Journal of Hydrology (2006) **331**, 495–510

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Changes in sediment loads and discharge from small mountain catchments following wildfire in south eastern Australia

Patrick N.J. Lane *, Gary J. Sheridan, Philip J. Noske

School of Forest and Ecosystem Science, University of Melbourne, P.O. Box 137, Heidelberg, Melbourne, Vic. 3084, Australia

Received 19 October 2005; received in revised form 18 May 2006; accepted 18 May 2006

KEYWORDS
Bedload;
Suspended load;
Water quality;
Erosion

Summary A severe wildfire burnt over 1 million ha of forested land in southeastern Australia in early 2003. Included in the burnt area were two 136 and 244 ha hydrologic research catchments in the East Kiewa valley that had been decommissioned following a 10 year study, and an adjacent larger (10,050 ha) gauged catchment, the West Kiewa River. The three catchments were re-instrumented to measure discharge and suspended sediment fluxes at 15 min time-steps, with additional measurement of bedload at the East Kiewa sites. Analysis of annual rainfall–discharge relationships and of flow duration curves for the first 2 post-fire water years indicated annual flow increases of around 65–75% for Slippery Rock Creek in both post-fire water years and 40% and 76–94% for Springs Creek in 2003–2004 and 2004–2005, respectively. The flow impacts on the less severely burnt West Kiewa River were far more subdued, and did not exceed pre-fire variability in annual flows. Flow duration curve analysis did not indicate changed runoff generating processes at the daily timescale, with the curves shifting upward uniformly over the flow regime. Total sediment exports increased by factors of 8–9 (up to 2.96 t ha^{-1} yr^{-1}) from the East Kiewa catchments in year 1 after the fire, diminishing to a 2–4-fold increase in year 2. Flow increases accounted for much of the year 2 exports as suspended sediment concentrations decreased toward pre-fire levels. Post-fire suspended load exports from the larger West Kiewa catchment were much lower per unit area, probably reflecting the smaller area of high intensity burn, less intensive burning of riparian areas and possible scale effects. The results were observed under near-average rainfall conditions, with the exception of one short duration high intensity storm that produced almost 50% of the combined sediment loads from the East Kiewa catchments.
© 2006 Elsevier B.V. All rights reserved.

* Corresponding author. Tel.: +61 3 94508719; fax: +61 3 94508644.
E-mail address: patrickl@unimelb.edu.au (P.N.J. Lane).

0022-1694/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2006.05.035

Introduction

Wildfires are a common occurrence in many forested environments. These same landscapes are also the headwaters of streams in many countries. In Australia, forested catchments designated for water supply are often closed to other landuses to maintain high water quality. Threats to water quality and quantity following fire are significant issues for water supply security. Although elevation of sediment and nutrient loads are widely recognised as consequences of intense wildfire, relatively few studies have quantified the changes in sediment or nutrient loads in a systematic and comprehensive way. This is not a criticism as wildfires are not predictable. Studies are generally opportunistic and therefore are often constrained by experimental designs which rarely address all aspects of fire impacts at a particular site. Optimally, either good pre-fire data or well calibrated paired-catchment studies are required. In the latter case, it is less common for high resolution sediment and nutrient data to be collected than streamflow, and the fire must be excluded from a control catchment. These are difficult requirements to meet. Where pre-fire data exist, the length of record and distribution of rainfall are crucial factors in comparing disturbance effects. Shakesby and Doerr (2006) have identified the lack of pre-fire data sediment yield data as a key problem in placing post-fire erosion rates in a longer term context.

Malmer (2004), Scott and Van Wyk (1992), Burgess et al. (1981), Helvey (1980) and Brown (1972) were able to compare pre- and post-fire suspended sediment concentrations and loads when fires burnt experimental (Malmer, Burgess et al., Scott and van Wyk, Helvey) and routine (Brown) monitoring catchments. However, the sediment sampling regimes that Helvey (1980) and Brown (1972) were able to implement were not ideal for accurate load estimation, although valuable data on the magnitude of sediment loads was captured. The former used weir pool deposition and grab samples, while the latter relied mostly on fixed interval samples. Malmer (2004) was able to use only 8–12 grab samples under baseflow conditions over 3 months during the pre-fire period because of drought. Scott (1993) and Chessman (1986) demonstrated significant levels of sediment flux following fires in catchments, but could not give absolute increases because of the lack of pre-fire data. Moody and Martin (2001a) had pre-fire sediment ratings curves for one of two burnt catchments. Burgess et al. (1981) were able to compare only 1 year of data from a logging study. Additionally, few studies are able to partition the bedload and suspended load components. The research by Scott and Van Wyk (1992) and Moody and Martin (2001a) are exceptions. Scott (1993) was able to report post-fire ratios, but not pre-fire. While the foregoing studies have delivered valuable information on fire impacts, unavoidable limitations in experimental design and sampling regimes have limited the accuracy of sediment export estimates. In particular the statistical assumptions associated with common load estimation methods are easily violated by data sets where pre- and post-fire sampling intervals do not match. For example, many streams may have regular weekly or monthly grab sampling for suspended sediment. These may be augmented by automatic storm event sampling following a fire. Comparing such data sets is statistically difficult. Development of sediment rating curves may be problematic where there is pronounced hysteresis (e.g. Olive and Rieger, 1985, Seeger et al., 2004).

Numerous studies into hillslope scale runoff/sediment/nutrient generation have reported enhanced generation rates following wildfire (see review by Wallbrink et al., in press). Such experiments yield excellent data on erosional processes and infiltration characteristics. Peak increases in hillslope sediment generation of one to three orders of magnitude are reported from varying environments and levels of fire severity (Johansen et al., 2001; Benavides-Solorio and MacDonald, 2001; Scott, 1993; Shakesby et al., 1993; Moody and Martin, 2001a; Morris and Moses, 1987). However, Prosser and Williams (1998) and Scott and Van Wyk (1992) observed increased runoff and sediment generation at the hillslope plot scale under natural rainfall, but no increase in catchment exports. Scott (1993) reported delivery ratios of 8%, 8%, 12% and 50% and Moody and Martin (2001a) 33%. These studies clearly demonstrate hillslope generation rates cannot be used to infer catchment fluxes.

Further, changes in runoff generation are frequently captured under rainfall simulation experiments (e.g. Robichaud, 2000; Johansen et al., 2001; Benavides-Solorio and MacDonald, 2001), often linked to soil water repellency. As with the disjunction between hillslope sediment generation and catchment sediment exports, there is not necessarily an easily defined functional relationship between hillslope ruonff generation and catchment discharge.

Catchment flow responses to wildfire are variable; Scott (1993, 1997), Brown (1972) and Mackay and Cornish (1982) reported marked increases in peak flows and stormflows in early post-fire periods. Scott (1993, 1997) found 12% annual yield changes to be relatively minor when compared with the peak flow and stormflow increases, while O'Loughlin et al. (1982) observed changes to baseflows only. Scott (1997) also found the opposite response for a clearfelled catchment where annual yield increases dominated over stormflow changes. Helvey (1980) reported 2–3-fold increases over the flow regime, persisting over 7 years, and Campbell et al. (1977) estimated a 700% increase in total flow. Moody and Martin (2001b) found runoff-rainfall relationships changed for rainfalls above a threshold (>10 mm h^{-1}) but did not report annual changes. Mackay and Cornish (1982) suggested that burn severity and recent logging exacerbated changes in stormflows. The above studies pertain to early post-fire responses. Langford (1976) and Kuczera (1987) demonstrated that long-term water yield responses from *Eucalyptus regnans* forests in the central highlands of Victoria, Australia, were significantly affected by fire over decades. The studies revealed an average 24% decrease in yield over 21 years as stands regenerated, with yields diminishing below pre-fire levels within five years of fire.

During January and February 2003 the largest wildfires since 1939 burned 1.3 million ha of mainly forested land in the state of Victoria, south-eastern Australia. Included in this area were the Upper-Murray, Kiewa, Ovens, Snowy, Tambo and Mitchell river basins, which are important for domestic, irrigation, and environmental water supply. There have been a number of studies into fire effects in Australia (e.g. Brown, 1972; Zierholz et al., 1995; Prosser and Williams, 1998; Leitch et al., 1984; Chessman, 1986; Burgess et al., 1981; Mackay and Cornish, 1982; Cornish and Binns, 1987; Dragovich and Morris, 2002; Shakesby et al., 2003; Blake et al., 2004; English et al., 2005; Wallbrink et al., in press) but precise data on catchment-scale responses of both discharge and water quality have not been well captured. To close this knowledge gap, a catchment experiment was commissioned to measure the response of discharge and sediment fluxes to a wildfire in mountainous terrain. Collection of high resolution data that minimised the uncertainty associated with many water quality studies was central to the project objectives.

Background

A paired-catchment experiment was initiated in 1978 to study the hydrologic impacts of logging in the East Kiewa valley mountain area of north east Victoria, Australia (Fig. 1a and b). The study sites are predominantly vegetated with *Eucalyptus delegatensis* (alpine ash). One catchment, Slippery Rock Creek (136 ha) was retained as the control, and Springs Creek (244 ha) underwent logging of 30% of the area after 4 years of calibration (Fig. 1c). Discharge, suspended sediment loads and to a lesser extent, bedload, were measured for a total of 10 years. Both catchments were subsequently burnt in January 2003, with a moderate-severe fire severity resulting in severe crown scorch for the majority of the catchment areas. A high proportion of the *E. delegatensis* were killed, comprising around 62–70% of the area in both catchments. Ground cover and understorey vegetation was completely burnt in both catchments, with the exception of approximately 1–2 ha in the upper Slippery Rock Creek catchment that escaped the fire or was lightly burnt. An adjacent larger gauged catchment, the West Kiewa River (10,050 ha, Fig. 1b) was burnt at the same time. The fire was less uniformly severe in this catchment, with far more instances of light to moderate crown scorch. Nevertheless, 43% of the catchment was mapped as severity class 1–2 (Table 1) from satellite imagery by

