P) are provided for each catchment prior to and following bushfire. Pre-and postfire periods cover 1908–1938 and 1942–2011 respectively for the Yarra River catchments, 1972–2002 and 2006–2011 for the Upper Murray catchments and 1973–2002 and 2006–2011 for the Murrumbidgee River catchment. The name and location of Bureau of Meteorology (BOM) precipitation stations used for regression analyses are also listed.

(BOM) station at Maroondah Reservoir (Figure 2). Since that time, the stream flow record has been reconstructed, using flow data collected at the Maroondah weir, back to 1908 by Melbourne Water and is current to 2011. We used the shorter 1926–1938 period for calibration for comparison purposes, but we also made use of the full 1908–1938 record to evaluate Kuczera's flow projections out to 2011.

2.1.2. Upper Murray and Murrumbidgee River Catchments

[13] To examine the potential hydrological impacts of the 2003 bushfires, we obtained data from the Victorian Water Resources Data Warehouse. Catchments were selected for analysis if they recorded flow unregulated by dams or human consumption, both prior to and following 2003, were within catchments comprising 2003 fire-killed ash stands and had not been affected by subsequent bushfires. A combination of aerial-photograph-interpreted species mapping as well as remotely sensed fire extent mapping, available via the Department of Sustainability and Environment's (DSE) online Forest Explorer, was used to determine vegetation composition as well as the extent of the 2003 and subsequent stand-replacing bushfires. During 2006 and 2007, bushfires killed regenerating post-2003 ash stands within several catchments in the study area. Since more recent regeneration might affect the expression of the effects of bushfires during 2003, catchments affected by the 2006 and 2007 bushfires were excluded from subsequent analyses.

[14] We identified four suitable Upper Murray catchments in northeast Victoria—Big River at Jokers Creek, Gibbo River at Gibbo Park, Nariel Creek at Upper Nariel and Snowy Creek below Granite Creek (Figure 2, Table 1). Flow data were available for 1972–2011 in each catchment. We identified three BOM stations, Tawonga (Big River and Snowy Creek), Uplands (Gibbo River), and Nariel Valley (Nariel River) (Figure 2), as suitable for modeling the Upper Murray gauges. The Tawonga precipitation series lacked data for July in 1971, 1982, and 1986. These missing data were in-filled with the long-term precipitation July average for the analysis period (1972–2011).

[15] In addition to Victorian catchments, we also sought data from catchments affected by the 2003 bushfires in New South Wales and the Australia Capital Territory (ACT). We applied the same selection criteria used in Victoria and identified only one gauge. That was in the Murrumbidgee River catchment's Cotter River at Gingera Creek (Figure 2, Table 1). Monthly flow data were available for 1973–2011 with no missing data. Monthly precipitation data (1973–2011, no missing data) for the Cotter River were obtained from the adjacent Sawpit Creek monitoring station (Figure 2) maintained by the catchment management authority, ACTEWAGL.

2.2. Prefire Flow Calibration

[16] We developed prefire regression equations for flow in each of the Yarra River catchments using the full record (1908–1938) (Table 2) and the shorter record (1926–1938) that was available to Kuczera.

[17] Data were available for the Upper Murray (1972–2011) and Murrumbidgee River (1973–2011) catchments that encompassed drought (1997–2009) and bushfire (2003) conditions. We developed prefire/predrought stream flow models (pre-1997) for all catchments (Table 2) and separately examined flow residuals (see later) for the 1997–2002 and 2006–2011 periods to test whether a fire effect could be detected independent of the drought.

[18] Our primary analyses of flow in the Upper Murray and Murrumbidgee River catchments were based upon annual totals. Unlike the Yarra River catchments, the upper reaches of the Upper Murray and Murrumbidgee River catchments are seasonally affected by snow during May to September (winter). This phenomenon may affect hydrological functioning in the study catchments. For example, accumulation of snow during winter reduces runoff in that season with snow melt during early spring dramatically increasing runoff [*Schreider et al*., 1997]. In addition, the greater altitudinal range of the Upper Murray and Murrumbidgee River catchments means that low temperatures and severe frosts limit tree growth during winter in high-elevation ash forests [*Davidson and Reid*, 1985; *Keenan and Candy*, 1983]. Evaporative demand and transpiration are also low during the austral winter (May to September) [*Honeysett et al*., 1992; *Pfautsch et al*., 2010]. Hence, we anticipated that the impact of water use by vegetation on

Table 2. Regression Equations for Calibration of Precipitation and Stream Flow[a]

Catchment/Gauge	Analysis Data Set	Regression Equation	r^2	Prob < F
Yarra River				
Watts	1908–1938 (Annual)	$Flow = -316.1 + 1.04^{*}\, precip$	0.686	<.0001
Graceburn	1908–1938 (Annual)	$Flow = -190.7 + 0.83^{*}\, precip$	0.612	<.0001
Donnellys	1908–1938 (Annual)	$Flow = -131.1 + 0.48^{*} precip$	0.519	<.0001
Upper Murray				
Big River	1972–1996 (Annual)	$Flow = -194.6 + 0.70^{*} precip$	0.754	<.0001
	1972–1996 (Summer)	$Flow = -46.6 + 0.48^{*} precip$	0.607	<.0001
Snowy Creek	1972–1996 (Annual)	$Flow = -263.8 + 0.65^{*} precip$	0.757	<.0001
	1972–1996 (Summer)	$Flow = -19.4 + 0.45^{*} precip$	0.610	<.0001
Gibbo River	1972–1996 (Annual)	$Flow = -345.3 + 0.60^{*} precip$	0.753	<.0001
	1972–1996 (Summer)	$Flow = -56.6 + 0.36^{*} precip$	0.554	<.0001
Nariel River	1972–1996 (Annual)	$Flow = -254.8 + 0.76^{*} precip$	0.799	<.0001
	1972–1996 (Summer)	$Flow = -32.2 + 0.30^{*} precip$	0.522	<.0001
Murrumbidgee River				
Cotter River	1973–1996 (Annual)	$Flow = -265.4 + 0.63^{*} precip$	0.769	<.0001
	1973–1996 (Summer)	$Flow = -118.8 + 0.50^{*} precip$	0.788	<.0001

