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[1] School of Mathematics, The University of New South Wales, Sydney, Australia
[2] Bureau of Meteorology, Sydney, Australia
[3] Rural Fire Office, NSW, Australia
[4] Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, P. R. China

The effects of bushfires on hydrological processes using a paired-catchment analysis

S. Liu[1,4], **L. M. Leslie**[1], **M. Speer**[2], **R. Bunker**[3], and **X. Mo**[4]

With 13 Figures

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Summary

Several problems associated with capturing the effects of bushfires on hydrological processes in the Goulburn River catchment (6810 km^2), Hunter Valley, Australia are investigated using a paired-catchment analysis. It is suggested, first, that the within-year-missing data, as defined in this paper, need to be examined carefully when using the double-mass curve of annual total discharge in a paired-catchment analysis. Second, in order to provide an accurate precipitation background, which is one of the most important prerequisites for a paired-catchment analysis, the use of annual average precipitation is strongly recommended together with annual total precipitation when there are large amounts of within-year-missing data. Third, caution is needed in comparing multi-year average precipitation and streamflow data before and after the fire when the data series is not statistically long enough, since the average values for precipitation and streamflow over a different number of years may produce completely contrasting results. Fourth, the analysis of the flow duration curve, which is another useful technique in paired-catchment analysis, needs to be interpreted from the precipitation duration curve. This is because the change of flow duration curve can be caused either from the change of precipitation or the fire. Fifth, the change in streamflow, calculated by subtracting the average streamflow for the non-fire years from the observed streamflow for the years in which fires occurred, is not an efficient way of capturing the fire effects. The problem associated with this approach is not just that the streamflow is strongly dependent on rainfall, as reported elsewhere, but also, it can lead to misinterpretation using the hydrograph when the average streamflow in *non-fire* years is close to the average streamflow in *fire* years.

By taking into account the above problems there was no effect of fires found on streamflow in the Goulburn River catchment. This result contrasts with the conclusions reported from other studies that have reported an immediate increase in streamflow by experimental analyses, paired-catchment analyses or modelling studies. Instead, it is shown that the spatial pattern of precipitation over the Goulburn River catchment is more important in shaping the hydrograph than the effects of bushfires. The ratio of fire extent to catchment area is approximately 4% in this study, which we suggest is a minimum area required to identify a hydrological response to the fires. The fact that other studies have focused more on capturing the generally expected effect of an immediate increase in streamflow after fire, than on why this effect occurs, makes it highly desirable to undertake micro-meteorological experiments to obtain observed evapotranspiration data before and after fire. Also, it is important to develop a coupled soil-vegetation-atmosphere-transfer dynamic mechanism and high resolution numerical weather prediction model with a distributed hydrological model in order to simulate more realistically the effect of fire on hydrological processes.

1. Introduction

As one of the foci of the International Project of Land Use/Cover Change (LUCC) of

International Geosphere and Biosphere Program (IGBP), the impact of bushfires on hydrological processes has been an important subject in meteorology, hydrology, forestry and soil science for a long time.

The main effect of fire on hydrological processes from documented studies is increased streamflow after the fire. Bosch and Hewlett (1982), and Sahin and Hall (1996) generalized that for a 10% reduction in cover by fire, the water yield from conifer-type forest increased by some 20–25 mm, by 6 mm from eucalyptus type forest and by 17–19 mm from deciduous hardwood. Scott (1997) analyzed the increases in stream-flow caused by both clear-felling and wildfire in South Africa. He showed that the clear-felling effect was dominated by large increases in total flow (96% over three years), of which storm-flow and quick-flow volumes formed only minor parts. After the wildfire, however, increases in total flow were small (12%), while the storm flow increases were three- to fourfold in the first year and approximately double in the second year. The wildfire caused fire-induced water repellency in the soils that led to overland flow on mid-slope sites, where soil permeability normally far exceeds local rainfall intensities. It is argued that these results support the hypothesis that stream-flow generation processes were changed by the wildfire in that overland flow made a direct contribution to storm flows, but that clear-felling had no such effect. With both experimental data and historical records from a catchment, Helvey (1980) found that the first post-fire year was a period of transition in which the soil profile retained more water than in previous years and measured runoff was 8.9 cm greater than the predicted value based on pre-fire conditions. Runoff from the burned catchment during subsequent years was much greater than measured values before the fire. With long-term fire data from 1949 to 1994 in southern California, Loaiciga et al (2001) also found the signal of annual streamflow increase up to 20–30% in fire-impacted water years (with 3 year carryover effect) relative to non-fire years. A group from Melbourne, Australia (Langford, 1976; Kuczera, 1987; Cornish and Vertessy, 2001; Watson et al, 2001) showed that fire in Eucalyptus forest was followed by a 2–3 year increase in streamflow, then decreases in streamflow over the following one to two decades when re-growth was established. They pointed out that a difference in transpiration is the most likely cause in the mature forest consuming less water than the re-growth forest. In the Bushrangers experiments (O'Loughlin et al, 1982), it was shown that the fire eliminated most transpiration in the following two summers, and caused a doubling in baseflow in relation to that from an undisturbed control. They then emphasized that analysis should be done separately for summer and winter periods, primarily because different responses between two catchments could only be expected when the potential for transpiration is high. By contrast, few other studies have reported no hydrological response, or only minor, hydrological response to fire (Van Lear et al, 1985; Lindley et al, 1988; Jakeman et al, 1993).

The classic method of exploring fire effects on hydrological processes is to perform laboratory experiments (Aston and Gill, 1976) and field experiments on runoff (Dobrowoski et al, 1992; Robichaud and Waldrop, 1994; Cerda et al, 1995; Keller et al, 1997; Nelson et al, 1999; Morales et al, 2000; Murakami et al, 2000; Robichaud, 2000; Benavides-Solorio and MacDonald, 2001; Veenhuid, 2001) and fire-induced soil water repellency (DeBano, 2000; Scott, 2000; Letey, 2001) with rainfall simulators. However, paired-catchment analysis becomes more appropriate when the research scale is extended from small plots to catchment scale. When the control and treated parts of the catchment are calibrated against each other using several years of data before and following fire, the catchment response to the fire can be evaluated. There are many documented studies using this method (e.g., Langford, 1976; Helvey, 1980; Homes and Wronski, 1982; Kuczera, 1987; Cornish and Vertessy, 2001; Loaiciga et al, 2001; Roberts et al, 2001; Townsend and Douglas, 2000; Watson et al, 2001) employing techniques of analysis such as double-mass curve, flow duration curve, statistical regression and others. On the other hand, paired-catchment analysis must be used with discretion.

For example, one of the drawbacks of a paired-catchment analysis is that it is difficult to assess the hydrological impact of fire solely when the changes in amount and temporal distribution of rainfall over the period are in question. The reason is that changes in the amount and dynamic behaviour of catchment scale runoff after a fire may be due to either alterations to the physical nature of the catchment surface, or natural variability in the climate such as the amount and intensity of incident rainfall, or both. Missing data is another problem, which can easily result in misleading conclusions. In addition, the data record may not be long enough for statistical analysis and can limit the value of paired-catchment analysis, which is a method that greatly relies on statistical techniques. To treat the problem of short data length, Watson et al (2001) proposed a seasonal regression model with lag-one auto-regressive error that can be applied to monthly streamflow data rather than yearly data, which can effectively increase the length of data record. Also, the need for catchment control data is another limitation of paired-catchment analysis. When control catchment data is not available, a dummy variable method can be applied (Scott and Wyk, 1990; Scott, 1997).