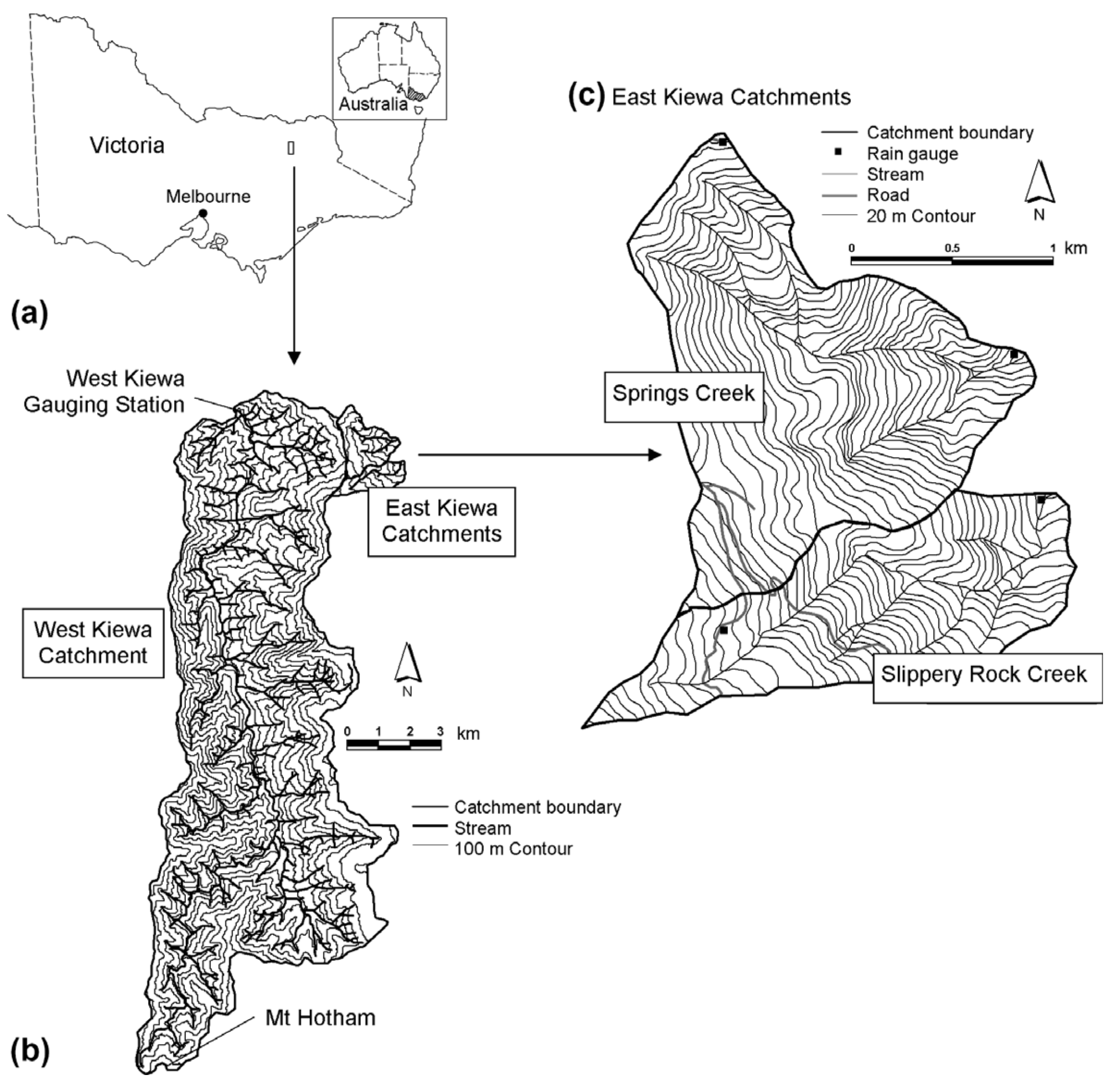

Figure 1 Location maps for East and West Kiewa catchments.

Table 1 Fire severity classes for East and West Kiewa catchments

Class	Description	Springs Creek	Slippery Rock Creek	West Kiewa River
		Catchment		
Very severe	Crown burnt	7	6	7
Severe	Severe crown scorch	88	65	36
Moderate	Moderate crown scorch	4	14	17
Light	Light crown scorch	1	15	38
Unburnt	Unburnt		1	2

Values are proportion of catchment area.

the Victorian Department of Sustainability and Environment. It is the authors' opinion that some of the area mapped as light severity in the West Kiewa catchment are unburnt. In these forest types, severity classes 1 and 2 generally indicate total overstorey, understorey and ground cover loss, while understorey and ground cover often survive or recover quickly under a class 4 severity.

Site description

East Kiewa catchments

The geology of the Slippery Rock Creek and Springs Creek catchments is highly faulted gneiss, quartz diorite, with small areas of granodiorite in the Slippery Rock Creek catchment. The topography is steep with elevations of 620–1380 m in Springs Creek catchment and 660–1520 m in Slippery Rock Creek catchment. Slope gradients >24° occur on 55% of the catchments (Fig. 1c).

Both catchments have friable stony brown gradational soils generally <1.5 m deep comprised of clay-loams and sandy clay-loams grading to coarse sand C horizons. Shallow uniform soils are found on the spurs with deeper black organic to sandy-clay loams in drainage lines. Mean bulk densities are 0.6 g cm^3 at 0.04 m, 1.1 at 0.5 m and 1.4 at 1.5 m. There are no long-term rainfall data from the sites, but the mean annual rainfall for the nearby Bogong village is 1800 mm, with a winter/spring dominant distribution. It is likely the annual rainfall depth for the higher elevation catchments is greater. Intense summer thunderstorms are common in the area. Snow fall can occur at elevations higher than 1100 m, and more intermittently at lower elevations. Mean daily maximum temperature is 17.2 °C and mean daily minimum is 5.4 °C.

At lower elevations (up to approximately 1100 m) vegetation is dominated by mixed eucalyptus, principally Narrow-leafed peppermint (*Eucalyptus radiata*), Candlebark gum (*E. rubida*) and Broad-leafed peppermint (*E. dives*). Above the mixed forest, Alpine Ash (*E. delegatensis* RT Baker) exists in almost pure stands, with some Mountain gum (*E. dalrympleana*) scattered amongst the Ash. Most of the *E. delegatensis* is mature to overmature (>100 years old), excepting the regrowth stands. These stands comprise 70% of the area of Springs Creek catchment, and 62% of the Slippery Rock catchment. Ferns, shrubs and herbs provide a more or less continuous low understorey, particularly in the Alpine Ash zone. Riparian communities have a well developed tall understorey, often with a dense cover of tree ferns in the gullies flanked by a dense fern and low shrub stratum.

West Kiewa River

The West Kiewa River catchment is broadly similar in geology, soils, vegetation and topography to the East Kiewa catchments, although it also includes high elevation snow gum (*E. pauciflora*) and alpine vegetation communities. Fifty five percent of the catchment is mapped as *E. delegatensis* and 28% as *E. pauciflora*. This catchment has on-going logging and roading operations in the mid and lower catchment. As such it does not represent the pristine condition of the untreated East Kiewa catchments in the 1978–1987 study. Fig 1b shows the catchment boundary and the gauging location of the West Kiewa catchment.

Prior research

The two East Kiewa catchments were instrumented to measure discharge and sediment exports in 1978. A series of reports describe in detail the objectives, instrumentation and results (Leitch, 1979, 1981; Papworth et al., 1990; Hartland et al., 1990). Briefly, there was a 3–4 year calibration period followed by a roading and logging treatment in the Springs Creek catchment. Slippery Rock Creek catchment was retained as the control. Observations of discharge and sediment concentration continued until December 1987. The treatment at Springs Creek included roading for access and cartage, and a regeneration burn in 1986. The operation did not adhere to current best practice for protection of water quality. There were no buffers strips around streams, roads were pushed through streams, near stream soil disturbance was considerable, and the hot regeneration burn removed riparian vegetation further reducing sediment trapping efficiency. Ten percent of the Slippery Rock Creek catchment was logged in the early-mid 1990s, with improved water quality protection and no new roading. No data from the post-logging period at Slippery Rock Creek is used in this study.

The study found there were small increases in total streamflow following treatment, and small but statistically significant increases ($p < 0.005$) in mean event flows. There were highly elevated total suspended sediment exports (TSS), with total annual exports estimated to have increased by a factor of 2–4. Analyses of event concentrations found increases of similar magnitude. This research provides excellent baseline data for streamflow and sediment generation under both undisturbed and disturbed conditions. Although the study was carried out 16–25 years prior to the bushfires, it may be assumed that the runoff–rainfall relationships from undisturbed mature *E. delegatensis* and mixed-species stands would be reasonably unchanged.

Methods

Experimental design

Discharge

Discharge at Slippery Rock Creek was measured through a 135° triangular broad-crested weir with a height of 0.83 m and width of 3.65 m. Stage height was recorded by a Mindata pressure transducer, placed in a stilling well. During the former study, discharge at Springs Creek was measured at a 1.52 m diameter culvert, calibrated by a portable H-flume. We installed a Parshall flume attached to the culvert outlet with a 0.457 m wide throat and a maximum discharge capacity of 0.695 $m^3 s^{-1}$. Stage height was also recorded by a Mindata pressure transducer, set in a stilling well welded to the flume wall. Stage height was measured at 15 min intervals, logged by a Mindata 3500 logger. There is an existing gauging station on the West Kiewa River that has been in operation since 1992. Discharge was estimated from stage using an established stage-discharge relationship for this station.

Suspended sediment

Total suspended sediment (TSS) concentration was predicted at 15 min time steps from *in situ* measurement of turbidity using regression relationships developed between TSS and turbidity from water sampling. This methodology has the attraction of yielding continuous data which solves the practical problem of sample collection from remote areas and the statistical problem of adequate representation of samples over the flow hydrograph and bias in sampling regime. The procedure was as follows: (1) an *in situ* Mindata model 2600 backscatter turbidity probe with a range of 0—1000 NTU gave 15 min readings. (2) The calibration of the *in situ* probe was maintained by taking water samples at the same time and position in the stream as the *in situ* probe and then measuring the turbidity of the samples in the laboratory using a Hach 2100N Turbidimeter immediately on receipt of sample from field. A relationship could then be developed between the pairs of matching *in situ* probe and laboratory determined turbidities. The *in situ* probe data were then corrected via the resulting calibration equation. (3) The samples used for the turbidity correction were then filtered for TSS and regressed against the laboratory turbidity reading. (4) The resultant TSS concentration—turbidity relationship yields 15 min estimations of TSS concentration. Stability of the *in situ* probe readings were maintained through constant checking of calibrations, including stratification by data range (e.g. <100 or >100 NTU) to preserve accuracy over the range of data, and analysis of individual storms. Twelve separate calibrations were used in total for the two East Kiewa sites, with $r^2 > 0.90$ for 10 calibrations, and a range of 0.96—0.99 for all NTU values >100. Of the $r^2 < 0.90$ (0.77, 0.86) the former was for NTU <50 for 2 months in 2004 at Slippery Rock Creek, and the latter for NTU < 50 for 2.5 months in late 2003.