[a]Parameter estimates, coefficients of determination (r^2), and significance (Prob < F) are shown for each catchment and data set (annual or summer [October to April]).

stream flow might not be detectable during May to September. In addition to analyses of annual variables, we also examined the seasonal relation between precipitation and flow. Consistent with our analyses of annual data, we developed prefire/predrought stream flow models (pre-1997) during summer (October to April) for all catchments (Table 2) and separately examined flow residuals for the 1997–2002 and 2006–2011 periods to test whether a fire effect could be detected.

2.3. Analysis of Postfire Residuals

2.3.1. Yarra River Catchments

[19] After prefire regression modeling, postfire (1942–2011) precipitation data were used to estimate runoff at each gauge. Nonlinear estimation was then used to estimate trends in postfire flow residuals using the two-parameter function adopted by *Kuczera* [1987] as a basis for estimating postbushfire flow deficits (equation (1)).

[20] Consistent with *Langford's* [1976] observation that postfire water yield reductions commenced 3 years after the 1939 bushfire (i.e., in 1942), *Kuczera* [1987] defined t_0 as 1941 and the first projection was made for 1942. We also adopted 1942 as the first year for which projections were made. We used postfire (1942–2011) residuals from prefire calibrated models to estimate $L_{\max}$ and K. All statistical analysis used the JMP [*SAS Institute*, 2010] software.

2.3.2. Upper Murray and Murrumbidgee River Catchments

[21] At the time of analysis, postfire data sets in the Upper Murray and Murrumbidgee River spanned only 8 years after the 2003 bushfires. This record length is insufficient for multidecadal analysis as we anticipate a complex response (Figure 1b). This limitation restricted our postfire analyses of the Upper Murray and Murrumbidgee River catchments to comparison of mean water yield reductions during the period affected by drought (1997–2002) alone and that affected by both drought and fire (2006–2011) in both annual and summer (October to April) time series. The latter of these periods was set as starting in 2006 to be consistent with the 3 year delay in the expression of yield reductions [*Langford*, 1976; *Kuczera*, 1987] as discussed above.

[22] Since reductions in water yield within the MDB during the 1997–2009 drought have previously been partly attributed to preferential declines in autumn rainfall in adjacent agricultural lands [*Potter and Chiew*, 2011], we also examined the relation between precipitation and flow in each of the forested mountain catchments by season.

3. Results

3.1. Yarra River Catchments

3.1.1. Stream Flow Calibration

[23] Gauged stream flow in each of the Yarra Valley catchments was highly correlated with annual precipitation (Figures 3a–3c) and regression results are highly significant during 1908–1938 (Figure 3g–3i). Note that the earlier study by *Kuczera* [1987] used the slightly wetter 1926–1938 period for calibration (Figure 3d–3f).

3.1.2. Yarra River Yield Projection

[24] The postbushfire flow reduction previously reported was clearly identified in the postfire observations in each of the Yarra catchments (Figures 3g–3i) with negative flow residuals from 1942, 3 years after the 1939 fire, clearly evident. Nonlinear estimation, based upon *Kuczera's* [1987] two-parameter function adequately describes the flow reduction in all three catchments (Figures 4a–4c) with no trend evident in the residuals (Figures 4d–4f).

[25] Estimation of $L_{\max}$ and, to a lesser extent, $1/k$ is sensitive to the data set used for both prefire calibration and postfire projection. $L_{\max}$ was 27 mm a^{-1} lower for the expanded 1908–2011 data set in the Watts catchment, 118 mm a^{-1} lower in Graceburn and 33 mm a^{-1} lower in Donnellys than for the shorter 1926–1981 data set used by *Kuczera* [1987]. Bias in the 1926–1938 flow residuals accounts for 96% (26 mm a^{-1}) of the difference in $L_{\max}$ between 1926–1981 and 1908–2011 analyses in the Watts catchment, 75% (89 mm a^{-1}) in Graceburn and 79% in Donnellys (26 mm a^{-1}).

[26] Parameter estimates for $L_{\max}$ and k differ from those reported previously for the Yarra River catchments (Table

