Impact of bushfire and climate variability on streamflow from forested catchments in southeast Australia

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Abstract

Most of the surface water for natural environmental and human water uses in southeast Australia is sourced from forested catchments located in the higher rainfall areas. Water yield of these catchments is mainly affected by climatic conditions, but it is also greatly affected by vegetation cover change. Bushfires are a major natural disturbance in forested catchments and potentially modify the water yield of the catchments through changes to evapotranspiration (ET) and soil moisture storage. This paper quantifies the impacts of bushfire and climate variability on streamflow from three southeast Australian catchments where Ash Wednesday bushfires occurred in February 1983. The hydrological models used here include AWRA-L, Xinanjiang and GR4J. The three models are first calibrated against streamflow data from the pre-bushfire period and they are used to simulate runoff for the post-bushfire period with the calibrated parameters. The difference in simulated streamflow between pre- and post-bushfire period provides an estimate of the impact of climate variability on streamflow. The impact of bushfire on streamflow is quantified by removing the climate variability impact from the difference in mean annual observed streamflow between post- and pre- bushfire periods. The hydrological modelling results for the three catchments indicate that there is a substantial increase in streamflow in the first 15 years after the 1983 bushfires. The increase in streamflow is attributed to initial decreases in evapotranspiration and soil infiltration rates resulting from the fires, followed by logging activity. After 15 years, streamflow dynamics are more heavily influenced by climate effects, although some impact from fire and logging regeneration may still occur. It is shown that hydrological models provide reasonable consistent estimates of forest disturbance and climate impacts on streamflow for the three catchments. The results might be used by forest managers to understand the relationship between forest disturbance and climate variability impacts on water yield in the context of climate change.

Keywords: bushfires, forests, hydrological models, runoff, climate variability, evapotranspiration

1. Introduction

Forested catchments are normally located in higher rainfall areas and they produce most of the surface water for environmental and human water use in major parts of the world. This is particularly important in southeast (SE) Australia. For instance, most of the water supply for Melbourne, the capital of the State of Victorian, comes from native eucalypt forest catchments (Lane et al., 2010).

Water supply in SE Australian native forest catchments has been significantly influenced by natural and/or anthropogenic disturbances (Langford, 1976; Kuczera, 1987; Cornish 1993; Cornish and Vertessy, 2001; Vertessy et al., 1996, 2001; Watson et al., 1999a; Lane et al., 2010). Bushfires are a major natural disturbance in SE Australia and have the potential to modify the hydrological response of forests by significantly altering interception, transpiration and soil properties. To give some scale of this issue, over 3 million ha of forests in SE Australia have been subject to bushfire in the past 9 years. The major anthropogenic forest disturbance is logging, which is a major source of pulp and timber in SE Australia. Like severe fire, clearfell logging substantially changes land cover and the associated hydrological response. In some catchments, salvage logging has combined with bushfire, changing hydrological processes and thus influencing runoff generation (Smith et al., 2011).

A number of studies have found that bushfires impact on streamflow by destroying the vegetation cover and litter layer, and altering the soil properties (e.g. Brown, 1972; Scott, 1993, 1997; Shakesby and Doerr, 2006; Mataix-Solera, et al., 2011; Soulis, et al., 2012). On the one hand, bushfires cause a dramatic ~~change~~ loss in vegetation cover, and present potential for a distinct temporal change in evapotranspiration (ET) as the early loss of leaf area transitions into regrowth or recovering forest. Secondly, bushfires destroy the organic matter destabilizing the soil structure in top soils (Mataix-Solera, et al., 2002), produce ash (a mixture of black carbon, soot, charred material, charcoal and mineral material) (Moody et al., 2009), and enhance the impacts of water repellency (Debano, 2000). Therefore, soil infiltration capacity can be reduced due to surface pores sealed by fine soil and ash particles and the hydrophobic compounds on the soil surface

(Shakesby & Doerr 2006; Sheridan et al. 2007). Cumulatively, these effects increase runoff, and peak flow magnitude (Soulis, et al., 2012).