In this paper, we will analyze a case study to highlight these problems by using a paired-catchment analysis to test the fire effects on hydrological processes in the Goulburn River catchment, Hunter Valley, Australia. The structure of the paper is as follows. Section 2 provides a brief description of the Goulburn River catchment and the timing and areal extent of fire to which the catchment has been subjected. This is followed in Sect. 3 by a description of five problems associated with paired-catchment analysis, which are often neglected by other studies, and the method we use to avoid the effects of these problems. In Sect. 4, a threshold of minimum area of burnt catchment vegetation is then proposed in order to identify the fire effects on hydrological processes, based on the results of the case study. An explanation for the effects of fire on streamflow is then explored in Sect. 5 with a comparison extended to the conclusions from other studies. Finally, conclusions are presented in Sect. 6.

2. The Goulburn River catchment and its fires

The Goulburn River catchment is a mid- to large-scale catchment in the Hunter Valley, NSW, Australia (Fig. 1). Its mean annual potential evaporation is about 1500 mm, which far exceeds its mean annual precipitation of 600 mm. Its climate therefore can be described as semi-arid.

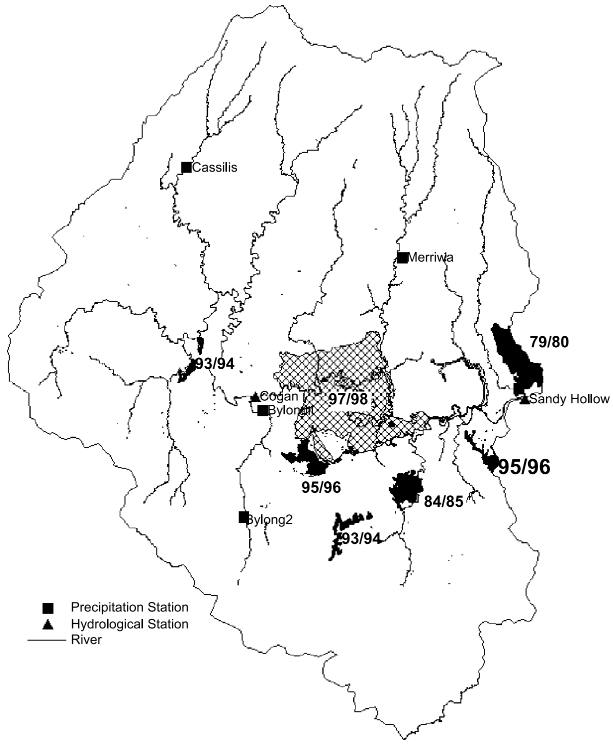

Fig. 1. Location map displaying burned areas from five fires in the Goulburn River catchment, Hunter Valley, Australia

The soils of the region comprise several types. Deep, fertile, alluvial soil along the floodplains is several kilometres wide in places. Cracking clays are derived from weathered basalt on the Merriwa Plateau. Skeletal soils are found in the southern sandstone plateau and in the eastern mountain area. On steep slope areas, podsolic and solentic soils are derived from carboniferous rocks. Owing to the highly erodible nature of the common soil profiles and rising groundwater table, the Goulburn River catchment experiences continuing problems of erosion and dryland salinity.

The vegetation consists of woodland-shrublands on the poor, thin soils of the sandstone hills surrounding the Goulburn River catchment. In the woodland-shrubland area, there is a shrub under-story. Woodlands occur in response to one or more of the environmental factors of poor soils, lower rainfall, exposure and/or extremes of temperature. The sub-formations occurring in the

Goulburn River catchment are Eucalyptus tall woodland, Eucalyptus woodland-shrubland, Eucalyptus woodland, Eucalyptus open-woodland and grassland.

In the Goulburn River catchment, there are two discharge stations, Sandy Hollow (32° 20′39″ S, 150° 6′5″ E), with a catchment area of 6,810 km^2 and the other one, Cogan (32° 20′49″ S, 150° 34′23″ E), with a catchment area of 3,340 km^2. Over the period from 1973 to 2000, the mean annual flow is 2.83 $m^3 s^{-1}$ at the outlet of Cogan and 5.81 $m^3 s^{-1}$ at the Sandy Hollow cross section, ranging from zero on many days each year at the two stations to 704.14 $m^3 s^{-1}$ (Cogan) and 1229.48 $m^3 s^{-1}$ (Sandy Hollow), on the same day of March 5, 1977. From Fig. 1, it can be seen that all the fires are concentrated downstream of Cogan station, which establishes it as a ‘‘control’’ catchment for paired-catchment analysis in our study. Precipitation data are available at five stations in the Goulburn River catchment. The averaged precipitation (Average_3) over the three stations consisting of Cassilis, Bylong1 and Bylong2 is used to represent the area of the catchment upstream of Cogan. The averaged precipitation (Average_5) over the five stations consisting of Cassilis, Bylong1, Bylong2, Merriwa and Sandy Hollow are used to represent the area of the catchment downstream to Sandy Hollow. There is no record of observed evaporation data for the Goulburn River catchment. The potential evapotranspiration data from Australia Sunken Tank at Scone (32° 03′48″ S, 150° 55′36″) and Paterson (32° 37′47″ S, 151° 35′31″ E) are used as the potential evaporation data closest to the Goulburn River catchment.

Records of fire data from 1970 to 1999 in the Goulburn River catchment show that there were five fire events with fire affecting an area covering over 15 km^2 as indicated in Table 1 and Fig. 1. It can be seen that although burning was not stable at a regular site, most of the areas burned towards the centre of the catchment. The geography relating to bushfire in the Goulburn River catchment is characterized by a few general patterns. Bushfire maps, including those shown in Fig. 1, suggest that most bushfires tend to be concentrated in the centre of the catchment and propagate eastward. This is because typically hot, dry and gusty westerly winds originating from inland Australia drive the fires (Speer et al, 1996). These winds are the result of a strong atmospheric pressure gradient near the Earth’s surface extending north from low-pressure systems south of the Australian continent. The westerly airflow is subsequently funnelled through the Goulburn Pass, located between the Great Dividing Range and the Liverpool Range, and through the Hunter Valley towards the coast. During summer and especially after several months of hot temperatures and low humidity, there is abundant, dry, combustible biomass in the study area. Under these conditions of hot temperatures, low humidity, gusty winds and dry vegetation, wildfires, once ignited, can burn substantial areas of the catchment.

Table 1. Fire data for the Goulburn River catchment (6810 km^2), 1970–2000

Year	Area burned (km^2)	Percentage of area burned (%)	Station
1979/80	39.93	0.59	Sandy Hollow
1984/85	20.5792	0.30	Sandy Hollow
1993/94	15.5364	0.23	Cogan
1993/94	5.24	0.16	Sandy Hollow
1995/96	24.6055	0.36	Sandy Hollow
1997/98	236.8	3.48	Sandy Hollow

3. Uncertainties arising from paired-catchment analysis

3.1 Double-mass curve

The double-mass curve is one of the most useful techniques in paired-catchment analysis. After computing the cumulative streamflow amounts for the treatment gauge and control gauge, and plotting the former on the y-axis versus the latter on the x-axis, a straight-line through the data points is called the double mass curve. If there are no errors or changes in the data for the treatment gauge, all points will fall (approximately) on a straight-line. Divergence from a straight-line indicates a possible link to land-use changes such as fire, to climatic change, to any data error or to change of gauge location. We will concentrate here on one of the reasons that may cause the divergence, namely, missing data, which can be easily neglected.