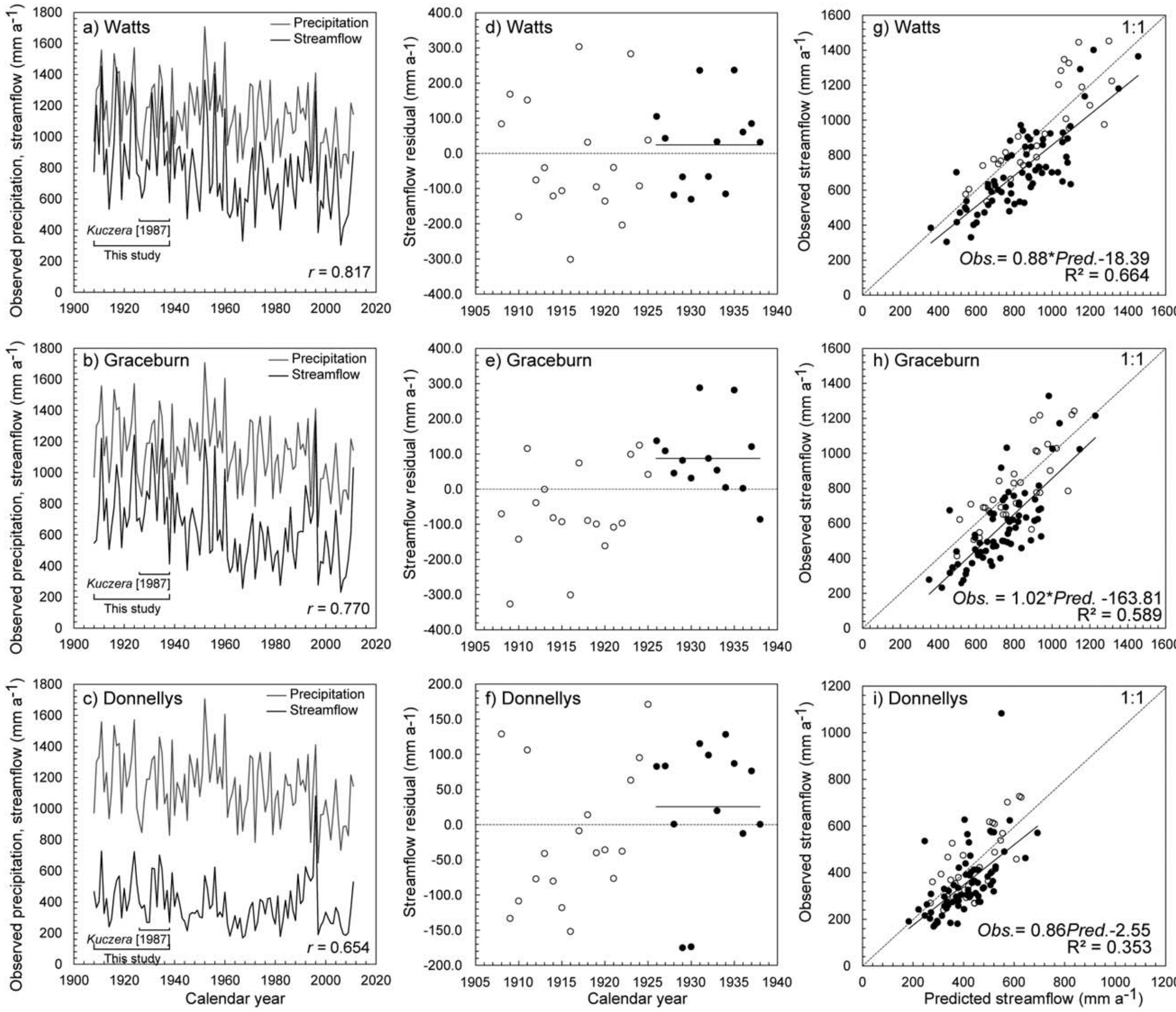

Figure 3. Yarra River rainfall and stream-flow with regression modeling. Precipitation (mm a^{-1}, mm per annum) and stream flow (mm a^{-1}) time series and the correlation coefficients are shown for the (a) Watts, (b) Graceburn and (c) Donnellys catchments for 1908–2011. (d–f) Residuals from regression equations between precipitation and stream flow (see Table 2) during 1908–1938 are shown for each catchment. Residual means are indicated for the 1908–1938 calibration period (dashed line) and for the 1926–1938 calibration period adopted by *Kuczera* [1987] (solid line). (g–i) The relationship between predicted and observed stream flows are shown for each catchment during the 1908–1938 calibration (empty circles) and 1942–2011 prediction periods (solid circles).

3) using the same dates as Kuczera (1942–1981 residuals and a 1926–1938 calibration period). We found values of $L_{\max}$ to be 25% (78 mm a^{-1}) lower for the Watts gauge, 18% (72 mm a^{-1}) lower for Graceburn, and 5% (10 mm a^{-1}) lower for Donnellys than those estimated by *Kuczera* [1987]. Similarly, $1/k$ is 9.2 years smaller, and hence the time of maximum flow decrease 9.2 years earlier, than those estimated by *Kuczera* [1987] for the Watts gauge, 10.8 years earlier for Graceburn and 6.3 years for Donnellys. The year in which postfire yield trends are no longer significantly ($\alpha = 0.05$) different to the prefire mean occurs 45 years earlier than reported by *Kuczera* [1987] for the Watts gauge (Table 4), 55 years earlier for Graceburn and 26 years earlier for Donnellys. Using longer periods for calibration (1908–1938) and post-fire predictions (1942–2011) yielded even larger differences in $L_{\max}$ but not in the timing of flow reduction (Table 3).