Flow increases have been largely reported following bushfires (eg. Brown, 1972; Helvey, 1980; Scott, 1993, 1997; Lane et al., 2006, 2012). However, Tan et al. (2011) also reported no flow increases in Melbourne's water supply catchments following the 2009 Black Saturday fires in Victoria, and a recent study measuring the evapotranspiration of *E. delegatensis* stands after fire found significant increases in stand ET in years 6-7 post fire (Buckley et al., 2012).

Most fire-related studies (and many other disturbance studies) reported in the literature focus only on immediate and short term impacts. Two landmark studies in Australia (Langford, 1976 and Kuczera, 1987) focused on multi-decadal flow sequences were the first to identify a significant flow decline as the forest recovers. These studies found that the regrowth stands of *Eucalyptus regnans* (Mountain Ash) killed in the 1939 bushfire were yielding significantly less water than the old growth stands they replaced. Kuczera (1987) proposed a model that, expressed as an age-yield curve, shows a 50% decline in flow by age 25-30 relative to an old growth baseline, with a gradual recovery over more than 100 years. Watson et al. (1999a) agreed with the general trend of the curve, with the major departure being a flow increase in the first few years. Kuczera's analysis (Kuczera, 1987) did not identify this early increase. Both models predict streamflow to begin decreasing below pre-fire level in less than 10 years. Feikema et al. (2013) recently suggested the reason for the discrepancy in the two models is due to the differences in the rainfall/soil moisture storage prior to and immediately following the disturbance.

The reasons for this age-yield relationship were untangled by a series of process studies (eg. Vertessy et al., 1995, 1996, 2001; Haydon et al, 1996; Watson et al., 1999b, Vaze et al., 2004; Vaze et al., 2009). Fire is the ecological trigger for *E. regnans* and other Ash-type eucalypt forests (mainly *E. delegatensis*). Moderate-hot fires kill the trees which results in very dense regeneration from seeds, leading to a rapid development of sapwood area and leaf area. These single aged stands thin out naturally with competition, leading to development of an understorey and gradual loss of overstorey density. As the stands thin, water use decreases.

In contrast to ash forests, the effect of fire on most other eucalypt species is far less dramatic as they are fire resistant, with relatively low incidence of mortality compared with ash stands (Benyon and Lane, 2013). Complete regrowth stands in these mixed species forests are rare. Loss of leaves in the canopy is compensated by growth of epicormic shoots from the trunk and branches, and seedling germination. Gradually the canopy is re-established and the dominant trees out compete seedlings. The non-ash ET-age relationship following fire is poorly understood. However any significant long-term changes are unlikely unless there is widespread mortality. It is generally conceded that this rarely occurs (eg. Gill, 1995; Purdie and Slatyer, 1976; Christensen et al., 1981, Vivian et al., 2008), which means the logging impact reported by Cornish (1993) and Cornish and Vertessy (2001) is unlikely. Although not well measured, it can be argued that these forests re-establish their canopy in less than 10 years (and often much faster) and return to the pre-fire equilibrium ET.

When considering bushfire impact on streamflow, climate variability is also an important factor that can greatly affect streamflow (Dam, 1999; Lane et al., 2005). Precipitation and potential evapotranspiration are two dominant climate factors in hydrological cycle. The high variability of rainfall and temperature observed in eastern Australia (Stone and Auliciems, 1992; Kiem and Franks, 2001) significantly influence catchment hydrology. For example, a prolonged drought since the mid-1990s in southeast Australia has had a serious impact on bushfire regimes and water availability for industrial and consumptive use (Verdon-Kidd and Kiem, 2009). There have been numerous studies investigating the impacts of land use/land cover change and climate variability on streamflow ((Li et al., 2007, 2009; Tomer and Schilling, 2009; Nangia et al., 2010; Li et al., 2012). Most of these studies focus on vegetation change due to afforestation, deforestation and other human activities. However, bushfire and climate variability impacts on streamflow are rarely concerned.