The turbidity probes have a lens protection devise (LPD) which covers the probe lens, preventing fouling from algal build-up. A flap opens when a measurement is taken. Off-line stilling tanks have been constructed to remove turbulence which can affect readings. The probes are mounted vertically from the top of the 20 l tanks with inflow and outflow is controlled to approximately 100 ml s^{-1} by a ball-valve. Inflow passes through a stainless steel filter of 1 mm diameter perforations prior to the tank inlet.

Sigma autosamplers are programmed collect multiple 1 l samples during storm events on a ''change in stage'' basis, triggered on both the rising and falling limb of the hydrograph. As the range of the turbidity probes is 0—1000 NTU, and this value was periodically exceeded during storm events, the autosamplers provide data that cannot be reliably collected by the probes. The setting of the range to 0—1000 NTU also results in poorer resolution at the lower turbidities. A Mindata turbidity probe and Sigma autosampler were also sited on the West Kiewa, giving a complimentary data set.

TSS concentration was also measured by autosampler during the previous phase of the study, set to take samples on an hourly basis following a change in stage., and supplemented by manual sampling during storms. Baseflow concentrations were obtained by twice weekly or greater manual sampling.

Bedload

Bedload was estimated in two ways. At Slippery Rock Creek, the 153 m^3 weir pool acts as a sediment pond, so bedload can be estimated by survey of the mass of sediment deposited. This is achieved by mapping the depth of the sediment deposit on a 1 m grid prior to de-silting. Samples were taken for sieving to ascertain the proportion of deposit that is bedload, and to calculate bulk density. Bedload was defined as particle size >1.0 mm diameter as this is the cut-off diameter for the off-take to the turbidity tank.

Additionally, bedload traps have been constructed at both sites to measure a continuous sub-sample of bedload. These consist of 1.0 m wide concreted flow-control structures with five 5 mm wide by 100 mm long slots in the direction of flow cut into a 1.0 m length of square rolled hollow section steel which is concreted level with the stream bed and perpendicular to the flow. Sampled water and sediment is delivered by gravity to a continuously overflowing 200 L settling tank via a 50 mm hose. The mass of sediment in the tank is measured on a fortnightly basis, and sieved to <1 mm to account for any trapped suspended sediment. Some problems were encountered with slot blockage and there are caveats regarding the trapping efficiency of all particle sizes at high flows. However, at a minimum the traps provide a relative measure of the bedload contribution between the catchments.

Precipitation

Tipping-bucket rain gauges have been installed at both East Kiewa gauging sites, and on the upper slopes at both catchments. These are paired with manual gauges. The precipitation for the West Kiewa River was obtained from a climate database maintained by the Queensland Department of Natural Resources and Mines, which produces interpolated climate data on a 0.05° grid.

Vegetation change

Vegetation surveys were undertaken in February 2003, January 2004 and February 2005. Nine 100 m transects were randomly sited from a central soil sampling point situated on a ridge crest. The presence/absence of cover was assessed at single points every 5 m along the transect using a 30 cm steel square. Cover was expressed as present/absent (any cover), and as cover type — litter, grass, or low shrub <50 cm high and bracken or shrub >50 cm but <2 m high. Data are expressed as a % ratio of ''cover present'' to total number of assessment points along the transect. A survey of riparian vegetation was undertaken in October 2004 in which the main stream in both catchments was surveyed at 10 m intervals using the same point classification scheme.

Water repellency

Nine soil sampling positions were selected to give a representative spread over the catchments. A central sampling point in each position was sited on a ridge. Four other points were then selected to give a ridge-midslope-valley transect, with the aim of incorporating variation in topography and aspect. At each sampling location samples were taken at 0–5 cm depth at 5 points 1 m apart. Six samples were also taken at 3 locations in the <1 ha unburnt area in Slippery Rock Creek. The water drop penetration time (WDPT) method was used to measure water repellency (King, 1981), and categorised as follows: non-repellent (N) where water is absorbed into the soil in 10 s or less; repellent (R) where water absorption is >10 s and 2-molar ethanol absorption is 10 s or less; or strongly repellent (S) where 2-molar ethanol absorption is >10 s (McDonald et al., 1990). The samples were taken two months after the fire, before any significant rainfall events.

Data analysis

The core field database consists of the 15 min observations of discharge, turbidity and rainfall. In addition, there are weekly or fortnightly measurements of bedload from the traps at both East Kiewa sites and intermittent bedload estimations from Slippery Rock Creek weir pond. There have been short periods of equipment failure. Autosampler data were used to infill event turbidities where values exceeded the range of the probes. Where there were gaps in the discharge record, regression equations with the other catchment could be used confidently. There is a high degree of correlation ($r^2 = 0.95$) between the catchment discharges on the 15 min timestep.

Precipitation

Precipitation from the upper and lower rain gauges is averaged within each catchment. Alternative methods for spatially distributing precipitation (e.g. Thiessen Polygons) were considered. However, as there is a clear orographic signature to the precipitation, areal interpolation methods would produce unwarranted errors. The bulk of precipitation is rainfall, with a small contribution from snow on the upper third of the catchments. Difficulties in accessing the upper sites during winter has meant the precipitation record is incomplete for those sites. Regressions of daily precipitation between gauges produced high correlations ($r^2 > 0.9$). We have assumed the ratio of precipitation between the gauges holds throughout the year. Consequently the rainfall measured at the stream gauging stations can be used to account for transient snowfalls. The low density of the snow strongly indicates there is no rain-on-snow runoff generation processes. The rainfall record for the pre-fire period is scaled by the post-fire method as no upper catchment observations were made.

Flow

Annual data is collated on a water-year basis, from May to April. Pre- and post-fire flows have been analysed in two ways: on an annual basis as a function of annual rainfall for both total flow and baseflow; and by analysis of flow duration curves (FDCs). The impact on the intra-annual variability in flow distribution (FDC) is a insightful measure of flow responses to catchment disturbance.

A baseflow separation was performed using Lyne and Hollick's (1979) algorithm (see Nathan and McMahon, 1990) with an α value of 0.90 for the East Kiewa catchments, and 0.925 for the West Kiewa River.

FDCs were computed from the distribution of daily flows for each water year of record. The problem in interpreting the FDCs is the establishment of a baseline FDC to quantify the fire impact. This is a similar problem to accounting for rainfall variability in assessing effects of vegetation change over time (Lane et al., 2005). A similar, simplified approach to the method of Lane et al. (2005), was employed in which:

(i) FDCs were constructed for each year of record.
(i) A series of regression models were fitted to the observed annual time series of pre-fire FDC percentiles with annual rainfall as the independent variable; i.e. 10th flow percentile for each year of record against annual mean daily rainfall for each matching year, 20th flow percentile for each year of record against annual mean daily rainfall for that year etc. The percentiles used to develop the models were 1st, 10th, 20th,...,90th, 99th, giving 11 models. This gives a pre-fire calibration model of flow as a function of mean daily rainfall for each percentile.
(iii) If there was a satisfactory model fit over the range of percentiles, the observed rainfall for post-fire years can be used to solve the equations derived from the pre-fire data, yielding a predicted FDC. We deemed a coefficient of determination >0.7 to be satisfactory.
(iv) A predicted ''non-burnt'' FDC for 2003/2004 and 2004/2005 is then developed by re-combining the adjusted percentiles.

The model is:

$$Q_{\%} = a + bP^2 + P \tag{1}$$

where $Q\%$ is the flow percentile and P is mean daily rainfall for each year.

The calculation of a predicted FDC for 2003/2004 and 2004/2005 allows us to compare observed post-fire flow percentiles with those predicted from the 2003/2004 and 2004/2005 rainfall. Differences between observed and predicted flow percentiles can be summed to give a total change in discharge. The latter two years of the pre-fire period could not be included in this analysis as the complete daily record is unobtainable.

Sediment loads and concentrations

Catchment suspended sediment exports are calculated as:

$$L = \sum_{i=1}^{i=T/t} \exp[\ln(C_i) + \ln(Q_i)] \quad (2)$$

where L is the TSS load, C_i is the TSS concentration and Q_i is discharge volume for the ith interval. T is the time period over which L is summed, and t is the interval between measurement or estimation of C_i and Q_i. For the pre-fire period t is determined from the frequency of the collection of water samples; hourly during storm events and twice weekly or greater during baseflow. Discharge volumes (Q) were integrated totals from chart recorder records. For the post-fire period, t = 15 min. Post-fire TSS concentration, C, is obtained from a regression relationship between the natural log of TSS and natural log of turbidity (NTU):

$$\ln(C) = a + b\ln(\mathrm{NTU}) \quad (3)$$

The data were log transformed to minimise the variance over the data range. There were storm events in which the turbidity exceeded the probe range. Autosampled concentration could be used to calculate loads by (2) with t dependent on the sample timing. When storm length exceeded the sampler capacity on one occasion, data were interpolated via a regression of TSS on discharge for other storm events.

Uncertainties in loads were estimated at each 15 min timestep from:

$$\mathrm{Var}[\ln(L)] = \mathrm{Var}[\ln(C)] + \mathrm{Var}[\ln(Q)] + 2\mathrm{Cov}[\ln(C)\ln(Q)] \quad (4)$$

$$\text{where } \mathrm{Cov}[\ln(C), \ln(Q)] = \rho\sqrt{\mathrm{Var}[\ln(C)]\mathrm{Var}[\ln(Q)]} \quad (5)$$

where ρ is the correlation between the natural logarithm of the instantaneous turbidity (NTU) measurements and the natural logarithm of the depth measurements.

The variance Var[ln(C)] in the estimated values of ln(C) was determined from the prediction intervals around the regression given in (3). The variance Var[ln(Q)] in the estimated values of ln(Q) was determined from prediction intervals in the log–log relationship between stage and discharge for the West Kiewa River. From the East Kiewa catchments Q was measured directly from gauging structures, and the variance Var[ln(L)] in the estimated values of ln(L) is equal to the variance in ln(C) as the last two terms in (4) are zero.