3.2. Upper Murray and Murrumbidgee River Catchments

3.2.1. Stream Flow Calibration

[27] Precipitation in the Upper Murray and Murrumbidgee River catchments is highly correlated with gauged annual river flow (Figures 5a–5e). During regression calibration periods, annual precipitation (pre-1997) explains 75–80% of the variance in gauged annual flow in the five catchments (Figures 5f–5j). By comparison, precipitation during October to April explains 52%–79% of variance in

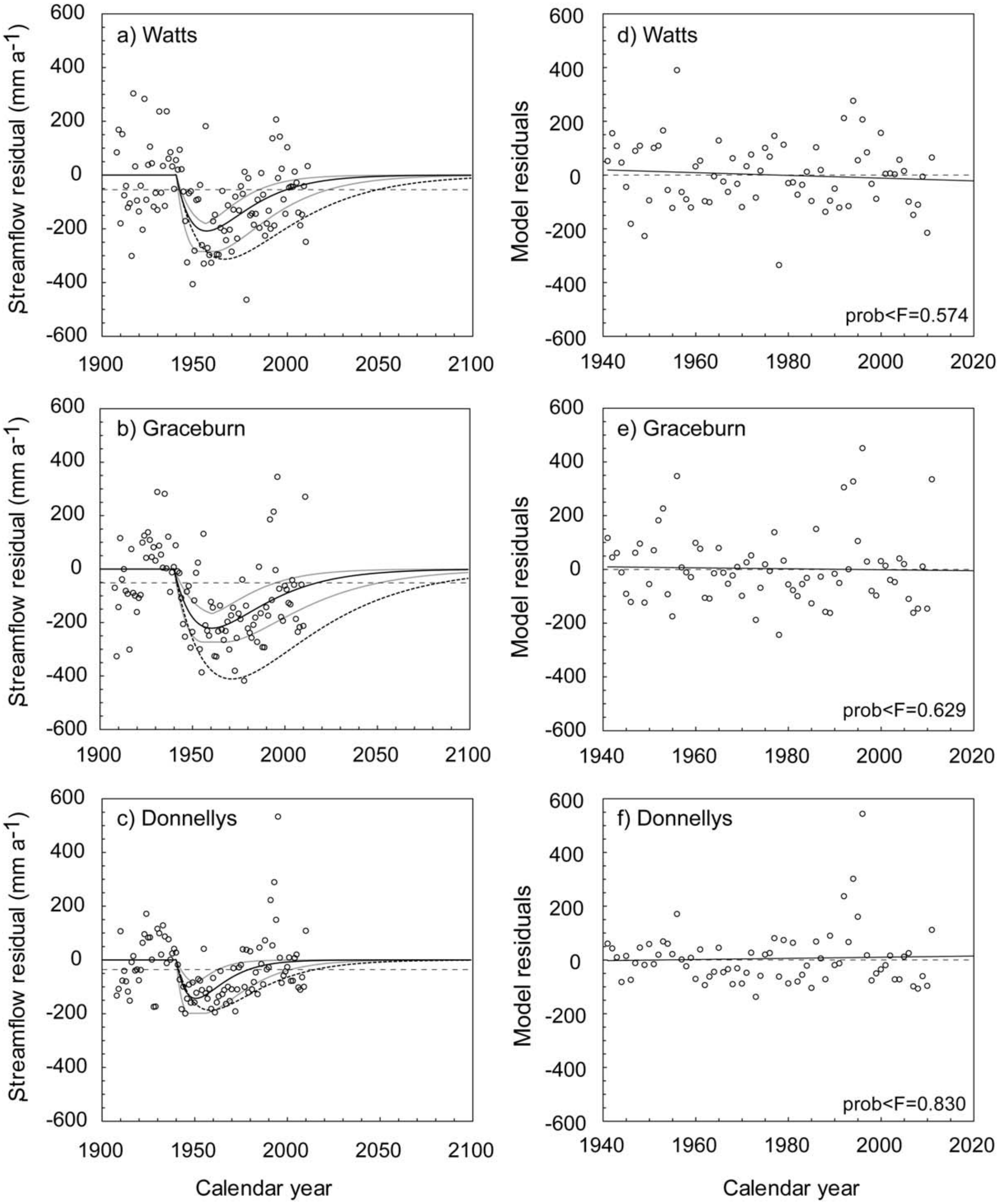

Figure 4. Postfire response model for the (a–c) Yarra River catchments and (d–f) the model residuals. Black lines denote the function derived in this study (Table 3b) and dotted lines denote original estimates by *Kuczera* [1987]. Solid curved lines denote the limit of postfire data used in this and *Kuczera*'s [1987] study. Confidence intervals ($\alpha = 0.05$) are shown (gray lines) for the results of this study. Dashed horizontal lines denote the confidence intervals ($\alpha = 0.05$) associated with prefire flow residuals.

October to April flow in the five catchments (Figures 5k–5o).

3.2.2. Upper Murray and Murrumbidgee River Yield Analysis

[28] No significant deviations in annual or October to April stream flow residuals are evident during the early part of the drought (1997–2002) in the four Upper Murray catchments (Table 4). In contrast, we report a significant reduction in annual, but not October to April, stream flow in the Murrumbidgee River catchment's Cotter River.

[29] For the postfire analysis period (2006–2011), we report reductions in annual and October to April flow relative to precipitation in all five catchments (Table 4).

Table 3. Postfire Response Parameter Estimates for the Yarra Catchments[a]

Gauge	L_{max} (mm a^{-1})	$1/k$ (a)	RMSE (mm a^{-1})	Return Year ($\alpha = 0.05$)
1926–1938 Calibration/1942–1981 Projection (Kuczera [1987])				
Watts	**235** (313)	**16.8** (26.0)	128.6	2005 (2050)
Graceburn	**339** (411)	**20.4** (31.2)	119.8	2030 (2085)
Donnellys	**177** (187)	**12.2** (18.5)	69.0	1989 (2016)
1908–1938 Calibration/1942–2011 Projection				
Watts	**208**	**16.4**	122.6	2001
Graceburn	**221**	**20.4**	134.9	2018
Donnellys	**144**	**10.6**	104.2	1980

[a]Values for L_{max} and $1/k$ and the year in which flow is projected to return to within pre-fire confidence intervals ($\alpha = 0.05$) using the original (a) 1926–1938 calibration period along with (b) the expanded 1908–1938 calibration period are shown. Values for L_{max} and $1/k$ that differ significantly ($p \leq 0.05$) from those reported by *Kuczera* [1987] are shown in bold typeface.