Missing data arises in two ways. The first is data that is missing for an entire year, which we

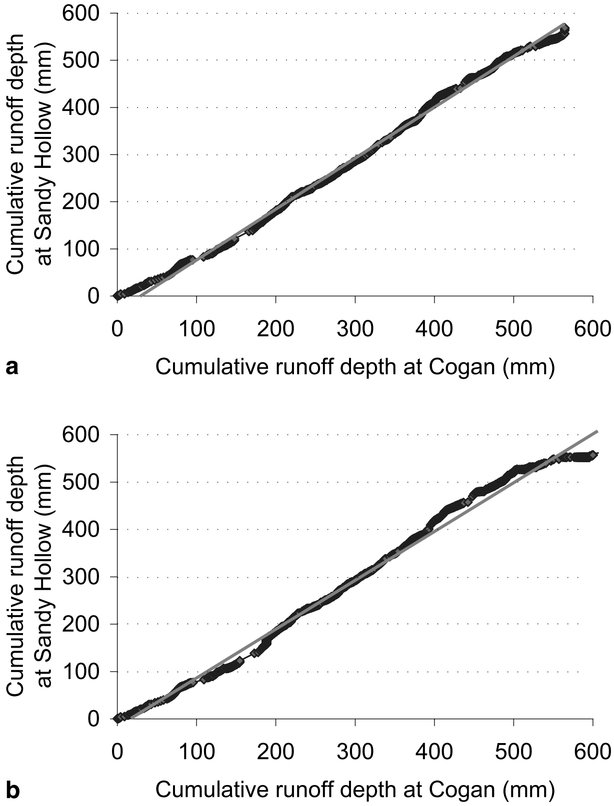

Fig. 2. Double mass curves based on (**a**) processed data, and (**b**) raw data, from locations in the Goulburn River catchment

refer to as all-year-missing data. Figure 2a shows the double mass curve based on the processed data for which we omit all the data at the two stations if correspondingly there are missing data at any one of the two stations. A detailed check of the data in this case is thus shown to be especially important, otherwise the change could be falsely interpreted to result from land-use change, namely, the result of vegetation burnt by fire. The second is data for missing days of less than one year, which we refer to as within-year-missing data. It is the latter to which much attention should be paid when drawing the double-mass curve of annual total discharge. This is exemplified, by a misleading double-mass curve of the streamflow at Sandy Hollow and Cogan stations (Fig. 2b), which is caused by a lot of within-year-missing data for many years.

3.2 Annual total precipitation

In paired-catchment analysis, the rainfall over the treatment catchment (in our case, the area burnt by fire) is always used to compare the pre-treatment and post treatment streamflow. If it is found that there is an increase in streamflow after the treatment and the rainfall decreased during that time, a signal of the effects of the treatment (fire in this case) on hydrological processes can be regarded as being well captured. An accurate estimate of the magnitude of rainfall amount is essential otherwise the signal of the effect of the treatment that is captured, is likely to be false.

In the Goulburn River catchment there are many within-year-missing data points in the precipitation series, as there are with discharge data. This renders a comparison between Average_5 and Average_3 difficult to make. In order to accurately compare the annual total precipitation, we define an annual average precipitation as the

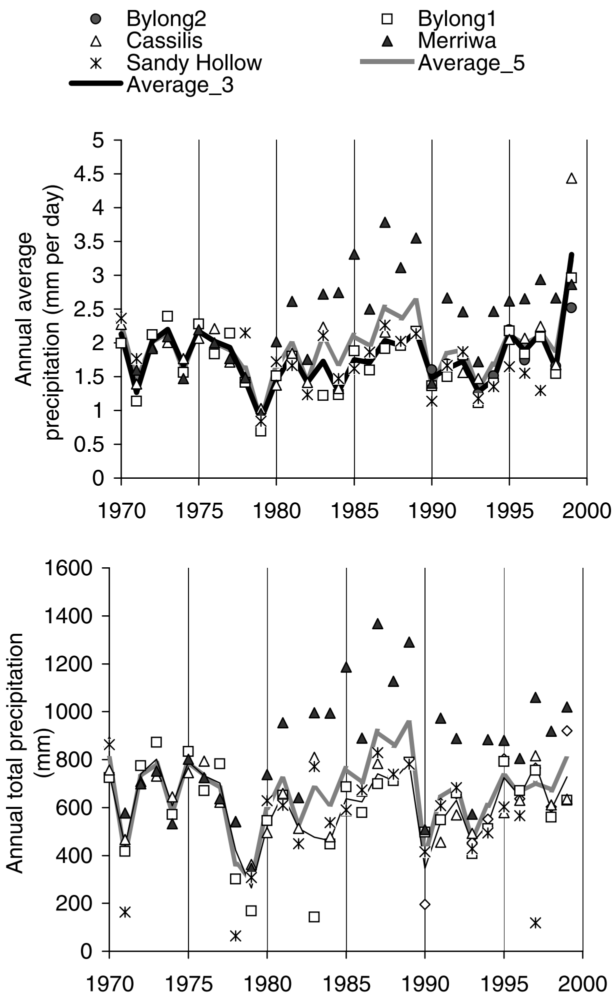

Fig. 3. The annual averaged precipitation and annual total precipitation based on raw data

averaged precipitation over the number of days in the year when daily data is available (mm day^{-1}).

The annual averaged precipitation and annual total precipitation based on the original data series are shown in Fig. 3a, b, respectively. The unusually high precipitation at Cassilis (Fig. 3a) is due to the fact that the available precipitation data for the corresponding year is only available for several days, which is too small a time period to represent an annual value. It can be also seen that the annual total precipitation for Average_3 in 1983 is less than that in 1982 while the annual average precipitation for Average_3 in 1983 is larger than that in 1982. If there was a land-use change, this may lead to a false conclusion of the effect of the land-use change on hydrological processes based on the precipitation record.

To avoid this problem, the series of annual total precipitation and annual average precipitation are compared. After omitting those years in the two data series which contain less than a year's worth of data points, the annual total precipitation and the annual average precipitation closely match each other, as should be the case (Fig. 4). The annual average precipitation and annual total precipitation can now be related to the same changing pattern, and we can use either annual average precipitation or annual total precipitation in further paired-catchment analysis.

It can be also seen in Fig. 4 that Average_3 and Average_5 follow each other closely prior to 1983. However, there is a large difference between them after 1983, which is related to the fact that precipitation at Merriwa station is significantly larger than precipitation at the other four stations during this period. By redrawing Fig. 4 without the contribution of Merriwa in calculating the spatial average precipitation, Average_5 actually becomes Average_4. It is not surprising that precipitation over the whole of the Goulburn River catchment (Average_4) and that for Average_3 now follow each other very closely as shown in Fig. 5. This provides an opportunity for us to explore and compare the impacts of the hydrological response to fire and the unique behavior of the precipitation at Merriwa station. It should be noted that all the values of variables in this study are calculated over the Australian fire year calendar, namely, from October 1 to September 30 in order to make them comparable with fire data.