To investigate forest disturbance and climate variability impacts on streamflow, hydrological modelling is extensively used. Modelling studies into forest disturbance in SE native Australian forests have included physically-based (eg. Vertessy et al., 1993, 1995; Watson et al., 1999b), empirical (Watson et al., 1999a; Cornish and Vertessy, 2001) and lumped rainfall-runoff models (eg. Post and Jakeman, 1996). The physically-based approaches are particularly attractive for the ash species because of the dynamic nature of stand responses. This is mainly because these models consider vegetation dynamics, simulate forest regrowth after disturbance, and then try to model runoff under transient conditions. The application of these models on catchments affected by bushfires or logging is subject to the availability of detailed catchment attributes which are necessary for the parameterisation of these models (Lane et al., 2010, Feikema, et al., 2013). These detailed catchment attributes at fine spatial resolution are seldom available for medium to large size catchments which normally constrains the successful application of these models. Lane et al. (2010) highlighted the strengths and weaknesses of physically-based approaches for fire modelling, and note that parameterisation for a wide range of vegetation types and climates is problematic. Bushfires disturb far greater areas and distribution of forest species than commercial logging, leading to parameterisation issues. Empirical models have been successfully applied for forecasting at large scales for recent Victorian fire events (Mannik et al, 2009). Although this approach avoids some parameterisation issues by neglecting rainfall dynamics and internal catchment processes, it is constrained by untested assumptions of vegetation response to fire and by application to highly variable forest and landuses with a paucity of response data.

Lumped rainfall-runoff models have simpler model structure, fewer model parameters and less input information, compared to the physical-based models. Therefore, the lumped rainfall-runoff models are easier to apply for hydrological modelling, and they provide a convenient method to estimate the relative impacts of catchment disturbances (such as bushfire and logging) and climate variability on streamflow for any size catchment. However, it is essential to calibrate and validate the rainfall-runoff models to get an optimum simulation result (Beven, 1989). Model calibration is an iterative process to refine model parameters by comparing simulated and observed data to satisfy the criterion of accuracy; model validation is to evaluate the ability of model predicting streamflow outside the calibration with the calibrated parameters (Refsgaard and Henriksen, 2004). This model validation exercise makes sure that a rainfall-runoff model can simulate runoff time series for an independent period or under different climatic conditions. The calibrated and validated rainfall-runoff models can be used to quantify impact of climate variability on catchment water yield and then to estimate disturbance impact (Tuteja, et al., 2007; Li et al., 2012).

The main objective of this paper is to quantify the impacts of climate variability and bushfires on streamflow from three southeast Australian catchments where Ash Wednesday bushfires occurred in February 1983 (Fig.1) using three conceptual rainfall runoff models (AWRA-L (Van Dijk, 2010), Xinanjiang (Zhao, 1992) and GR4J (Perrin et al., 2003)). The three models are first calibrated against observed streamflow obtained from the pre-bushfire period, and then the calibrated models are applied to predict streamflow for the post-bushfire period. The difference between the observed and simulated streamflow for the post-bushfire period is the impact of bushfire.

2. Catchment and Data

2.1 Study Catchments

The three bushfire impacted catchments are located in the Central Highlands of Victoria, east of Melbourne ((a), (b) and (c) in Fig.1 (Ⅱ)). Elevations range from 112-901 m (Yarra River), 207-1126 m (Latrobe), and 320-940m (Starvation Creek). The geology of the catchments is dominated by Devonian granites with smaller areas of Devonian metamorphics (mainly hornfels), and some sandstones. They are characterised by deep, well structured and highly conductive soils (eg. Davis et al., 1999, Lane et al, 2004), mainly red or brown ferrosols or dermosols (red or brown earths). These soils can be more than 5 m deep and have large storage capacities. They support a mix of pure E. regnans (mountain ash) and mixed damp eucalypt species, predominantly *E. obliqua*, *E. cypellocarpa* and *E. sieberi.* The area of ash is 56% for the Latrobe River catchment, 50% for the Yarra River catchment and 51% for Starvation Creek. The ash stands were all regrowth originating from the 1939 bushfires (State Forest Resource Inventory (SFRI)).