Reductions are as much as three times greater than annual reductions during 1997–2002 and up to eight times greater than 1997–2002 reductions in October to April. A particularly large and significant reduction in annual flow is evident in the Cotter River. Significant reductions in flow are also evident in the Upper Murray's Big River and Snowy Creek. The reduction in flow in the Gibbo River is large but marginally nonsignificant.

3.2.3. Seasonal Flow Sensitivity

[30] The sensitivity of stream flow to precipitation varies seasonally within each of the Upper Murray catchments (Figure 6). Specifically, slope parameters are greater in spring (September to November; SON) and winter (June to August; JJA) than for summer (December to February; DJF) and autumn (March to May; MAM) in each of the catchments. In contrast, the sensitivity of stream flow to precipitation does not appear to vary seasonally in the Murrumbidgee River catchment's Cotter River.

4. Discussion

4.1. Re-Estimation of Kuczera's Two-Parameter Yield Function

[31] *Kuczera's* [1987] two-parameter function is central to estimations of postdisturbance trends in seedling-regenerated ash forests [e.g., *SKM*, 2009; *Watson et al.*, 1999a]. However, *Kuczera's* [1987] yield function and flow estimates generated through its application remain untested since the original publication.

[32] The results of our re-examination of the Yarra River catchments indicate that *Kuczera*'s [1987] function adequately describes postfire trends of water yield in ash catchments (Figure 4). However, estimation of L_{max} and $1/k$ is sensitive to the length of record used for both prefire calibration and postfire projection. Most of the differences in L_{max} between analyses appear to reflect the additional calibration (1908–1925) data that have become available since the earlier analysis. However, $1/k$ appears to be relatively insensitive to differences in prefire calibrations (Table 3). The relatively small differences between our estimates of $1/k$ for the two analysis periods we used (1926–1981 and 1908–2011) appear to reflect the additional 30 years of postfire data in the expanded postfire data set.

[33] Our estimates of L_{max} and $1/k$ for the 1926–1981 data set differ from those generated by *Kuczera* [1987] based upon the same period. Further analysis (data not shown here) has revealed that these differences reflect an adjustment in the Maroondah rainfall that is reported in *Kuczera* [1985] to address a discontinuity within the Maroondah Reservoir precipitation record in 1963. We based our analyses upon unadjusted data sourced from the Bureau of Meteorology as resolving the nature of discontinuity within the precipitation record was outside the scope of this study. Moreover, irrespective of the difference in the underlying precipitation record, the results of our analyses of postfire reductions in stream flow are qualitatively consistent with *Kuczera's* [1987].

Table 4. Stream Flow Residuals for the Upper Murray and Murrumbidgee River Catchments During 1997–2002 and 2006–2011[a]

	Average Residual (mm a^{-1}) [Prob < t]			
	Annual		October to April	
Gauge	1997–2002	2006–2011	1997–2002	2006–2011
Big River	−4.7 [0.906]	−16.0 [0.642]	−19.8 [0.414]	**−79.8*** **[0.020]**
Snowy Creek	−32.2 [0.431]	−82.6 [0.135]	14.4 [0.617]	**−70.2*** **[0.035]**
Gibbo River	−6.2 [0.758]	−8.5 [−0.806]	−0.5 [0.975]	−34.8* [0.054]
Nariel River	16.7 [0.837]	−68.4 [0.060]	−22.8 [0.348]	−30.2 [0.333]
Cotter River	**−41.5 [0.022]**	**−105.1 [0.027]**	−8.8 [0.552]	**−67.5*** **[0.046]**

[a]Statistical significance is shown in square brackets. Significant results ($\alpha \leq 0.05$) are shown in bold typeface. Significant differences ($\alpha \leq 0.05$) between 1997–2002 and 2006–2011 residuals are indicated by asterisks for each catchment, $n = 6$ in all analyses.

4.2. Drought- and Fire-Related Effects in the Upper Murray and Murrumbidgee River Catchments

[34] We analyzed stream flow, relative to pre-1997 conditions, separately during two periods of drought prior to and following the 2003 bushfire. During the first period (1997–2002) only drought affected water yield while during the second period (2006–2011) both drought and fire affected water yield in the catchments examined. This approach was designed to isolate the effect of bushfire on stream flow reductions. Whilst reductions in annual flow during 2006–2011 are only significant in the Murrumbidgee River catchment's Cotter River, reductions during the austral summer (October to April) are significant or marginally nonsignificant in three of the four Upper Murray catchments as well as for the Cotter River.