Variances in log–log space for each 15 min timestep were back transformed to the original scale using:

$$\mathrm{Var}(L) = \mathrm{Var}[\ln(L)]L^2$$

The variance for each 15 min timestep were then summed for the water year to give the variance on the annual load, Var(L). The uncertainty in annual loads is expressed as the standard deviation.

An analysis of storm event data for pre and post-fire was carried out, based on data presented in Papworth et al. (1990) in which, mean daily sediment concentrations were tabulated for days where there was an increase in mean daily of discharge >7 l/s. This value was considered to define a storm event. Consequently, we extracted the mean concentration for days in which the mean daily discharge exceeded that of the previous day by >7 l/s. These data allow a direct comparison with the previous data set. The concentrations probably encapsulate the peak concentrations, the upper part of the rising limb of the hydrograph and the early part of the hydrograph recession.

The event data were non-normally distributed. Consequently differences in the means of pre- and post-fire populations were tested by the Mann–Whitney U test for large samples. Additionally, the comparative impact of the logging treatment at Springs Creek could be tested.

Results

Precipitation

There was significantly higher precipitation at Slippery Rock Creek than at Springs Creek The annual average difference for pre-fire years was 8%, with a 14% difference in 2004–2005. Anecdotal evidence from forestry workers familiar with the area supports the data, with apparent small scale orographic effects bringing consistently higher rainfall to the upper slopes of Slippery Rock Creek. The post-fire annual totals of 1825 mm and 1993 mm at Slippery Rock Creek in 2003–2004 and 2004–2005, respectively compare with a pre-fire mean of 1978 mm. At Springs Creek the post-fire totals of 1658 mm and 1681 mm were below the pre-fire mean of 1849. The interpolated rainfall for the West Kiewa River was 1581 mm in 2003–2004 and 1603 in 2004–2005, also below the pre-fire mean of 1748. Maximum daily rainfall post-fire was 98 mm at Slippery Rock Creek. This value was exceeded in four pre-fire measurement years. There were no high intensity storms immediately following the fires, which is often the cause of large magnitude erosion events. The first 10 weeks post-fire saw less than 50 mm of rainfall from 4 events with a peak intensity of 5 mm h^{-1}. The long-term intensity–duration curves given by the Australian Bureau of Meteorology (BOM) for the area are plotted in Fig. 2, along with the 5 year maximum intensity curve for 1978–1982 (the only complete pre-fire sub-daily

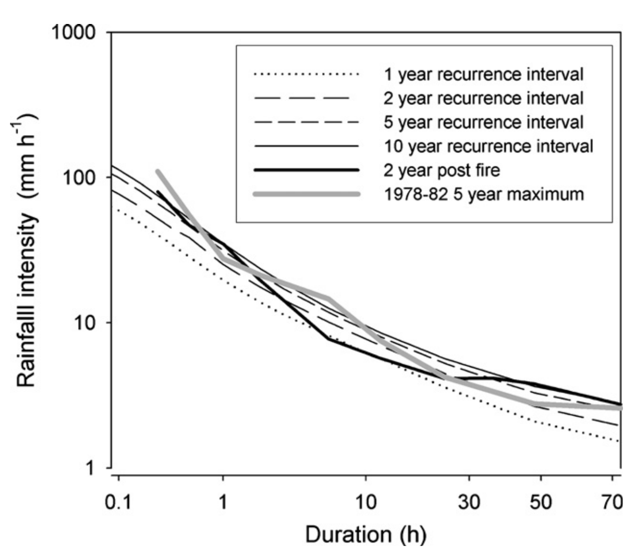

Figure 2 Intensity–duration curves for East Kiewa catchments.

data set) and the post-fire curve for Slippery Rock Creek. It is likely that the long-term curves are under estimated for these small catchments as the frequent, but highly spatially variable, summer convective storms may not have been captured by the BOM analysis. The post-fire curve shows the impact of a >2 h 43 mm storm in January 2004 with a peak 15 min intensity of 80 mm h^{-1}, and a 1 h intensity of 35 mm h^{-1}, and a 3 day event of 243 mm in July 2003.

Vegetation survey

The January 2004 survey in the East Kiewa catchments returned an average 56% ground cover of litter and grass, with 42% coverage of low shrubs and bracken. It is not known precisely what the percentage of cover was before the fire, but it would have approached 100% in some lower slope areas, and perhaps 70–80% higher in the catchments. There was zero ground cover immediately following the fire over all but the 10% of the upper slopes of Slippery Rock Creek, with a subsequent litter fall as dead leaves dropped. There was negligible regrowth until spring 2003, with the bulk of regrowth occurring from October 2003 onwards. The percentages for both ground and shrub cover had increased to 75% by February 2005. The riparian survey in October 2004 found 80% ground coverage. Recovery of canopy in the mixed species eucalyptus has been largely confined to epicormic shoots. There has been the expected seedling germination beneath the dead *E. delegatensis*.

Water repellence

The fire does not appear to have increased water repellency at 0–5 cm depth (Fig. 3). All samples from the unburnt sites were repellent or strongly repellent, while 13% of the burnt samples were non-repellent. These data suggest there was no increase in near surface water repellency as a result of the fire.

Flow

The annual flow–rainfall relationships are given in Fig. 4. The correlations are acceptable given the variability in the intra-annual distribution of rainfall which influences hydrologic processes. The annual total discharges reflect in part the precipitation differences between the catchments. Springs Creek annual flow depth is consistently lower than Slippery Rock Creek. The average difference over the pre-fire years is 26%.

Residual values from the regressions (Fig. 4) at Slippery Rock Creek for 2003/2004 and 2004/2005 are 477 and 606 mm, respectively. These values represent flow increases of 66% and 73%. At Springs Creek, the residual for 2003/2004 is 190 mm (38%) and 388 mm (76%) in 2004/2005. The estimated increase from the West Kiewa in 2003–2004 is 237 mm, (23% change) and 118 mm (11%) in 2004–2005. However, the scatter around the regression line suggests the post-fire yields may not exceed the noise

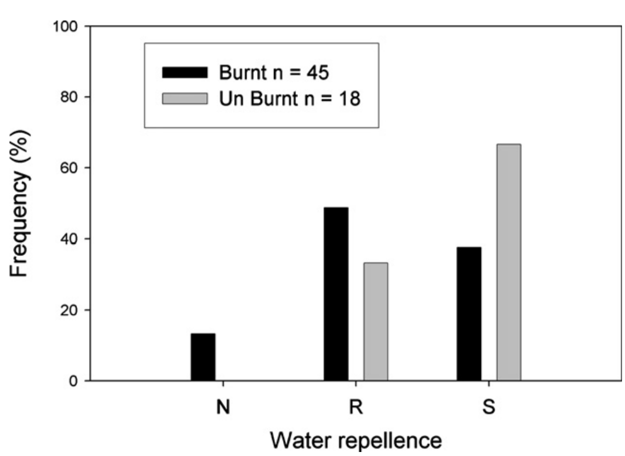

Figure 3 Frequency distribution of burnt vs. unburnt water repellency. N denotes non-water repellent, R denotes water repellent, and S denotes strongly water repellent.

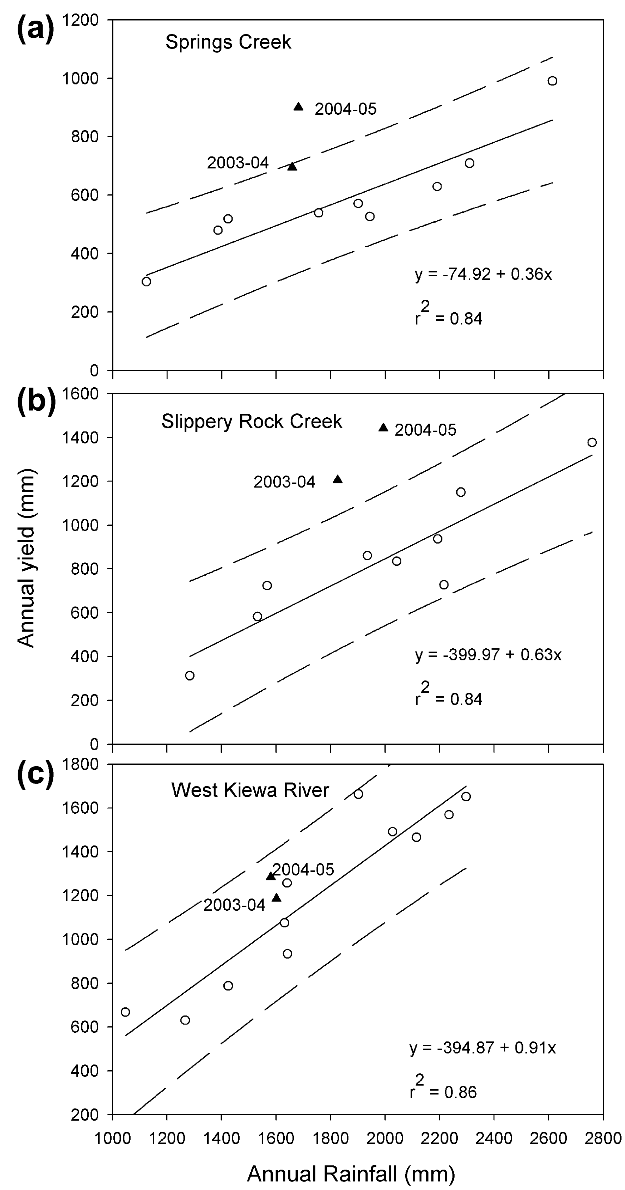

Figure 4 Annual rainfall vs. catchment yield for pre- and post-fire years for: (a) Springs Creek, (b) Slippery Rock Creek and (c) West Kiewa River. Dashed lines are 95% prediction limits, triangles denote post-fire data.

in the data, with the post-fire points falling outside the 95% prediction limits. The flow—rainfall relationship is clouded by the paucity of raingauges in this catchment and some snowmelt from peaks, which may not accounted for in the rainfall record, and by a variable landuse which includes logging. The baseflow index (BFI), the ratio of baseflow to total flow, was 0.77 and 0.78 at Slippery Rock Creek for 2003—2004 and 2004—2005, respectively, compared with a pre-fire mean of 0.79. The BFI values for Springs Creek were 0.81, 0.80 (pre-fire mean = 0.83), and 0.67, 0.63 and a pre-fire mean of 0.65 for the West Kiewa River.