Table 1 provides the catchment areas, burnt area, percentage burnt and study period of record and Table 2 summarises the rainfall and areal potential evapotranspiration (*APET*) data.

Apportioning the vegetation impact of the burn area is not straightforward. Based on forest inventory data we can establish a minimum impact via ash mortality. This is based on the SFRI data set that gives species and age distributions. However, the impact on the non-ash species is far less certain. We have no fire severity data for this fire. It is unlikely there was broadscale mortality, but it is impossible to know exactly what the mixed-species disturbance was. Fig. 2a shows the cumulative mortality/regrowth for mountain ash for the catchments. It is assumed that any regeneration area from 1984 was salvage logging if the ashes in this area were not killed by fires. The known fire-mortality rates for the catchments were 10%, 25% and 3% for the Latrobe, Yarra and Starvation Creek catchments, respectively. Fig. 2b includes the non-ash data, but it is unlikely that increased regeneration percentages are realistic. The area burnt for Starvation Creek is 84%, but as only 3% results in a fire-kill of ash it appears the severity was not high in that catchment. Fig. 2 shows clearly that, subsequent to 1983/84 there was a significant percentage of further disturbance. This is clearfell logging (in the 1990s and early 2000s) of mountain ash and some other eucalpypt species as the post 1939 fire regrowth reached prime harvest age. Thus the analysis in this paper considers a mix of fire, logging and climate effects on streamflow.

Fig.1 about here

Fig.2 about here

Table 1 about here

The four median-size forested catchments around the three bushfire impacted catchments are selected for model validation. These four catchments are unregulated and they were not affected by the bushfires (Fig.1 (Ⅱ), catchments (1) – (4) named 405205, 405209, 405227 and 227202). All these four catchments have long term reliable streamflow records spanning from pre-bushfire to post-bushfire period. Therefore, they can be used for investigating the transposability of calibrated model parameters in time.

The catchment area for the four catchments varies from 109 to 1080 km^2 (Table 1). The four catchments are largely covered by eucalypt forest, with a forest ratio varying from 0.86 to 1.0. Mean elevations for catchments 405205, 405209, 405227, and 227202 are 670.5m, 604.4m, 751.4m, and 155.3m, respectively.

2.2 Data

This study uses more than 30 years of historical streamflow data (Q_{obs}) extending from pre-bushfire to post-bushfire periods (Table 1). The data for the Latrobe, Yarra and Starvation Creek catchments and the four validation catchments are available for 1966-2007, 1973-2004, 1971-2000 and 1975-2009 respectively. The daily streamflow data is obtained from the Victorian Water Resources Data Warehouse (http://www.vicwaterdata.net) and checked for data quality to be used for hydrological modeling (Vaze et al., 2010a). The climatic data (daily precipitation, *P*, areal potential evapotranspiration, *APET*, maximum temperature, T_{max}, minimum temperature, T_{min}, actual vapour pressure, *e,* and solar radiation, R_s) used in this study come from the 'SILO Data Drill' produced by the Queensland Department of Environment and Resource Management (www.derm.qld.gov.au/silo ; Jeffrey et al., 2001). The daily gridded SILO dataset (0.05°×0.05°) are interpolated from 4600 point measurements across Australia (Jeffrey et al., 2001). The ordinary kriging was used to interpolate daily and monthly precipitation and cross validation indicates precipitation with a mean absolute value of 12.2 mm/month, indicating good quality of interpolation. The daily climatic data are used to drive the three rainfall-runoff models (AWRA-L, Xinanjiang and GR4J model). The *APET* used in Xinanjiang and GR4J model is calculated from the 0.05° T_{max}, T_{min}, R_s, *and e* using Morton's wet environment (or equilibrium evaporation or areal potential evaporation) algorithms (Morton, 1983).