[35] Evaporative demand and transpiration in the high-elevation ash (*E. delegatensis*) stands of southeast Australia increase sharply during the growing season that begins in October rising to a maximum during late summer in January to February and declining thereafter to a minimum during the southern winter in May to August [*Buckley et al.*, 2012; *Honeysett et al.*, 1992; *Pfautsch et al.*, 2010]. Soil water content is inversely related to this seasonal pattern of water use [*Honeysett et al.*, 1992]. These observations indicate that water use by *E. delegatensis* stands during late autumn to early spring (May to September) is lower than that observed during late spring to early autumn (October to April). We suggest that runoff from ash stands comprising *E. delegatensis* is also sensitive to seasonal variation of

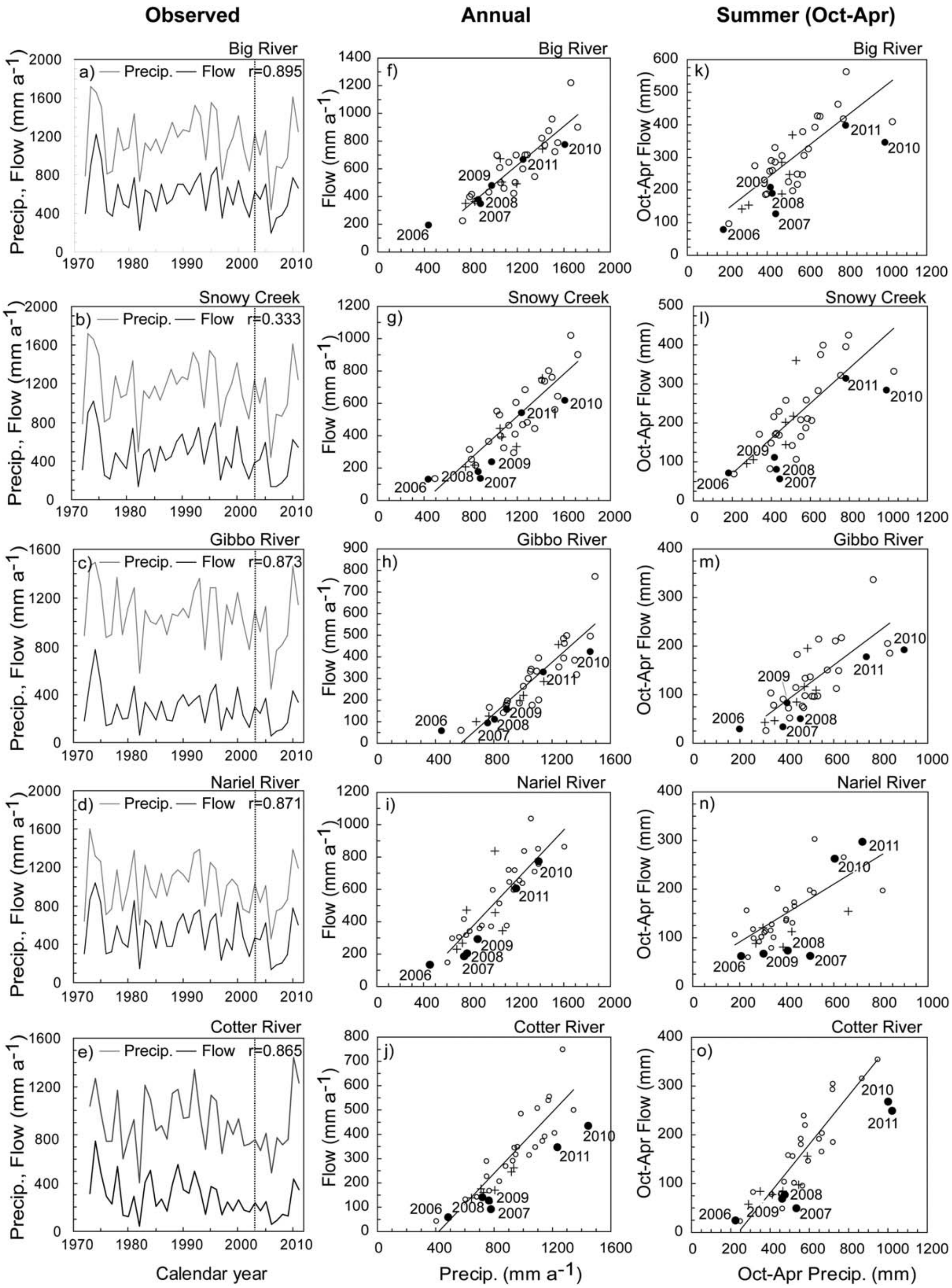

Figure 5. Rainfall-stream flow relations in the Upper Murray and Murrumbidgee River catchments. (a–e) 1972–2011 time-series plots and rainfall-stream flow plots for (f–j) annual and (k–o) Summer periods. Pearson's correlation coefficient (r) between annual precipitation and flow is shown in Figures 5a–5e, Observations used as the basis for calibration of regression equations (Figures 5f–5o) between precipitation and stream flow (1972–1996) are shown as empty circles, 1997–2002 drought observations are shown as crosses and 2006–2011 drought and fire observations as solid circles. All calibration regressions are highly significant ($\alpha < 0.0001$).