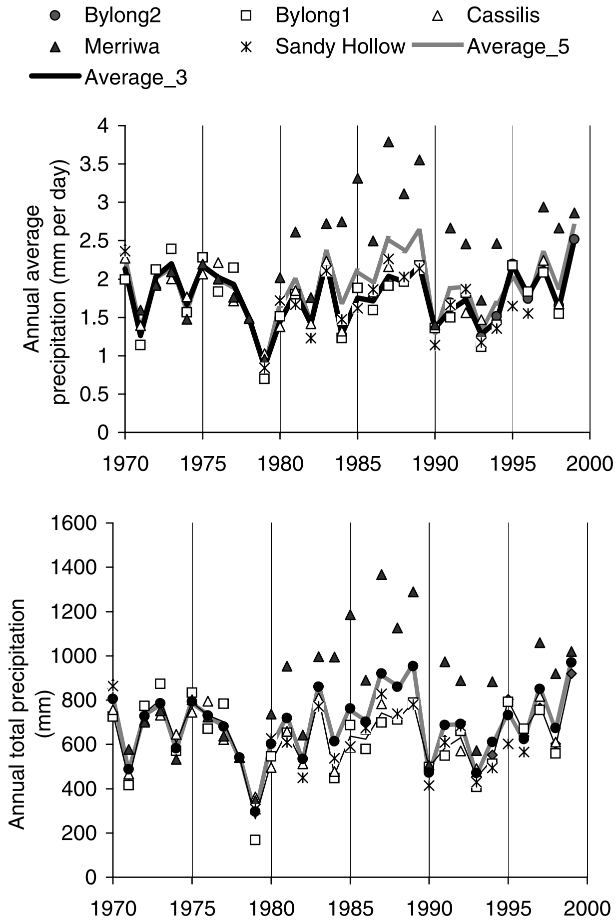

Fig. 4. As in Fig. 3, except based on processed data

3.3 Comparison of multi-year average precipitation and streamflow

In comparing pre-fire and post-fire streamflow and precipitation, caution must be exercised on the number of years used in calculating multi-year average precipitation and streamflow. Statistically, any hydrological analysis is meaningful only when the data time period is of sufficient length, usually about 30 years. However, for fire studies, especially those related to field experiments, it is very difficult to obtain such a long data series. Many studies draw conclusions based on only a few years of data (for example, Helvey, 1980).

This problem is highlighted in Fig. 6 by exploring the effect of a 1993/94 fire on the streamflow at Cogan station. Prior to and after the 1993/94 fire, there were no fires in the catchment near Cogan (see Table 1), so pre-fire and post-fire multi-year average streamflow and precipitation can be directly compared. Indicted in Fig. 6 is the multi-year average over 1 to 20 years before the fire and over 1 to 7 years after the fire,

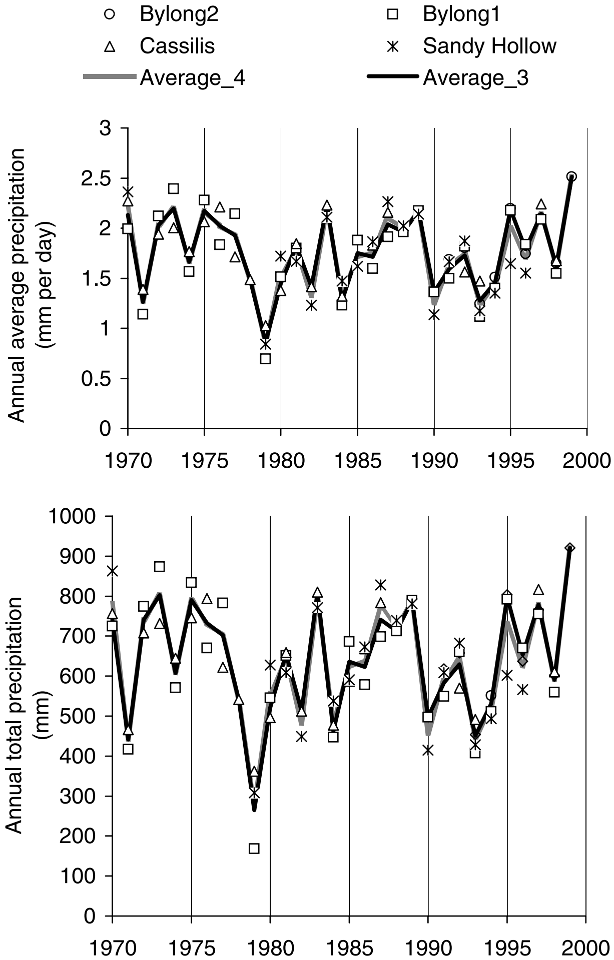

Fig. 5. As in Fig. 4, except excluding Merriwa in calculating the spatial average

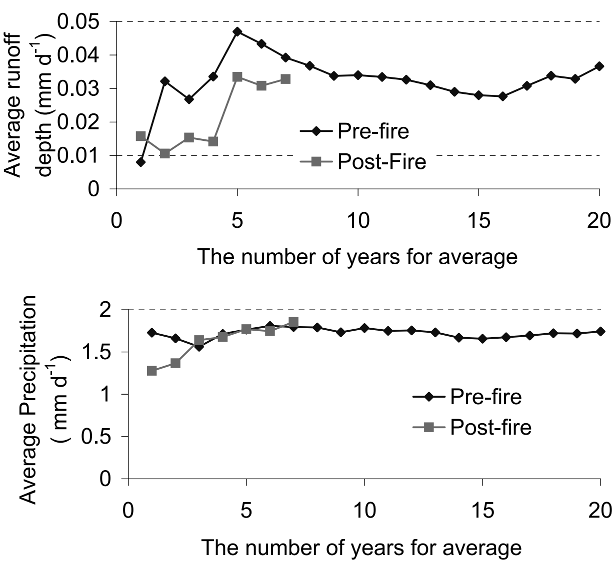

Fig. 6. The change in averaged streamflow and precipitation using the total number of years to calculate the average

respectively, for streamflow and precipitation. It can be seen that there is a problem in attempting to compare the magnitude of the precipitation with that of the streamflow, both of which highly depend on the number of years used to calculate the average. For example, if we compare the pre-fire and post-fire average precipitation and streamflow, shown in Table 2, over the same number of years, there are three possible conclusions that we may draw from the comparison: (1) fire effect is captured in the hydrological processes, that is, precipitation decrease is related to streamflow increase, (2) there is a normal rainfall-runoff relationship in the catchment, namely, that precipitation increase/decrease corresponds to discharge increase/decrease, and (3) further explanation is needed if an increase in precipitation is followed by a decrease in discharge. These conclusions also apply when the averages of the post-fire and pre-fire years are calculated over a different number of years. As a result, we can have no confidence in saying whether or not the correct signal of the effects of the 1993/94 fire on hydrological processes at Cogan has been captured.

3.4 Flow duration curve

Investigation of the flow duration curve is another technique commonly used in paired-catchment analysis. The flow duration curve displays a cumulative distribution that illustrates the fraction of time that flows are exceeded over the period of the record. The contrast in flow duration curves before and after the fire is used to represent the fire effect (Helvey, 1980). However, again, we must be very careful to interpret the curve correctly.

The flow duration curve for Sandy Hollow (Fig. 7), will be used to analyze the effects of the fires recorded from 1973 to 2000 on streamflow at Sandy Hollow. A three year carryover effect following a bushfire (Loaiciga et al, 2001) was used as the criterion to establish whether or not streamflow was affected by vegetation burning (see Table 1 and Fig. 1). Thus, for example, the 1979/80 fire was considered to impact streamflow during fire years 1979–1980, 1980–1981 and 1981–1982. If a bushfire occurred within three years of a previous one, then a three-year carryover period was measured from the time of the last bushfire. The three-year carryover effect of bushfires was based on field

Table 2. Conclusions to be drawn on fire effect based on multi-annual average precipitation (P) and discharge (D) over the different number of years before and after the fire

Number of years for average	P-increase	D-decrease	P-decrease	D-increase	Conclusion
1			X	X	Fire effect
2		X	X		Normal in hydrology
3	X	X			Why?
4		X	X		Normal in hydrology
5	X	X			Why?
6		X	X		Normal in hydrology
7	X	X			Why?