The FDCs are presented in Fig. 5, with the results of the model fitting to Eq. (1) given in Table 2. The plotting points are the 1st and 99th percentiles and every 10th percentile (decile). The time series of the deciles were well correlated with annual mean daily rainfall for each year, Coefficients of determination 0.7 or better were returned for all but 3 time series and all but 5 regressions returning $p < 0.05$. The poorest model fits were for the 1st percentile at all three catchments. This is not surprising as the peak flows are more likely to be correlated with individual events rather an annual total. The consequent predicted FDCs for a unburnt scenario can be compared

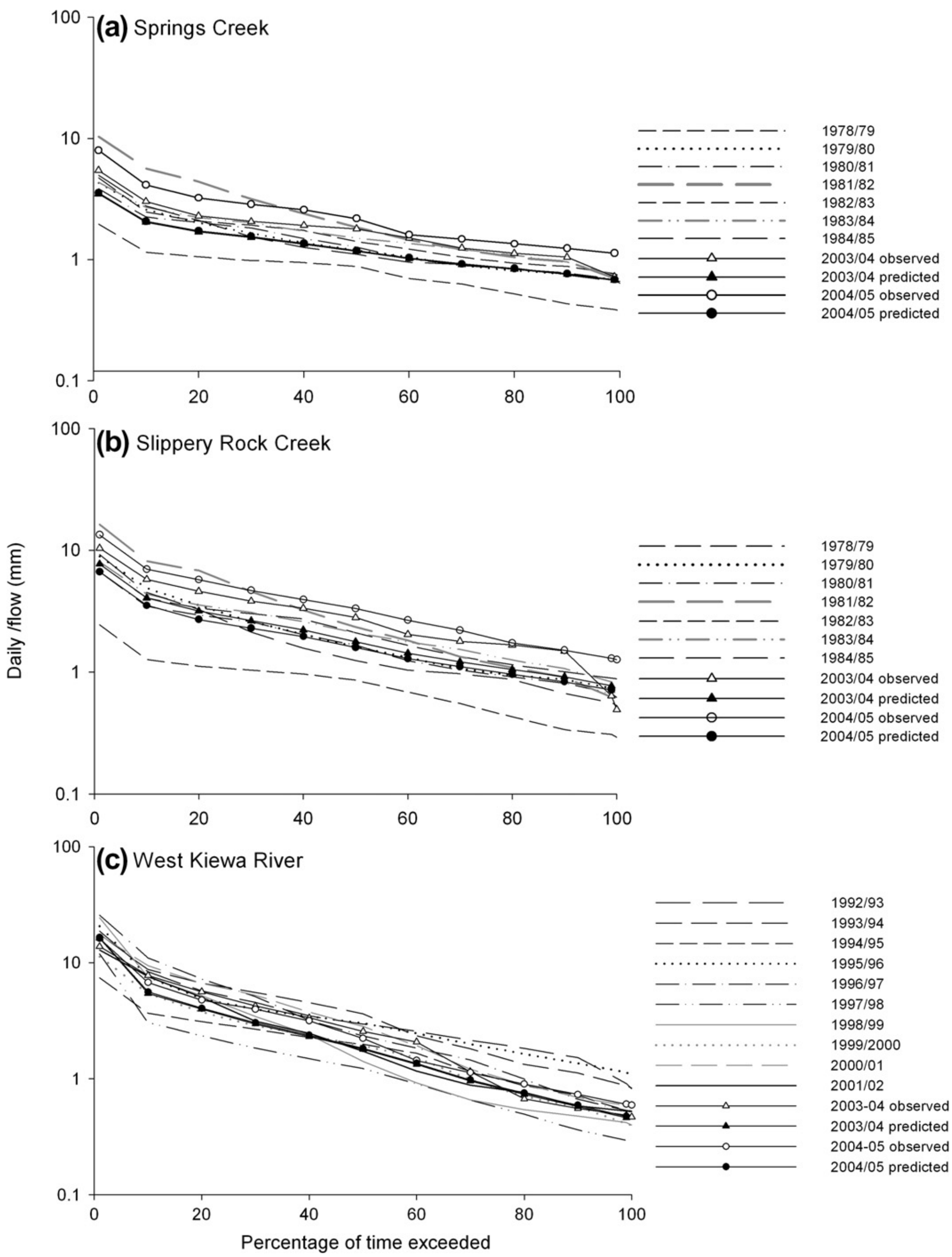

Figure 5 Flow duration curves for pre- and post-fire years for (a) Springs Creek, (b) Slippery Rock Creek and (c) West Kiewa River.

Table 2 Goodness of fit for flow duration curve prediction models

Percentile	Springs Creek		Slippery Rock Creek		West Kiewa River	
	R^2	*P* value	R^2	*P* value	R^2	*P* value
1%	0.77	0.0537	0.68	0.1000	0.40	0.1691
10%	0.80	0.0410	0.70	0.0894	0.78	0.0052
20%	0.85	0.0222	0.81	0.0350	0.75	0.0083
30%	0.94	0.0035	0.92	0.0061	0.81	0.0028
40%	0.94	0.0033	0.86	0.0191	0.91	0.0003
50%	0.96	0.0013	0.87	0.0164	0.90	0.0004
60%	0.90	0.0101	0.81	0.0354	0.79	0.0043
70%	0.84	0.0272	0.75	0.0640	0.78	0.0047
80%	0.81	0.0354	0.80	0.0404	0.73	0.0098
90%	0.89	0.0128	0.88	0.0134	0.73	0.0108
99%	0.88	0.0141	0.86	0.0200	0.71	0.0132

with those observed for all years of record. The summed increases in flow for the post-fire years are 68% and 76% for Slippery rock Creek for 2003/2004 and 2004/2005, respectively and 43% and 94% for Springs Creek. The summed increases from the West Kiewa River are 31% and 12% for 2003/2004 and 2004/2005, respectively. For both Slippery Rock Creek and the West Kiewa River the flow increases estimated by the FDCs accord reasonably with those from the annual data.

The observed curves for 2003/2004 and 2004/2005 plot above the predicted curves, and above all other curves with the exception of the 1981/1982 curve at both East Kiewa sites. The Slippery Rock Creek FDC suggests that the median and lower flows are elevated relative to all other years despite the below average rainfall. The higher percentiles are exceeded only by the 1981/1982 curve. That year received almost 1000 mm more rain than 2003/2004 and over 800 mm more than 2004/2005. The shape of the curves do not indicate there were significant changes to the runoff generating processes through changes in the flow regime at a daily scale. The FDCs from Springs Creek and from the West Kiewa River support this. The sharp drop off at the 90th and 99th percentiles in 2003/2004 is a function of the very low flows recorded in early April that were typical of the pre-fire and immediate post-fire dry conditions. The observed curves from the West Kiewa River demonstrate the subdued fire impact relative to the preceding 10 years. The 2003–2004 and 2004–2005 curves are exceeded by at least three other years at all deciles. The highest percentiles (1st and 10th) plot under the predicted values. This may be simply due to the poor model fit for the 1st percentile, although the fit for the 10th percentile ($r^2 = 0.68$) is better.

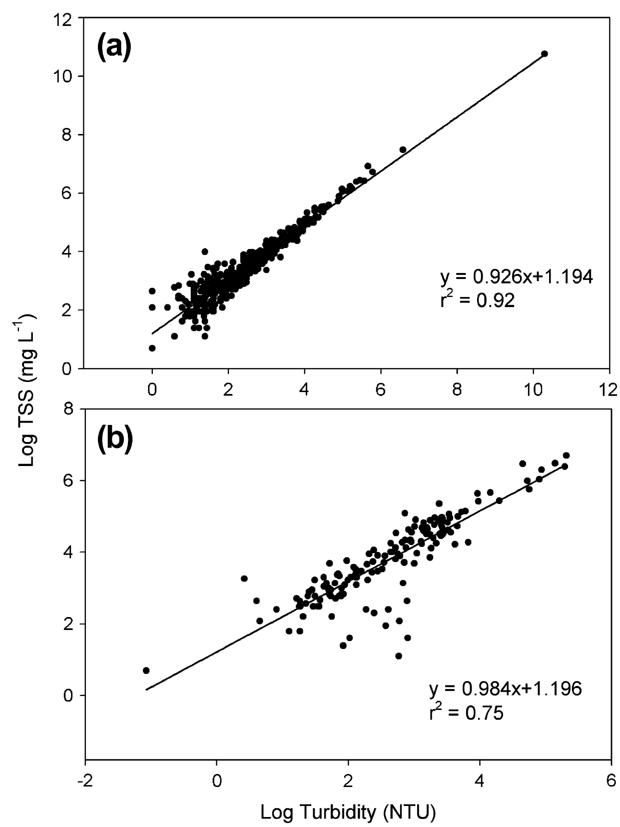

Figure 6 Laboratory derived turbidity vs. TSS relationship for (a) the East Kiewa and (b) West Kiewa catchments.

Total suspended sediment concentrations

TSS concentrations vs. turbidity

The log–log relationship between laboratory measured turbidity and TSS concentration is given in Fig. 6, with data bulked for the two East Kiewa catchments, and for the West Kiewa River. Untransformed coefficients of determination were 0.98 and 0.92 for the East and West Kiewa catchments, respectively.