Table 3 about here

3. Methodology

3.1 General Framework

Streamflow is controlled not only by climate conditions, but catchment characteristics. It can be assumed that streamflow changes as a result of climate variability and the changes in catchment characteristics, which can be written as:

$$\Delta Q_{tot}=\Delta Q_{cc}+\Delta Q_{clim} \tag{1}$$

where ΔQ_{tot} is the total streamflow change in two periods, 1 and 2, estimated as $\Delta Q_{tot} = \overline{Q_{obs}^{2}} - \overline{Q_{obs}^{1}}$, $\overline{Q_{obs}^{1}}$ is the mean annual streamflow observed in the period 1 when catchment disturbance is negligible (the baseline) and $\overline{Q_{obs}^{2}}$ are the mean annual streamflow observed in the period 2 when catchment disturbance is significant; ΔQ_{cc} is the change in streamflow caused by the change in catchment characteristics, ΔQ_{clim} is the change contributed by climate variability.

The three forested catchments selected in this study are not subject to dam regulations or diversions. Therefore, changes of catchment characteristics are primarily due to bushfire caused vegetation cover loss and changes in soil properties (ΔQ_{fire}). As a result, ΔQ_{cc} is replaced by ΔQ_{fire} and Eq. (1) can be rewritten as:

$$\Delta Q_{tot}=\Delta Q_{fire}+\Delta Q_{clim} \tag{2}$$

ΔQ_{tot} can be estimated from streamflow data observed from the two periods. ΔQ_{fire} can be quantified once ΔQ_{clim} is available. Here, the lumped rainfall-runoff models are used to estimate ΔQ_{clim}. First, these models are driven by climate inputs and calibrated against observed streamflow data in the period 1. Secondly, the calibrated models are driven by climate inputs in the period 2 to simulate streamflow in that period. Since these calibrated models are only driven by climate variables, rainfall and areal potential evaporatranspiration (*APET*), the changes in the simulated streamflow from the two periods are solely caused by climate variability. Therefore, the climatic variability impact on streamflow (ΔQ_{clim}) can be estimated as:

$$\Delta Q_{clim} = \overline{Q_{sim}^{2}} - \overline{Q_{sim}^{1}} \tag{3}$$

where Q_{sim1} is the mean annual streamflow simulated in the calibration period, Q_{sim2} is the mean annual streamflow simulated in the test period (or post-bushfire period).

This approach assumes that there are no noticeable changes in model bias from model calibration period (pre-bushfire) to model test period (post-bushfire) and the calibrated parameter set can be transferred from the calibration period to the test period. Once ΔQ_{clim} is quantified, ΔQ_{fire} is calculated from Eqs. (2) and (3).

3.2 Hydrological modelling

Three hydrological models, GR4J (Perrin et al., 2003), Xinanjiang (Zhao, 1992) and AWRA-L (Van Dijk, 2010), are used in this study. Table 4 summarises the major characteristics and differences between the three models. All these three models have runoff generation soil stores and account for actual evapotranspiration processes. The main feature for the AWRA-L model is grid based , and includes flexible land cover types described at sub-grid scale (tall deep-rooted vegetation and short shallow-rooted vegetation are included in this study). The XAJ model considers that the soil water storage is distributed in a statistical way in space across the catchment. The GR4J model adopts two unit hydrographs for routing. The three models are briefly described below.

Table 4 about here

3.2.1 Model description

GR4J

The GR4J model (Perrin et al., 2003) is a daily lumped conceptual rainfall-runoff model. Streamflow is estimated from mean areal daily *P* and *APET* time series. It has two stores, the production and routing stores, and four parameters to calibrate. It has been applied over a wide range of hydro-climatic conditions (Perrin et al., 2003, Coron et al., 2012; Lerat et al., 2012) including application across southeast Australia (Vaze et al., 2010a) and used in the MOPEX experiment of rainfall-runoff models intercomparison (Andréassian et al., 2006).

Xinanjiang

Xinanjiang model (Zhao, 1992) is also a lumped conceptual daily rainfall-runoff model. Model inputs include *P* and *APET* time series. It has been widely applied in humid and semi-humid regions in China since its publication in 1980 (Zhao et al., 1980; Zhao, 1992; Jayawardena and Zhou, 2000; Cheng et al., 2002). And It has been successfully applied in southeast Australia (Zhang and Chiew, 2009; Li et al, 2012). TheXinanjiang model includes 14 parameters and four submodels: a three-layer evapotranspiration submodel, a runoff generation submodel, a runoff separation submodel and a runoff routing submodel.