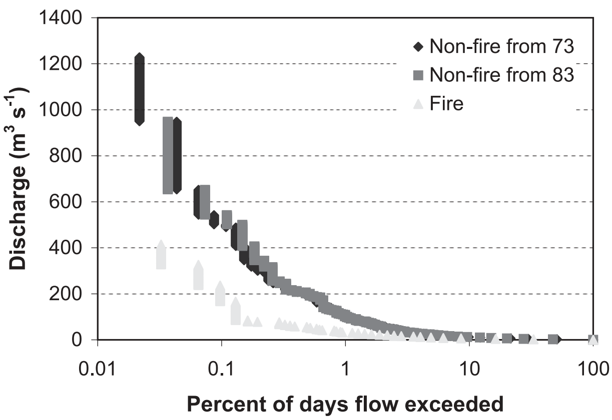

Fig. 7. Flow duration of streamflow at Sandy Hollow in fire and non-fire years

observations reported by a number of researchers (Langford, 1976; Helvey, 1980; Cornish and Vetessy, 2001).

If in Fig. 7 we find that streamflow at each cumulative percent value after the fire was larger than that compared to pre-fire values, we can then confidently conclude, as other researchers have, that fire has affected streamflow. However, Fig. 7 reveals information contrary to that found elsewhere, which needs further explanation. Since the flow duration for non-fire years based on data from 1973 is the same as that from 1983, we can be sure that the streamflow itself is consistent for both periods, and so the difference in discharge between fire years and non-fire years must be due to other factors. The first factor to consider is the difference in precipitation amounts. Shown in Fig. 8 are the duration curves for precipitation where the precipitation at Merriwa is excluded from the spatial average precipitation based on data from 1973 and 1983 (Fig. 8a, b, respectively), and where the precipitation at Merriwa contributes to the spatial average precipitation based on data from 1973 to 1983 (Fig. 8c, d, respectively). There is a significant difference between fire and non-fire years in precipitation when considering the contribution of Merriwa based on data dated from 1973. Keeping in mind the fact that the precipitation at Merriwa since 1983 is much higher than at the other stations and higher than the precipitation at Merriwa before 1983, it is clear that it is the change in precipitation at Merriwa that explains the difference in discharge between fire and non-fire years at Sandy-Hollow, and not fire.

The corresponding difference between the discharge and precipitation before and after the 1993/1994 fire (Figs. 9 and 10), again supports the contention that precipitation amount plays a more significant role than the effects of fire. Furthermore, the difference in the duration, based on data either starting from or ending at different dates, is very small, which indicates that our conclusion is independent of how much data is used.

In summary, for a paired-catchment analysis, we strongly recommend use of both the flow duration curve and the precipitation duration curve, in order to draw both a statistically and physically-based conclusion.

3.5 The change in discharge

In paired-catchment analysis, another technique that may be used to investigate the effect of fire on streamflow, is to calculate the change in streamflow by subtracting the average streamflow and precipitation for the non-fire years from the observed streamflow and precipitation for the fire years (Post et al, 1996). In Figs. 11 and 12, it can be seen that the temporal trend reflected from the change in streamflow/precipitation is similar

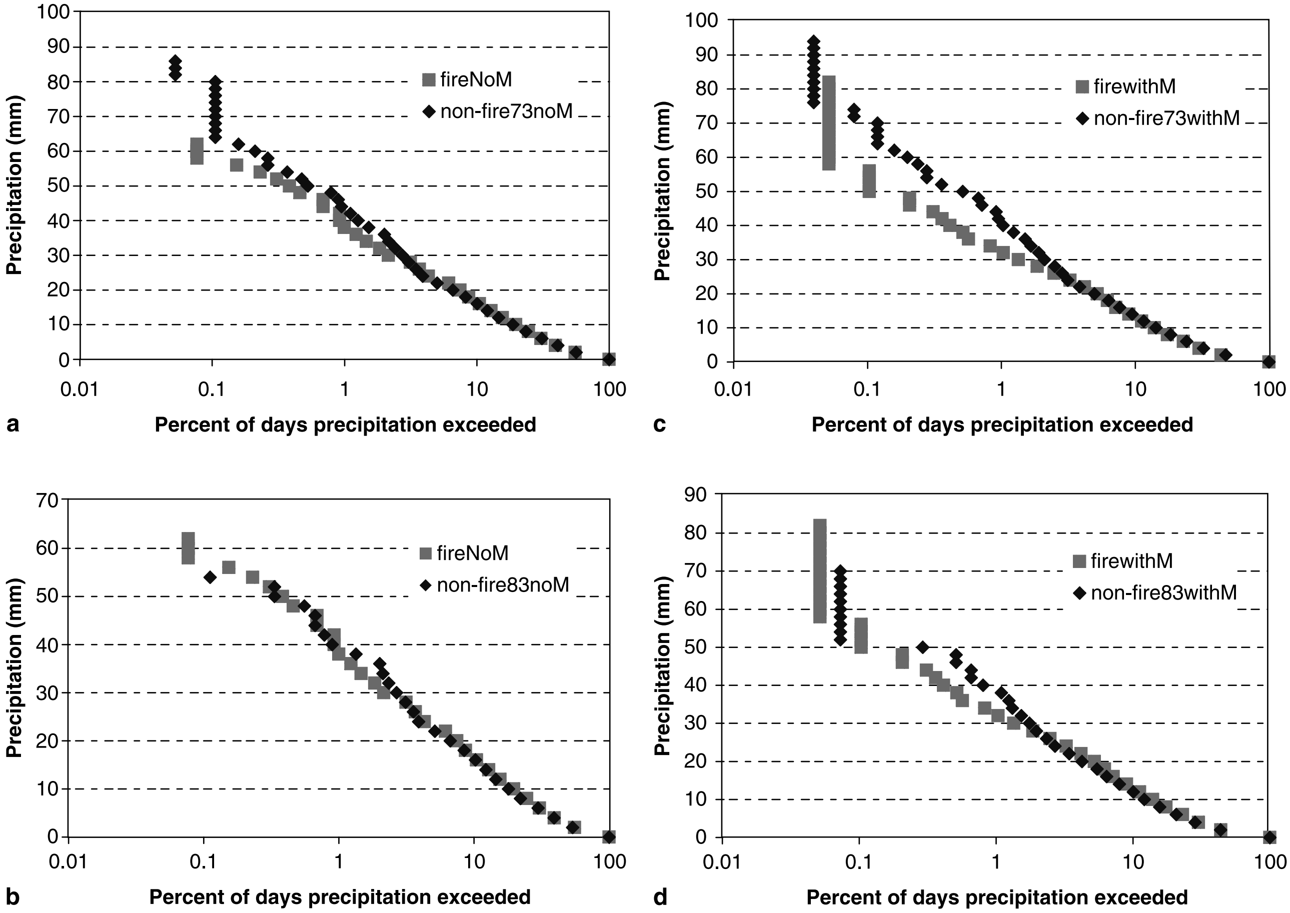

Fig. 8. Duration curves for averaged precipitation excluding (**a** and **b**) and including (**c** and **d**) Merriwa precipitation for fire and non-fire years from 1973 (upper panel) and 1983 (lower panel)