TSS concentrations

Descriptive statistics and the results of the Mann–Whitney *U* Test for pre- and post-fire mean daily event concentrations are presented in Table 3, split into a bulked pre-fire population and for the two separate post-fire water years. The 2003–2004 data also contains one storm event from mid April 2003, which was the first major post fire event. The Mann–Whitney *U* Test returned significant differences between the pre-fire and post-fire concentrations for both 2003–2004 and 2004–2005 at Springs Creek, but only 2003–2004 at Slippery Rock Creek. The 2003–2004 concen-

Table 3 Mean daily TSS concentrations for flow events defined by >7 l s^{-1} change in mean daily flow pre- and post-fire

Site	*N*	Mean	Median	Minimum	Maximum	Lower quartile	Upper quartile	10th (%)	90th (%)	SD
						(mg L^{-1})				
Slippery Rock pre-fire	201	51.4	35.4	6.6	250.3	23.2	56.9	17.3	111.6	45.1
Slippery Rock 2003/2004	35	174.1	50.5	14.8	1744.6	30.0	81.2	18.4	329.8	373.4
Slippery Rock 2004/2005	35	45.7	37.9	14.7	237.2	26.1	53.4	23.9	61.4	36.7
Springs Creek pre-treat[a]	91	63.5	38.0	7.0	529.5	22.1	65.8	18.0	134.0	78.7
Springs Creek pre-fire	210	105.9	59.1	7.0	946.3	29.1	120.3	20.9	197.7	145.1
Springs Creek 2003/2004	31	154.9	47.3	5.8	1281.1	24.8	111.6	21.6	203.2	311.9
Springs Creek 2004/2005	29	57.8	53.8	26.1	220.3	42.5	60.1	32.9	69.8	34.7

Mann-Whitney *U* test	N T1	N T2	Rank Sum T1	Rank Sum T2	*U* Test	*Z* Test	*Z* crit $\alpha/2$	Statistically significant
SRC pre-fire vs. SRC 2003/2004	201	35	23,005	4961	2704	−2.18	−0.98	[c]
SRC pre-fire vs. SRC 2004/2005	201	35	23,635	4331	3334	−0.49	−0.98	
SCC pre-fire vs. SCC 2003/2004	210	31	25,589	3572	3076	0.49	0.98	
SCC pre-treat.[b] vs. SCC 2003/2004	91	31	5351	2152	1165	−1.44	−0.98	[c]
SCC pre-treat.[b] vs. SCC 2004/2005	91	30	5206	2175	1020	−2.07	−0.98	[c]

[a] Treatment refers to the logging treatment initiated in 1981.
[b] Treatment is the logging treatment initiated in 1981. T1 and T2 denote pre-fire and post-fire, respectively.
[c] Denotes statistically significant at the 0.05 level.

trations are clearly highly elevated relative to the pre-fire data, with the population mean increasing by factors of 3–4. The median and upper quartiles increased by around 50%. The 90th percentile quadrupled at Slippery Rock Creek and doubled at Springs Creek. The concentrations have decreased to pre-fire levels in 2004–2005 at Slippery Rock Creek. The Springs Creek 2004–2005 mean is identical (given measurement errors) with that of the pre- logging treatment but the median and upper and lower quartiles were still elevated. There was a decrease in the 90th percentile to below the pre-fire value. Interestingly, there was no statistically significant difference between the sediment concentrations following logging and those following fire at Springs Creek. The maximum instantaneous concentration measured in the post-fire period of 47,152 mg L^{-1} at Springs Creek exceeded any in the pre-fire data by a factor of 10. This was measured during the event on 16/1/2004.

The pre-fire baseflow concentrations have proven difficult to obtain. Post-fire values are in the order of 10–20 mg L^{-1} at all three sites. The resolution of the turbidity probes at these low concentrations means exact TSS concentrations for the 15 min data are subject to measurement errors.

Sediment loads

Total suspended sediment load

The total suspended sediment loads for water years are plotted against rainfall for both East Kiewa catchments in Fig. 7. The load for 2003/2004 was 280 t (±30) at Slippery Rock Creek and 216 t (±23) at Springs Creek. For a similar annual rainfall, these values indicate perhaps a 9 times increase at Slippery Rock and an 8 times increase at Springs Creek. The 2004–2005 loads have decreased to 56 t (±0.4)

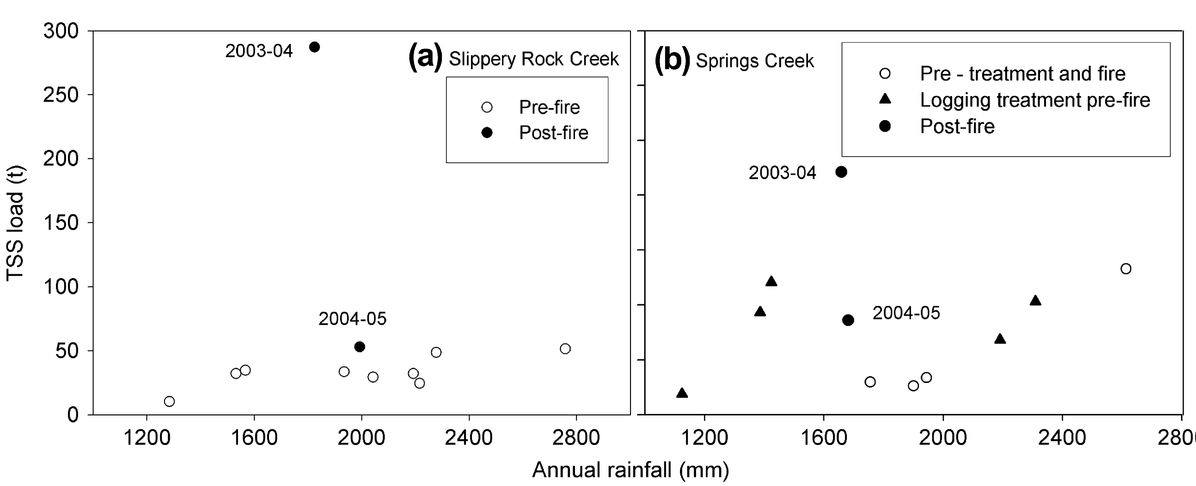

Figure 7 Annual loads of TSS vs. annual rainfall for (a) Slippery Rock Creek and (b) Springs Creek.

Table 4 Spatially averaged (t ha y^{-1}) pre- and post-fire sediment loads for the East and West Kiewa catchments

Site	Slippery Rock Ck.	Springs Ck.	West Kiewa R.
Pre-fire mean TSSL	0.23	0.23[a]	NA
2003–2004 TSSL	2.05	0.88	0.29
2004–2005 TSSL	0.39	0.35	NA
2003–2004 TSSL + BL	2.96		
2004–2005 TSSL + BL	0.68		

TSSL = total suspended solids load, BL = bedload.
[a] The pre-logging treatment mean is skewed by a value of 0.55 t ha y^{-1} in 1981, which is 10 times greater than the preceding 3 years.

at Slippery Rock Creek and 84 t (±0.4) at Springs Creek. These loads appear to be still 1.5–3 times those for a similar pre-disturbance annual rainfall. However, in concert with the concentration data, the logging treatment loads from Springs Creek are clearly also elevated compared with the undisturbed state. Spatially averaged values (t ha y^{-1}) are given in Table 4. The estimated load from the West Kiewa River in 2003–2004 was 2890 t (±60). The 2004–2005 data was not of sufficient quality to compute loads. Autosampler data suggests concentrations had diminished after January 2004 in this catchment.

The fluxes of TSS in the East Kiewa catchments are dominated by two events, July 23 and 24 2003 and January 16 2004. These events produced 79% and 76% of the total 2003–2004 TSS load at Slippery Rock Creek and Springs Creek, respectively. The January 2004 event alone yielded 127 t at Slippery Rock Creek and 101 t at Springs Creek, despite the recovery of 50% of vegetation cover.

Bedload

There are only two measurements of total bedload from the pre-fire data, estimated from the mass of sediment trapped in the weir pool at Slippery Rock Creek in May 1981 and March 1982. The total estimated bedload was 19.2 t and 1.5 t. It is not clear over what time period the 1981 mass of sediment had collected. Anecdotal evidence from workers who have de-silted the weir regularly since its construction suggest the mass of background trapped sediment to be in the order of 20–40 m^3 annually. Thirty-nine percent of the sieved samples from the post-fire deposits was >1.0 mm diameter. Assuming a similar pre-fire size distribution, the bedload would be 10–20 t, although analysis of samples from the sediment deposited before any post-fire influx showed there to be only 17% coarse fraction. Spatially, these estimates equate reasonably to the volume per unit area of sediment (20–50 m^3 km^2 y^{-1}) trapped by a dam located immediately downstream of the confluence of Slippery Rock Creek and the East Kiewa River (Hartland et al., 1990). The 2003–2004 bedload estimate is 116 t. Perhaps two thirds of this sediment was deposited during the two events referred to in the previous section. In both cases the weir pool was largely filled. In 2004–2005 the total load is estimated to be 40 t. The ratio of bedload to suspended load at Slippery Rock Creek was 0.4 in 2003–2004 and 0.75 in 2004–2005.

The likely increase in bedload from pre-fire levels is approximately one order of magnitude in 2003–2004. The mass of bedload sampled by the bedload traps at each catchment was slightly higher at Slippery Rock Creek, by 15% in 2003–2004 and 4% in 2004–2005, suggesting the bedload exports are of similar magnitude at both Springs Creek and Slippery Rock Creek.

Discussion

Overview

The results give a catchment scale response to a severe wildfire for the first two years after disturbance. We have attempted to minimise the uncertainties associated with many post-fire sediment sampling regimes. The 10 year pre-fire data set allows comparison with exports generated over a wide range of climatic conditions and with the impacts of a logging treatment. With the exception of two storms with very different intensity-durations, the post-fire rainfalls were average or below. However, the short duration high-intensity January 2004 storm and the long duration-low intensity July 2003 storm produced around 75% of the suspended load and bedload from the East Kiewa catchments. It is clear from this study and many others that the key driver of post-fire sediment production is the rainfall intensity-duration. In contrast, the January 2004 storm produced only a median daily flow.

Measurement

Successful estimation of TSS is highly dependent on two factors; an accurate turbidity reading from the probe, and a strong relationship between turbidity and TSS concentration. It has proved a challenge to maintain a high quality continuous turbidity record in these environments subject to highly flashy discharge and sediment events, turbulent flow, and interference from hillslope debris including logs, branches, and cobble and boulder size bedload. A high quality continuous turbidity record was achieved in this study through construction of off-take tanks to reduce turbulence effects, careful attention to anomalies in the data set, and crucially, a rigorous continual checking of *in situ* probe calibration. The autosampler data has provided both a check of the turbidity record and a back up data set for use where turbidity observations were interrupted, imprecise or out of range. Statistical error on load estimations has not been reported for fire effects previously. In general, there are few attempts to deal with this issue in the literature. For example, the errors associated with interpolating between autosampled points of varying frequency over a storm, or extrapolating for unsampled storms are substantial. The higher standard deviations on the 2003–2004 East Kiewa data are a product of the variance increasing for the high event values where there are fewer data in the turbidity-TSS regression.

Flow impacts

The estimated annual flow increases at Slippery Rock Creek in both post-fire years are at the high end of the range that would be expected from disturbance impacts in wet eucalypt forests (e.g. Cornish and Vertessy, 2001, Vertessy et al., 2001, Watson et al., 1999, 2001). The Springs Creek response in 2004–2005 is of a similar magnitude to the literature values for the annual rainfall. The 237 mm deviation from the West Kiewa regression line (Fig. 4) is consistent with an expected response scaled for the area of high fire severity. However, the FDCs indicate the post-fire curves do not stand out from the envelope of pre-fire curves.