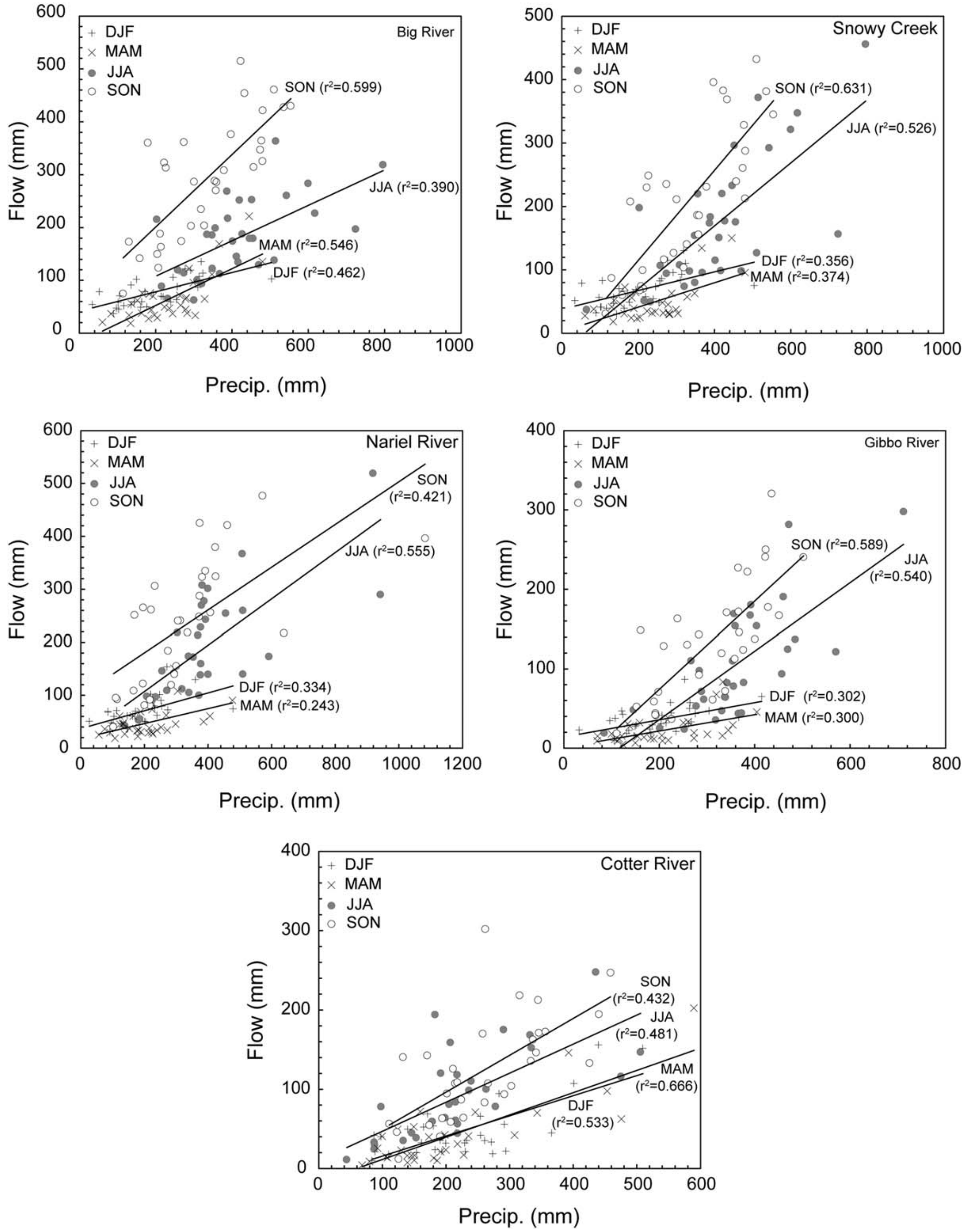

Figure 6. Seasonal rainfall-stream flow relations in the Upper Murray and Murrumbidgee River catchments. Analyses for spring (SON), summer (DJF), autumn (MAM) and winter (JJA) are denoted. Linear regression (line) and coefficients of determination are shown for each season.

water use. That is, runoff from *E. delegatensis* stands is lower during October to April as a result of stand water use and the depletion of soil water during summer. Given the observations made by *Buckley et al*. [2012] of age-dependent water use by stands of *E. delegatensis*, this seasonal pattern in water use is likely to be greater in regenerating than in mature ash stands. The response of stream flow to seasonal water use by *E. delegatensis* stands, suggested by our analysis of postfire stream flow during October to April, is consistent with the smaller proportion of precipitation that becomes stream flow during summer and autumn in the Upper Murray and Murrumbidgee River catchments (Figure 6).

[36] The detectability of stream flow reductions in the Upper Murray catchments may also partially reflect seasonal snow dynamics. Substantial parts of both the Big River and Snowy Creek catchments are snow covered during winter. In such catchments, snow melt saturates the soil profile, significantly contributing runoff during winter and spring [*Schreider et al*., 1997], reducing the sensitivity of stream flow to precipitation in winter and spring. Also, since it is released during periods of low water use by stands of *E. delegatensis*, snow melt may obscure any vegetation-related effects during both seasons.

[37] Prolonged dry conditions, mostly associated with declines in autumn rainfall in south-east Australia during 1997–2009 have been hypothesized as leading to a disconnection between ground water and surface water [*Potter and Chiew*, 2011]. *Potter and Chiew* [2011] suggested that this disconnect may explain yield reductions during 1997–2008 in the MDB's Campaspe River basin. In the catchments we examined, reductions in stream flow relative to rainfall were generally much smaller in the 1997–2002 drought when compared to the combined drought and postfire 2006–2011 period. These results, combined with the weak response of stream flow to autumn precipitation (Figure 6), suggest that the disconnection proposed by *Potter and Chiew* [2011] in a lower elevation agricultural catchment is unlikely to be responsible for the reduction in postfire water yield in the higher elevation forested catchments that dominate the Upper Murray catchments. Instead, our observations are consistent with age-dependent differences in stand-level water use between regrowth and mature ash-type forests [*Buckley et al*., 2012; *Dunn and Connor*, 1993; *Haydon et al*., 1996; *Jayasuriya et al*., 1993; *Roberts et al*., 2001; *Vertessy et al*., 2001; *Vertessy et al*., 1995; *Vertessy et al*., 1996]. Hence, in the absence of other obvious explanations, we suggest that widespread regeneration of ash-type forests following the 2003 fire is likely to have played an important role in the stream-flow declines reported here.