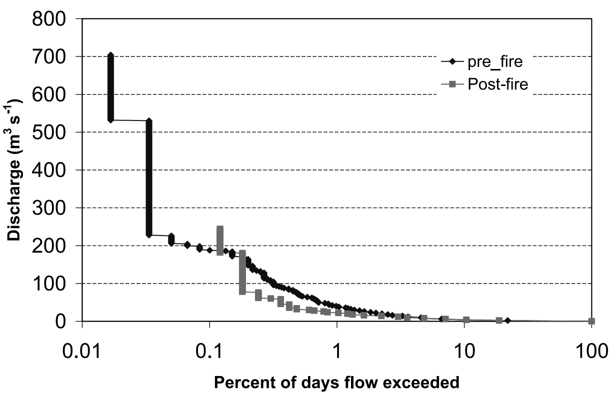

Fig. 9. Flow duration of streamflow at Cogan before and after the 1993/94 fire

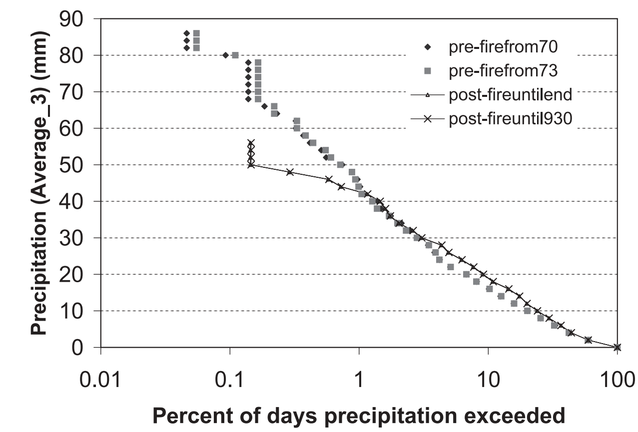

Fig. 10. Precipitation duration curve (Average_3) before and after 1993/94 fire

to that of streamflow/precipitation itself. Apart from the 1993/1994 fire, the increase/decrease in discharge after each of the bushfires is always followed by an increase/decrease in precipitation upstream Sandy Hollow. Since the 1993/1994 fire could potentially have affected the streamflow at both Cogan and Sandy Hollow and also, because it is the fire that covered the smallest area, it is too difficult to draw a valid conclusion about the hydrological response to the fire from

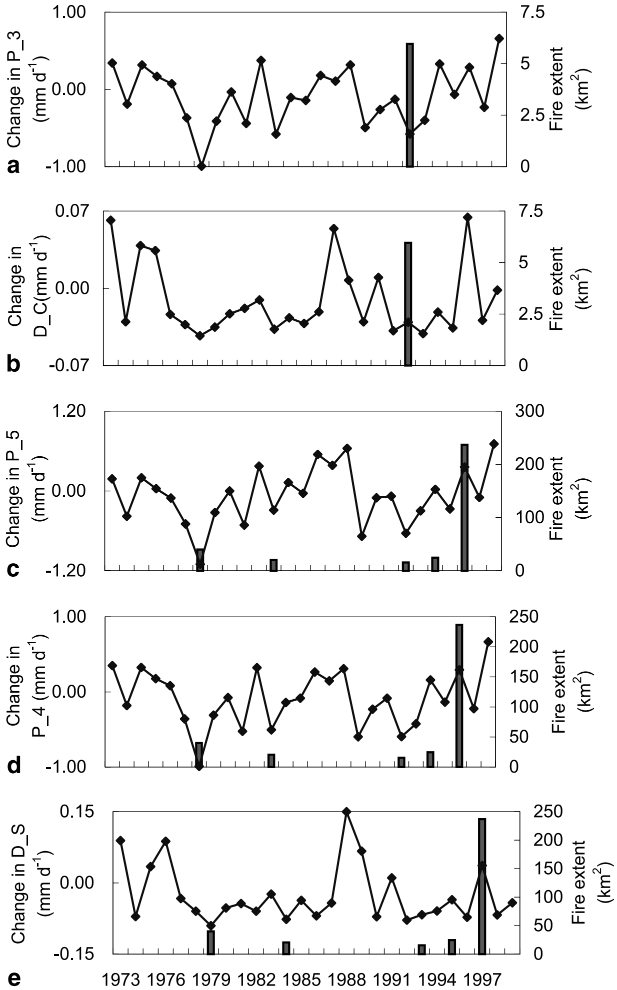

Fig. 11a. The change in precipitation (Average_3), (**b**) streamflow at Cogan, (**c**) precipitation (Average_5), (**d**) precipitation (Average_4), and (**e**) streamflow at Sandy Hollow

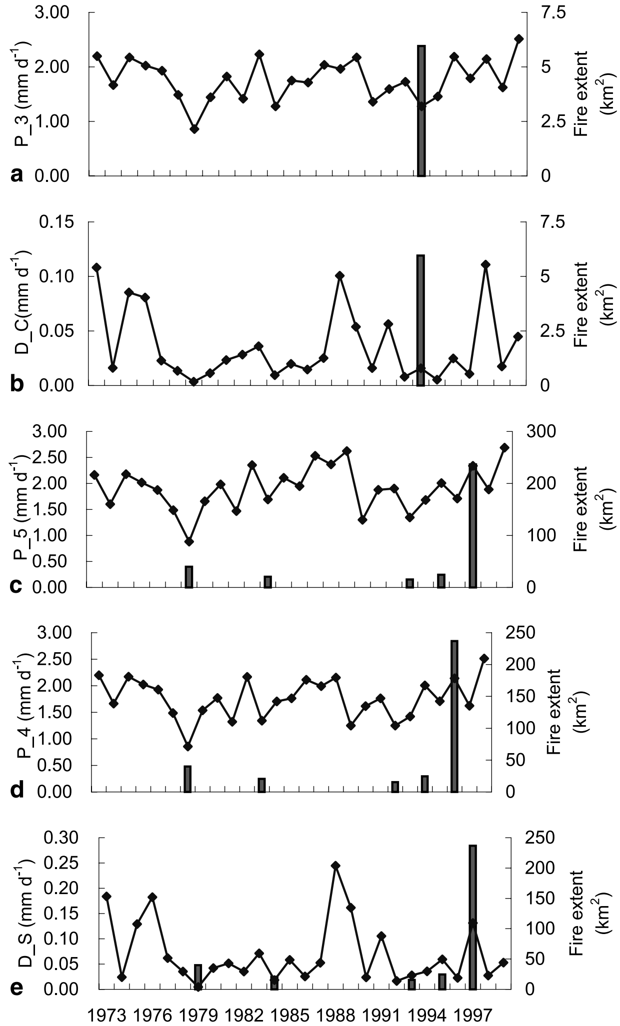

Fig. 12a. Precipitation (Average_3), (**b**) streamflow at Cogan, (**c**) precipitation (Average_5), (**d**) precipitation (Average_4), and (**e**) streamflow at Sandy Hollow

the relationship between the increase in streamflow at Sandy Hollow and the decrease in precipitation upstream Sandy Hollow.

In brief, the rainfall-runoff relationship after most of the fires is indicative of a normal hydrological response. This allows us to confidently conclude that at least the hydrological response to fire in the Goulburn River catchment is not large enough to alter the naturally occurring rainfall-runoff relationship. In other words, precipitation still plays the main role in shaping the hydrograph in the Goulburn River catchment. Actually, the double mass curve shown in Fig. 2 has already provided a clue that there was no abnormal process acting on the hydrograph at either Cogan or Sandy Hollow.