The FDCs do not indicate there has been a pronounced change in storm or peak flow relative to total flow, contrary to several other studies (see review by Shakesby and Doerr, 2006). Rather, the whole FDC has shifted upward uniformly, similar to the results of Helvey (1980). A significant change in runoff generating processes should also be reflected in a lower baseflow index, which has not been observed. The FDCs imply that the reduced transpiration is driving flow increases, rather than changes to soil hydraulic properties through fire-related development of water repellency. This is further supported by the water repellency data. The development of natural seasonal water repellency in eucalypt forest soils as observed in this study has been observed by Crockford et al. (1991), Burch et al. (1989), Gilmour (1968) and Leitch et al. (1984) in Australia, and world wide in eucalypt plantation soils (e.g. Leighton-Boyce et al., 2005; Shakesby et al., 1993; Doerr et al., 1996, 1998). Infiltration-excess overland flow is a rarity in Victorian mountain forests, implying that the development of summer water repellency does not result in infiltration rates that are less than rainfall intensity. However, using daily flows to construct the FDCss may not capture sub-daily storm responses.

There were greater flow increases recorded in 2004–2005 in the East Kiewa, despite recovery of shrubs and grasses and some limited overstorey canopy growth. It is likely the 2003–2004 response was dampened by filling of highly depleted soil moisture storages as a result of the dry weather preceding the fires. The interpolated rainfall for the West Kiewa River in 2002–2003 was 700 mm less than the 10 year average. The 2003/2004 flow from Springs Creek is surprisingly low. One hypothesis is that storage deficits may have been greater due to the 30% area with 20 year old regrowth *E. delegatensis* stands. This species has a similar ecological response to fire as *E. regnans*. There is a substantial body of research that shows young *E. regnans* stands transpire at greater rates that mature stands (e.g. Langford, 1976; Kuczera, 1987; Vertessy et al., 1996, 2001).

Sediment impacts

The sediment exports from the East Kiewa catchments approach an order of magnitude increase for both TSS and bedload. Although the pre-fire record of the latter is sketchy, we postulate that the total increase in sediment export from the East Kiewa sites is at least 10-fold in the first year following the fire, reducing to a 3-fold increase for 2004–2005. The major factor in the load reduction in 2004–2005 was the decrease in suspended sediment concentration. At Slippery Rock Creek the suspended load was still elevated relative to pre-fire levels because of the persistent flow increases rather than high concentrations. As it is likely that flow increases will persist for several years before the pre-fire leaf area recovers, loads may continue to be elevated despite sediment concentrations declining to pre-fire levels. In contrast to the concentrations, available evidence suggests continued increased bedload production at Slippery Rock Creek in 2004–2005, possibly related to the stream power associated with the flow increases. The magnitude of the estimated bedload is significant as it demonstrates the potentially serious underestimation of sediment responses to disturbance if TSS only is considered. This is particularly true in these steep mountain headwater streams. The estimated baseflow values are somewhat higher than observations from other undisturbed forested catchments in SE Australia. However, the pre-fire total TSS loads from the East Kiewa catchments suggest comparatively high sediment production for an undisturbed state. There is no conclusive data to show a fire-induced increase under baseflow conditions.

The spatially averaged first year TSS load estimates for the West Kiewa River are substantially lower than those from the East Kiewa. The loads per unit area are a third of Springs Creek and 14% of Slippery Rock Creek in 2003–2004. Although there is an incomplete data set for 2004–2005 all indications are that the suspended sediment concentrations had decreased substantially following the spring/summer vegetation regrowth in late 2003. The lower fire severity and consequent faster vegetation recovery is an obvious reason. Scale differences between the East and West Kiewa catchments also may obscure the impacts. Subcatchment responses in the West Kiewa could be of the same magnitude as the East Kiewa catchments, but the overall impact may be reduced by lightly or unaffected areas. Crucially, there were significant areas of riparian vegetation that were only very lightly burnt in the West Kiewa catchment. Scott (1993) identified the importance of intact riparian zones in trapping sediment. Additionally, the presence of riparian vegetation is likely to have a proportionally greater impact on the suppression of yield increases than upslope vegetation because of the water availability for transpiration.

The spatially averaged suspended sediment flux rates sit within a continuum of reported catchment scale results which are highly dependent on the time period of sampling, rainfall intensity, burn severity, vegetation recovery rates and sampling and estimation methods. For example, Scott's (1993) summary of multi-catchment impacts in South Africa reported a post-fire range of 0.15–6 t ha^{-1} y^{-1}, and Scott et al. (1998) measured rates of 7.8 t ha^{-1} y^{-1} These South African catchments are similar in scale to the East Kiewa catchments. Helvey (1980) found a rate of 0.13 t ha^{-1} y^{-1}, but considered this to be a 8–10-fold increase on pre-fire values. Brown (1972) suggested that one catchment experienced a 1000-fold increase in sediment exports in the first 18 months after burning. Peak measured concentrations were around double those from the East Kiewa. However, the data on rainfall conditions are incomplete, and the load estimates are from sediment ratings curves with substantial scatter, making comparisons difficult. Chessman (1986) presented TSS loads for the first 3 months post-fire for 3 Victorian catchments, with estimated fluxes of 1.13, 0.72 and 0.13 t ha^{-1} for burnt areas of 98%, 50% and 7%, respectively. Again the data were sparse and the calculated loads likely to be subject to substantial uncertainty. The total sediment fluxes given by Moody and Martin (2001a) appear to be higher than the East Kiewa totals. Kunze and Stednick (in press) reported a peak storm suspended sediment yield of the same magnitude as the January 2004 event in the East Kiewa, although generated from less total rainfall. They found that 2 events produced 90% of the sediment load. Similar to the peak event in the East Kiewa, these events occurred over a year after the fire. The bedload to suspended load ratios from the East Kiewa are far higher than those reported by Scott (1993) and Scott and Van Wyk (1992) who observed bedload to be an order of magnitude less than TSS. In contrast Moody and Martin (2001a) suggest lowering of the bedload ratios.

None of the above studies incorporated the catastrophic events of the scale reported by Leitch et al. (1984), where an estimated 800 t of sediment was mobilised from a 35 ha catchment, or the examples given by Ice et al. (2004) and Wells (1987). The recovery rates are also variable, where reported, and few data with which to compare the cause of elevated loads – increased concentrations and or higher discharges. The data from the Kiewa catchments suggests the likelihood of high sediment yield events have diminished with vegetation recovery. However the elevated discharges, and therefore loads, may be expected for some years.

Comparison with logging disturbance

The pre-fire data from Springs Creek also affords an opportunity to compare the effect of a non-BMP logging operations with the fire impact on water quality. The TSS concentrations and loads indicate that the 1980s logging impact was of a similar, though lesser, magnitude. Riparian areas would be undisturbed and compacted areas minimised under the current Victorian Code of Forest Practice, although roading could pose a water quality threat in these catchments unless managed well. The area affected by logging was one third of the area severely burnt. It is likely that compaction from machinery during logging operations would act to increase the impact per unit area through a large reduction in infiltration and disturbance of upper soil layers.

Implications

This study demonstrates that even under relatively unexceptional rainfall inputs there are still significant increases in both water yield and sediment exports. While the more extreme responses receive most attention, both in the scientific literature and the general public's perceptions, these ''average'' responses still hold significant implications for water and catchment managers. Many catchments in Australia have ''end of valley'' sediment and nutrient targets, often with the aim of reducing existing loads through improved landuse practices. Even small fire-related increases confound these strategies. Many rivers in Australia are under stress from demands for irrigation, environmental flow allocations and domestic water supply. Changes in flows, both in volume and intra-annual distribution, have significant implications. Knowledge of the magnitude and longevity of post-fire flow increases may be crucial for buffering storage and allocation systems against possible yield declines as forests regenerate.

As discussed in Section 'Introduction' there are few studies that link hillslope processes with catchment scale effects. Future work will be aimed at providing that link for these catchments.

Conclusions

The principal findings from this study are that there have been annual flow increases of 60–70% over the first two post-fire water years at the heavily burnt East Kiewa catchments. Flow duration curves do not indicate changed runoff generating processes at the daily timescale. Total sediment load increases from the East Kiewa catchments were at least 10-fold in year 1 and 2–4-fold in year 2, with much of the second year increases accounted for by the flow increases. The decrease in sediment concentrations in year 2 appear to be related to vegetation recovery. Bedload is clearly an important contributor to the total sediment load. Two storms with vastly different intensity-durations produced over 70% of the sediment fluxes, with the largest magnitude sediment event occurring almost a year after the fire. The larger and less fire-impacted West Kiewa River has sustained much more subdued changes in flow and most likely in sediment loads. It may be expected that sediment loads will continue to decline as suspended sediment concentrations return to pre-fire levels due to good vegetation recovery, but that elevated flows will continue to deliver higher suspended sediment loads, and possibly higher, bedloads until evapotranspiration recovers.

Acknowledgements

The authors would like to thank John Costenaro, Phill McKenna, Chris Sherwin and Gabi Szegedy for their tireless efforts in data collection and analysis, and the anonymous reviewers for their comments that led to a much improved the paper. This study was jointly funded by the Victorian Department of Sustainability and Environment Bushfire Recovery Program, the DSE Parks and Forests Division, and Land and Water Australia project DSE1.

References

Benavides-Solorio, J., MacDonald, L.H., 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. Hydrological Processes 15, 2931–2952.

Blake, W.H., Wallbrink, P.J., Doerr, S.H., Shakesby, R.A., Humphreys, G.S., 2004. Sediment redistribution following wildfire in the Sydney region, Australia: a mineral magnetic tracing approach, In: Golosov, V., Belyaev, V., Walling, D.E. (Eds.), Sediment Transfer through the Fluvial System. Proceedings of the International Association of Hydrological Science (IAHS) Symposium, Moscow, August, 2005. IAHS Publication 288, 2004, pp. 52–59 .

Brown, J.A.H., 1972. Hydrologic effects of a bushfire in a catchment in South-Eastern New South Wales. Journal of Hydrology 15, 77–96.

Burch, G.J., Moore, I.D., Burns, J., 1989. Some water repellent effects on infiltration and catchment runoff. Hydrological Processes 3, 211–222.

Burgess, J.S., Rieger, W.A., Olive, L.J., 1981. Sediment yield change following logging and fire effects in dry sclerophyll forest in southern New South Wales. In: Davies, T.R.H., Pearce, A.J. (Eds.), Erosion and Sediment Transport in Pacific Rim Steeplands, vol. 132. IHAS Pub., Christchurch, New Zealand, pp. 375–385.