4.3. Hydrological Implications

[38] Our analyses of precipitation and flow in catchments of the Upper Murray and Murrumbidgee River suggest that post-2003 regeneration is significantly reducing rainfall-adjusted water yield in the MDB. In the absence of long-term postfire data, precise estimation of $L_{\max}$ and $1/k$ is not yet possible for the Upper Murray and Murrumbidgee catchments. In the Yarra River catchments, the stream-flow impact following the 1939 fire peaked at around 20 years after the fire. If that pattern holds in the Upper Murray and Murrumbidgee catchments, then we expect the peak reduction in stream flow by around 2023. Furthermore, given that a substantial proportion of the 2.4 million ha of forest burnt in south-east Australia during the 2003 fire as well as subsequent fires in 2006–2007 and 2009 comprise stands of ash eucalypts, the potential exists for further widespread yield declines in the MDB during coming the decade.

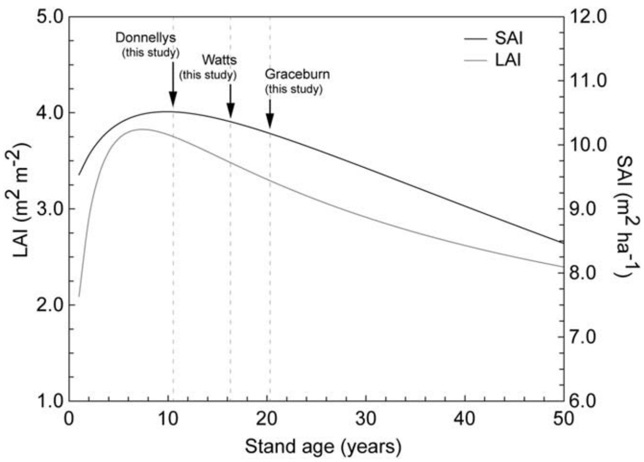

Figure 7. Age-dependent changes in stand-level leaf area index (LAI, m^2 m^{-2}) and sapwood area index (SAI, m^2 ha^{-1}) (per *Vertessy et al*. [2001]) compared with catchment level estimates of the timing of maximum postfire flow reduction ($1/k$) from this study (per Table 3).

[39] The magnitude of postfire yield declines appears to partially reflect the extent of ash regrowth and density of ash regeneration in the affected catchments [*Langford*, 1976; *Kuczera*, 1987]. Hence, previous empirical studies have focused upon differences between regrowth and mature ash forests in stand-level attributes, such as sapwood area index (SAI), to provide an explanation for postfire reductions in water yield. Whilst age-dependent trends in SAI are of an appropriate magnitude to explain the yield reductions observed by *Kuczera* [1987], the timing of the peak in SAI of around 9 years [*Vertessy et al*., 2001] substantially precedes Kuczera's estimates of $1/k$. Our estimate for $1/k$ using the expanded data sets approximates age-dependent trends in SAI and stand-level leaf-area (LAI) (Figure 7) in the Donnellys catchment. Our estimate for $1/k$ is also similar to the timing of the peak in SAI in the Graceburn catchment. However, neither stand-level variable coincides with the period of maximum postfire impact ($1/k$) in the Watts or Graceburn catchments. Hence, taken at face value, neither of those stand attributes appears to adequately describe the form of yield reductions from fire-affected ash catchments. While a greater discrepancy exists between $1/k$ estimated by *Kuczera* [1987] for each of the catchments and the timing of peaks in both LAI and SAI, the difference between Kuczera's results and our own may reflect adjustments Kuczera made to address a discontinuity within precipitation records. Nevertheless, in establishing a context for his formulation of water yield reductions from ash forests *Kuczera* [1985] explicitly associated stand-level basal area increment with forest water use. The relationship between age-dependent trends in stand water use and increment deserves further investigation.

5. Conclusions

[40] In this study, we examined the impact of bushfire on water yield from catchments containing ash eucalypts. We first re-examined a formulation originally proposed by *Kuczera* [1987] for estimating water yield in fire-affected

ash catchments after 1939 bushfires. Following that we explored the impact of the 2003 fire on water yield from five other catchments in the MDB.

[41] Our analyses of the Yarra River catchments qualitatively verify *Kuczera's* [1987] two-parameter yield function. Quantitative differences between our estimates of $L_{\max}$ and k for data sets spanning different periods revealed the sensitivity in projections from Kuczera's function to the span of the available data. The mismatch between our estimates of the timing of $L_{\max}$ $1/k$ and reported stand-level attributes of ash forests suggests that the mechanism responsible for postfire reductions in runoff from ash forests is not well understood.

[42] We found a significant prefire, drought-related reduction of runoff relative to rainfall (1997–2002) in only one of the five MDB catchments we examined. In contrast significant postfire reductions in stream flow relative to rainfall (2006–2011) were evident in three of the five MDB catchments. Much of the postfire reduction was restricted to October to April (summer) when tree growth and transpiration is at a maximum in the affected ash forests. Coupled with our finding that water yield in the studied catchments is relatively insensitive to variations in autumn rainfall we conclude that disturbance-related changes in vegetation structure have likely contributed to recent reductions in water yield relative to rainfall within the MDB. If qualitatively consistent with the form of *Kuczera*'s [1987] function of postfire water yield, further yield reductions are likely in MDB catchments affected by the 2003 fire during the coming two decades. Ongoing monitoring of stream flow data from the affected catchments will be critical during this period.

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