4. Threshold percentage of influential fire area to catchment area

In this study, the percentage of catchment fire area to total catchment area is approximately 4%. From the paired catchment analysis above, there was no significant signal of fire effect on streamflow captured. By choosing only those fires, which burned 4% or more of a catchment, Loaiciga et al (2001), captured a signal of the effects of fire on streamflow. The size of the catchment area in their study was 272.21 km^2, which is the largest catchment area we are aware of in similar studies. In a study showing that fire has an effect on hydrology, the ratio of the treatment area in the study, including either an area of catchment or an area of experimental plot, is much larger than 4% (Sahin and Hall, 1996). In that sense, 4% can be regarded as a possible threshold minimum area of catchment affected by fire for which fire can produce marginal effects on the hydrological processes of the catchment.

5. Possible explanation of fire effects on streamflow

For those catchments where fire effects on hydrology have been found, there have been very few studies to explain the reasons. Scott (1997) explained fire effects by analyzing the catchment evapotranspiration (E), which is the sum of evaporation from soil surface (E_s) and open water (E_o), of transpiration (E_t) and intercepted precipitation (E_i) (Hewlett, 1982), expressed as

$$E = E_s + E_o + E_t + E_i. \tag{1}$$

In a well-wooded catchment, E_i and E_t will be the main components of the evapotranspiration. After a fire, the original major components of the above equation, namely, E_t and E_i are reduced to almost zero. This is compensated for by an increase in E_s as a consequence of increased net radiation on the ground through reduced albedo of the ash-blackened soil surface and increased wind speed over it (Scott, 1997). Since observed evapotranspiration data over the catchment before and after a fire are not available, it is very difficult to make a physically-based comparison of the main component, E_s after a fire with the main component, E_t before a fire. Other studies concentrate only on transpiration. For example, from field observations, Langford (1976), and Roberts et al (2001) found that a difference in transpiration is the most likely cause in the mature forest consuming less water than the re-growth forest. They reported a reduction in streamflow from three to five years after the burn, when re-growth was established. Yet a difference in transpiration seems sufficient to explain the flow decrease with the re-growth after the fire. However, it is not sufficient to physically explain why the flow increased immediately after the fire. Without offering any measurable or calculated value of the evapotranspiration before the fire (where E_i and E_t are the main components), or, of the evapotranspiration after the fire (where E_s is the main component), Scott (1997) stated anyway that, "overall, however, a reduction in evapotranspiration from the burned catchment can be expected after fire".

It would seem that the main reason streamflow increases after fire, especially in a small catchment, is due to the removal (from combustion) of plant litter from the soil surface. This effect is important in reducing surface storage capacity (retention and detention) on the site, in removing obstacles from the flow of water, and in transporting away eroded soil particles. Evapotranspiration will not cause an immediate increase in streamflow since while it is raining, evapotranspiration is small. The most significant process that evapotranspiration will effect, is the base flow. Observational data is not available to confirm this. However, the fact that the annual averaged potential evaporation at Scone remains the same ($4\,\mathrm{mm\,day}^{-1}$) in both fire and non-fire years and that other studies show that fire influences storm flow more than total flow (Scott, 1997), are two supporting arguments.

From the above discussion, there is much scope for future work. Firstly, obtaining micrometeorological experiments before and after a fire is very important because fire or other land use change activities can affect the surface forcing conditions of the system, and consequently the partitioning of the available energy into the densities of sensible and latent heat fluxes. This will provide sufficient observed data of evapotranspiration before and after fire, physically explaining why and how streamflow responds to a bushfire.

With observations of energy exchange data available, the second step is to establish a dynamic distributed hydrological model. As it will contain many measurable parameters related to land use change from the effects of fire, such as leaf area index and albedo, both water and energy transfer in the vertical direction and water movement in the horizontal direction the distributed hydrological model should be integrated with a Geographical Information System (Mackay and Band, 1997; Storck et al, 1998; Matheussen et al, 2000; Mengelkamp et al, 2001; Kosner, 2001). It is reasonably straightforward to simulate the effects of fire via the physical mechanism of water and energy transfer within a Soil-Vegetation-Atmosphere-Transfer system (SVAT), which can explicitly reflect the change in vegetation before and after a bushfire. The SVAT model to be used in further research is one developed by Mo (1998).

Also, in future, work will commence on the significant small-scale hydrological responses to rainfall events that occur before and after a bushfire. This work will link a high resolution atmospheric prediction model (Speer et al, 1996; Mölders, 1998; Yu et al, 1999; Ibbitt et al, 2000, Kalma, 2001; Mölders, 2001) to the dynamic hydrological model. The numerical weather prediction model we will use is The University of New South Wales HIgh RESolution model (HIRES) developed by one of authors (LML) (see, for example, Leslie et al, 1985; Leslie and Purser, 1995; Speer et al, 1996).

6. Conclusions

A paired-catchment analysis carried out on the Goulburn River catchment, Hunter Valley, Australia revealed five problems after a detailed check of the data used in the analysis. First, within-year-missing data needs to be examined carefully when using the double-mass curve of annual total discharge in a paired-catchment analysis. Second, in order to provide an accurate precipitation background, which is one of the most important prerequisites for paired-catchment analysis, the use of annual average precipitation is strongly recommended together with annual total precipitation when there are large amounts of within-year-missing data. Third, caution is needed in comparing multi-year average precipitation and streamflow data before and after the fire when the data series is not statistically long enough, since the average values for precipitation and streamflow over a different number of years may produce completely contrasting results. Fourth, the analysis of the flow duration curve, which is another useful technique in paired-catchment analysis, needs to be interpreted from the precipitation duration curve. This is because the change of the flow duration curve before and after fire can be due to either fire or a change in precipitation. Fifth, the change in streamflow, calculated by subtracting the average streamflow for the non-fire years from the observed streamflow for the years in which fires occurred, is not an efficient way of capturing the fire effects. The problem associated with this approach is not just that the streamflow is strongly dependent on rainfall, as reported elsewhere, but, also, it can lead to miss-interpretation using the hydrograph when the average streamflow in *non-fire* years is close to the average streamflow in *fire* years. After taking into account the possible effects of these five problems there was no signal found on the effect of fires on streamflow in the catchment. Instead, precipitation at one of the five stations plays the dominant role, indicating that the spatial pattern of precipitation in this catchment is more important in shaping the hydrograph than the effects of bushfires. The percentage of the total catchment area affected by fire in this study is less than 4%, which we suggest as a minimum threshold area needed to identify if there is a hydrological response to the fires. Future work will concentrate on micro-meteorological experiments and the development of a coupled SVAT dynamic mechanism to a high resolution numerical weather prediction model with distributed hydrological model. This is required to better explore the causes of fire effects on hydrological processes by model simulation.

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References

Aston AR, Gill AM (1976) Coupled soil moisture, heat and water vapor transfers under simulated fire conditions. Aust J Soil Res 14: 55–66

Benavides-Solorio J, MacDonald LH (2001) Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. Hydrol Process 15(15): 2931–2952

Bosch JM, Hewlett JD (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J Hydrol 22: 3–23