Campbell, R.E., Baker Jr., M.B., Folliott, P.F., Larson, F.R., Avery, C.C., 1977. Wildfire effects on a Ponderosa Pine ecosystem: An Arizona case study. USDA Forest Service Research Paper RM-191, USDA for. Serv. Rocky Mountains Forest and Range Experiment Station, Fort Collins, Colarado.

Chessman, B.C., 1986. Impact of the 1983 wildfires on river water quality in East Gippsland, Victoria. Australian Journal Marine Freshwater Research 37, 399–420.

Cornish, P.M., Binns, D., 1987. Streamwater quality following logging and wildfire in dry sclerophyll forest in southeastern Australia. Forest Ecology and Management 22, 1–28.

Cornish, P.M., Vertessy, R.A., 2001. Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest. Journal of Hydrology 242, 43–63.

Crockford, H., Topalidis, S., Richardson, D.P., 1991. Water repellency in a dry sclerophyll eucalypt forest – measurements and processes. Hydrological Processes 5, 405–420.

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 1996. Soil water repellency variations with depth and particle size fraction in burned and unburned *Eucalyptus globulus* and *Pinus pinaster* forest terrain in the Agueda Basin, Portugal. Catena 27, 25–47.

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 1998. Spatial variation of soil hydrophobicity in fire-prone eucalyptus and pine forests, Portugal. Soil Science 163, 313–324.

Dragovich, D., Morris, R., 2002. Fire intensity, slopewash and biotransfer of sediment in eucalypt forest, Australia. Earth Surface Processes and Landforms 27, 1309–1319.

English, P.M, Wallbrink P.J., Chafer C., Humphreys G.S., Shakesby R.A., Blake W.H., Doerr S.H., Vigneswaran, B., 2005. Tracer assessment of post-fire sediment and nutrient redistribution on hillslopes: Nattai National Park, NSW. CSIRO Land & Water Report, April 2005.

Gilmour, D.A., 1968. Water repellence of soils related to surface dryness. Australian Forestry 32, 143–148.

Hartland, R., Papworth, M.P., Slater, S.J.E. 1990. Logging Alpine Ash in the East Kiewa river catchment. Part II: Prediction of sedimentation effects in junction dam and clover dam. Department of Conservation and Environment Land Protection Division. Research Report No.5, 21p.

Helvey, J.D., 1980. Effects of a north central Washington wildfire on runoff and sediment production. Water Resources Bulletin 16 (4), 627–634.

Ice, G.G., Neary, D.G., Adams, P.W., 2004. Effects of wildfire on soils and watershed processes. Journal of Forestry 102, 16–20.

Johansen, M.P., Hakonson, T.E., Breshears, D.D., 2001. Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. Hydrological Processes 15, 2953–2965.

King, P.M., 1981. Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. Australian Journal of Soil Research 19, 275–285.

Kuczera, G.A., 1987. Prediction of water yield reduction following a bushfire in ash-mixed species eucalypt forest. Journal of Hydrology 94, 215–236.

Kunze, M.D, Stednick, J.D., 2006. Streamflow and suspended sediment yield following the 2000 Bobcat fire, Colorado. Hydrological Processes, 20, 1661–1681.

Lane, P.N.J., Best, A.E., Hickel, K., Zhang, L., 2005. The response of flow duration curves to afforestation. Journal of Hydrology 310, 253–265.

Langford, K.J., 1976. Change in yield of water following a bushfire in a forest of *Eucalyptus regnans*. Journal of Hydrology 29, 87–114.

Leighton-Boyce, G., Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., Ferreira, A.J.D., Boulet, A-K., Coelho, C.O.A., 2005. Temporal dynamics of water repellency and soil moisture in eucalypt plantations, Portugal. Australian Journal of Soil Research 43 (3), 269–280.

Leitch, C.J., 1979. Effects of Alpine Ash logging on stream sediment levels in the East Kiewa River catchment. 1. First Progress Report. Forest Commission of Victoria, Research Branch Rep. 148, (unpubl.), 19pp.

Leitch, C.J., 1981. Effects of Alpine Ash logging on stream sediment levels in the East Kiewa River catchment. 2. First Calibration Report. Forest Commission of Victoria, Research Branch Rep. 176, (unpublished), 30pp.

Leitch, C.J., Flinn, D.W., van de Graaff, R.H.M., 1984. Erosion and nutrient loss resulting from Ash Wednesday (February 1983) wildfires: a case study. Australian Forestry 46 (3), 173–180.

Lyne, V.D., Hollick, M., 1979. Stochastic time-varying rainfall-runoff modelling. Hydrology and Water Resources Symposium, Perth. Institution of Engineers, Australia, pp. 89–92.

Mackay, S.M., Cornish, P.M., 1982. Effects of wildfire and logging on the hydrology of small catchments near Eden, NSW. In: The First National Symposium on Forest Hydrology, The Institution of Engineers, Australia, National Conference Publication No. 82 pp. 111–117.

Malmer, A., 2004. Stream water quality as affected by wildfires in natural and manmade vegetation in Malaysian Borneo. Hydrological Processes 18, 853–864.

McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J., Hopkins, M.S., 1990. Australian Soil and Land Survey Field Handbook. Inkata Press, Melbourne, p. 198.

Moody, J.A., Martin, D.A., 2001a. Initial hydrologic and geomorphic response following a wildfire in the Colorado front range. Earth Surface Processes and Landforms 26, 1049–1070.

Moody, J.A., Martin, D.A., 2001b. Post-fire, rainfall intensity-peak discharge relations for three mountainous watersheds in the western USA. Hydrological Processes 15, 2981–2993.

Morris, S.E., Moses, T.A., 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. Annals of the Association of American Geography 77 (2), 245–254.

Nathan, R.J., McMahon, T.A., 1990. Evaluation of automated techniques for baseflow and recession analysis. Water Resource Research 26 (7), 1465–1473.

O'Loughlin, E.M., Cheney, N.P., Burns, J., 1982. The bushrangers experiment: Hydrological response of a eucalypt catchment to fire. The First National Symposium on Forest Hydrology, The Institution of Engineers, Australia, National Conference Publication No. 82, pp. 132–138.

Olive, L.J., Rieger, W.A., 1985. Variation in suspended sediment concentration during storms in five small catchments in southeast New South Wales. Australian Geographical Studies 23, 38–51.

Papworth, M.P., Hartland, R., Lucas, A., 1990. Logging Alpine Ash in the East Kiewa River Catchment. Part I: Effects on Stream Sediment Levels. Department of Conservation and Environment Land Protection Division. Research Report No. 4, 71pp.

Prosser, I.P., Williams, L., 1998. Effect of wildfire on runoff and erosion in native Eucalyptus forest. Hydrological Processes 12, 251–264.

Robichaud, P.R., 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. Journal of Hydrology 231–232, 220–229.

Scott, D.F., 1993. The hydrological effects of fire in South African mountain catchments. Journal of Hydrology 150, 409–432.

Scott, D.F., 1997. The contrasting effects of wildfire and clearfelling on the hydrology of a small catchment. Hydrological Processes 11, 543–555.

Scott, D.F., Van Wyk, D.B., 1992. The effects of fire on soil water repellency, catchment sediment yields and streamflow. In: van

Wilgen, Richardson, D.M., Kruger, F.J., van Hensbergen (Eds.), Fire in South African mountain Fynbos. Springer-Verlag, Berlin, pp. 216—239.

Scott, D.F., Versfeld, D.B., Lesch, W., 1998. Erosion and sediment yield in relation to afforestation and fire in the mountains of the Western Cape Province, South Africa. South African Geographical Journal 80, 50—59.

Seeger, M., Errea, M-P., Begueria, S., Arnaez, J., Marti, C., Garcia-Ruiz, J.M., 2004. Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish pyrenees. Journal of Hydrology 288, 299—311.

Shakesby, R.A., Doerr, S.H., 2006. Wildfire as a hydrological and geomorphological agent. Earth-Science Reviews 74, 269—307.

Shakesby, R.A., Coelho, C.O.A., Ferreira, A.D., Terry, J.P., Walsh, R.P.D., 1993. Wildfire impacts on soil erosion and hydrology in wet Mediterranean forest, Portugal. International Journal Wildland Fire 3 (2), 95—110.

Shakesby, R.A., Chafer, C.J., Doerr, S.H., Blake, W.H., Wallbrink, P., Humphreys, G.S., Harrington, B.A., 2003. Fire severity, water repellency characteristics and hydrogeomorphological changes following the Christmas 2001 Sydney forest fires. Australian Geographer 34 (2), 147—175.

Vertessy, R.A., Hatton, T.J., Benyon, R.J., Dawes, W.R., 1996. Long term growth and water balance predictions for a mountain ash (*Eucalyptus regnans*) forest catchment to clearfelling and regeneration. Tree Physiology 16, 221—232.

Vertessy, R.A., Watson, F.G.R., O'Sullivan, S.K., 2001. Factors determining relations between stand age and catchment water balance in mountain ash forests. Forest Ecology and Management 143, 13—26.

Wallbrink, P.J., English, P.M., Chafer, C., Humphreys, G.S., Shakesby, R.A., Doerr, S.H., Blake, W.H. Post-fire erosion in the south-eastern Australian sandstone tablelands: a case study viewed in the global context. Forest Ecology and Management, in press.

Watson, F.G.R., Vertessy, R.A., McMahon, T.A., Rhodes, B.G., Watson I.S. 1999. The hydrologic impacts of forestry on the Maroondah catchments. Cooperative research Centre for Catchment Hydrology, Melbourne, Technical Report 99/1, 80pp.

Watson, F.G.R., Vertessy, R.A., McMahon, T.A., Rhodes, B.G., Watson, I., 2001. Improved methods to assess water yield changes from paired-catchment studies: application to the Maroondah catchments. Forest Ecology and Management 143, 189—204.

Wells, C.G., 1987. The effects of fire on the generation of debris flow in Southern California. In: Costa, J.E., Wieczorek (Eds.). Debris flows/avalanches: processes, recognition and mitigation. Reviews in Engineering Geology, vol. 7, pp. 105—114.

Zierholz, C., Hairsine, P.B., Booker, F.A., 1995. Runoff and soil erosion in bushland following the Sydney bushfires. Australian Journal of Soil and Water Conservation 8, 28—37.