Cerda A, Imeson AC, Calvo A (1995) Fire and aspect induced differences on the erodibility and hydrology of

soils at La Costera, Valencia, Southeast Spain. Catena 24: 289–304
Cornish PM, Vertessy RA (2001) Forest age-induced changes in evapotranspiration and water yield in a eucalyptus forest. J Hydrol 242(1–2): 43–63
De Bano LE (2000) The role of fire and soil heating on water repellency in wildland environments: a review. J Hydrol 231(special issue): 195–200
Dobrowoski J, Balckburn WH, Pearson HA (1992) Changes to infiltration and interrill erosion from long-term prescribed burning in Louisiana. Water Res Bull 28(2): 287–298
Helvey JD (1980) Effects of a north-central Washington wildfire on runoff and sediment production. Water Res Bull 16(4): 627–634
Homes JW, Wronski EB (1982) On the water harvest from afforested catchments. 1st National Symp. on Forest Hydrology. National Conference Publication, Institute of Engineers, Australia, pp 1–6
Ibbitt RP, Henderson RD, Copeland J, Wratt DS (2000) Simulating mountain runoff with meso-scale weather model rainfall estimates: a New Zealand experience. J Hydrol 239: 19–32
Jakeman AJ, Littlewood IG, Whitehead PG (1993) An assessment of the dynamic response characteristics of streamflow in the Balquhidder catchments. J Hydrol 145: 337–355
Kalma JD (2001) On the representation of land surface fluxes from atmospheric modelling. Meteorol Atmos Phys 76: 53–67
Keller EA, Valentine DW, Gibbs DR (1997) Hydrological response of small watersheds following the Southern California Painted Cave Fire of June 1990. Hydrol Process 11(4): 401–414
Kostner B (2001) Evaporation and transpiration from forests in Central Europe-relevance of patch-level studies for spatial scaling. Meteorol Atmos Phys 76: 69–82
Kuczera G (1987) Prediction of water yield reductions following a bushfire in ash-mixed species eucalyptus forest. J Hydrol 94: 215–236
Langford KJ (1976) Change in field of water following a bushfire in a forest of eucalyptus regnans. J Hydrol 29: 87–114
Leslie LM, Mills GA, Logan LW, Gauntlett DJ, Kelly GA, Manton MJ, MaGregor JL, Sardie JM (1985) A high resolution primitive equations NWP model for operations and research. Aust Met Mag 33: 11–35
Leslie LM, Purser RJ (1995) Three-dimensional mass-conserving semi-Lagrangian scheme employing forward trajectories. Mon Wea Rev 123: 2551–2556
Letey J (2001) Causes and consequences of fire-induced soil water repellency. Hydrol Process 15(15): 2867–2875
Lindley AJ, Bosch JM, van Wyk DB (1988) Changes in water yield after fire in Fynbos catchment. Water SA 14: 7–12
Loaiciga HA, Pedreros D, Roberts D (2001) Wildfire-streamflow interactions in a chaparral watershed. Adv Environ Res 5: 295–305
Mackay DS, Band LE (1997) Forest ecosystem processes at the watershed scale: Dynamic coupling of distributed hydrology and canopy growth. Hydrol Process 11(9): 1197–1217
Matheussen B, Kirschbaum RL, Goodman IA, O'Donnell GM, Lettenmaier DP (2000) Effects of land cover change on streamflow in the interior Columbia River Basin (USA and Canada). Hydrol Process 14(5): 867–885
Mengelkamp HT, Warrach K, Ruhe C, Raschke E (2001) Simulation of runoff and streamflow on local and regional scales. Meteorol Atmos Phys 76: 107–117
Mo X (1998) Modeling and validating water and energy transfer in soil-vegetation-atmosphere system. Acta Meteorol Sinica 56(3): 323–332 (in Chinese with English abstract)
Mölders N (1998) Landscape changes over a region in East Germany and their impact upon the processes of its atmospheric water-cycle. Meteorol Atmos Phys 68(1–2): 79–98
Mölders N (2000) Application of the principle of superposition to detect nonlinearity in the short-term atmospheric responses to concurrent land-use changes associated landscapes. Meteorol Atmos Phys 72: 47–68
Morales HA, Navar J, Dominguez PA (2000) The effect of prescribed burning on surface runoff in a pine forest stand of Chihuahua, Mexico. Forest Ecol Manag 137: 199–207
Murakami S, Tsuboyama Y, Shimizu T, Fujieda M, Noguchi S (2000) Variation of evapotranspiration with stand age and climate in a small Japanese forested catchment. J Hydrol 227: 114–127
Nelson EJ, Miller AW, Dixon E (1999) Chino well fire: A hydrologic evaluation of rainfall and runoff from the Mud Canyon watershed. Inter J Wildland Fire 9(1): 1–8
O'Loughlin EM, Cheney NP, Burns J (1982) The bushranger's experiments: hydrological response of a Eucalyptus catchment. 1st National Symp. on Forest Hydrology. National Conference Publication, Institute of Engineers, Australia, pp 132–138
Post DA, Jakeman AJ, Littlewood IG, Whitehead PG, Jayasuriya MDA (1996) Modelling land-cover-induced variations in hydrologic response: Picaninny Creek, Victoria. Ecol Model 86: 177–182
Roberts S, Vertessy R, Grayson R (2001) Transpiration from Eucalyptus sieberi (L. Johnson) forests of different age. Forest Ecol Manag 143: 153–161
Robichaud PR (2000) Fire effects on infiltration rates after prescribed fire in Northern Mountain forests, USA. J Hydrol 231–232: 220–229
Robichaud PR, Waldrop TA (1994) A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. Water Res Bull 30(1): 27–34
Sahin V, Hall MJ (1996) The effects of afforestation and deforestation on water yields. J Hydrol 178: 293–309
San Jose JJ, Meirelles ML, Bracho B, Nikonova N (2001) A comparative analysis of the flooding and fire effects on the energy exchanges in a wetland community (Morichal) of the Orinoco Llanos. J Hydrol 242: 228–254

Scott DF, van Wyk DB (1990) The effects of wildfire on soil wettability and hydrological behaviors of an afforested catchment. J Hydrol 121: 239–256

Scott DF (1997) The contrasting effects of wildfire and clearfelling on the hydrology of a small catchment. Hydrol Process 11(6): 543–555

Scott DF (2000) Soil wettability in forested catchments in South Africa, as measured by different methods and as affected by vegetation cover and soil characteristics. J Hydrol 231–232: 87–104

Storck P, Bowling L, Wetherbee P, Lettenmaier DP (1998) Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest. Hydrol Process 12(6): 889–904

Speer MS, Leslie LM, Colquhoun JR, Mitchell E (1996) The Sydney Australia wildfires of January 1994 – meteorological conditions and high resolution numerical modeling experiments. Int J Wildland Fire 6(3): 145–154

Speer MS, Leslie LM (2000) A comparison of five flood rain events over the New South Wales north coast and a case study. Int J Climatol 20: 543–563

Townsend SA, Douglas MM (2000) The effect of three fire regimes on stream water quality, water yield and export coefficients in a tropical savanna (Northern Australia). J Hydrol 229: 118–137

Van Lear DH, Douglass JE, Cox SK, Augspurger MK (1985) Sediment and nutrient export in runoff from burned and harvest pine watersheds in the South Carolina Piedmont. J Environ Qual 14: 169–174

Veenhuid JE (2001) Hydrological recovery of two watersheds after a wildfire, Bandelier National Monument. Proceedings of the Rocky Mountain (53rd) and South-Central (35th) Sections, GSA, Joint Annual Meeting, April 29–May 2, 2001. Albuquerque, New Mexico

Watson F, Vertessy R, McMahon T, Rhodes B, Watson I (2001) Improved methods to assess water yield changes from paired-catchment studies: application to the Marinade catchments. Forest Ecol Manag 143: 1 89–204

Yu Z, Lakhtakia MN, Yarnal B, White RA, Miller DA, Frakes B, Barron EJ, Duffy C, Schwartz FW (1999) Simulating the river-basin response to atmospheric forcing by linking a meso-scale meteorological model and hydrological model system. J Hydrol 218: 72–91

Corresponding author's address: Dr. Suxia Liu, School of Mathematics, The University of New South Wales, Sydney 2052, NSW, Australia (E-mail: suxia@maths.unsw.edu.au)