AWRA-L

Australian Water Resources Assessment system Landscape Model (AWRA-L) (Van Dijk, 2010) is a one-dimensional, grid-based water balance model that simulates water stores and flows in the soil, groundwater and surface water systems. Each grid cell consists of two hydrological response units (HRUs): deep-rooted and shallow-rooted vegetation. Soil and vegetation water and energy fluxes are simulated separately for each HRU and individual HRUs are linked together by groundwater and surface water. The AWRA-L model contains 17 calibration parameters and four submodels for simulating runoff generation, radiation and energy, vapor fluxes and vegetation phenology, respectively. The forcing data include daily precipitation, maximum temperature, minimum temperature and solar radiation and the outputs include daily water fluxes and vegetation dynamics. The AWRA-L model has been successfully applied across Australia (Vaze et al., 2013).

3.3.2 Calibration

The particle swarm optimization (Eberhart and Kennedy, 1995) is used for model calibration. This method can find the so-called global or near-global optimum and has been successfully used for calibrating hydrological models (Chau, 2006; Gill et al., 2006; Zhang and Chiew, 2009).

All conceptual hydrological models need to be calibrated before they can be applied for catchment water balance assessments. The Nash-Sutcliffe Efficiency (NSE, defined by Nash and Sutcliffe, 1970) is the most widely used for calibration and evaluation of hydrological models. The hydrological models (AWRA-L, Xinanjiang and GR4J models) are calibrated by maximising the objective function which is a weighted combination of

NSE of monthly runoff and a logarithmic function of bias (total model error divided by total observed streamflow, *B*) (Viney et al., 2009; Vaze et al, 2010b) given by:

$$F = NSE - 5\,|\ln(1+B)|^{2.5} \tag{4}$$

NSE is expressed as

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{\mathrm{obs,i}} - Q_{sim,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i} - \overline{Q_{obs}}\right)^2} \tag{5}$$

B is defined as:

$$B = \frac{\sum_{i=1}^{n} Q_{sim,i} - \sum_{i=1}^{n} Q_{obs,i}}{\sum_{i=1}^{n} Q_{obs,i}} \tag{6}$$

Where Q_{obs} is recorded monthly runoff, Q_{sim} is simulated monthly runoff, $\overline{Q_{obs}}$ is the arithmetic mean of the observed runoff, i is ith month, and n is the number of months. This objective function provides a smooth but less severe bias constraint, compared to the bucket constraint and an advantage of the log-bias constraint is that it does not suffer from the numerical issues which can influence predictions/simulations using the non-continuous bucket constraint (Viney et al., 2009).

The pre-bushfire period (start of flow record to 1982) is used for model calibration and the post-bushfire period (1983 to end of flow record) is used as the test period. Table 1 summaries the calibration and test periods for each catchment, with the first year of calibration period used for model warm up.

3.3.3 Cross-validation

Validation is to determine the suitability of the calibrated models for predicting streamflow over any period outside the calibration period with the same catchment characteristics (Vaze et al., 2012). However, the study catchments in this paper suffered from significant changes in vegetation cover and soil properties due to the 1983 bushfires. There was also a prolonged drought in the mid-1990s. As such, it was necessary to evaluate whether the models are able to adequately reproduce catchment hydrology behavior in post-bushfire period. Therefore, four unregulated (unburnt) forested catchments around the three study catchments are selected for cross-validation (Table 1).

For the four selected catchments, the pre-bushfire period (1975-1982) is used for model calibration and three post-bushfire periods, 1983-2009, 1983-1998 and 1999-2009, are used for model validation (Table 6). The calibrated parameter sets from pre-bushfire period are used to simulate the streamflow in post-bushfire period. The NSE and WBE in the validation period are compared to those in the calibration period to assess whether the model calibrated in the pre-bushfire period can reproduce the hydrological behavior in the post-bushfire period.

4. Results and Discussion

4.1 Hydrological model calibration

The hydrological models calibration and test periods and the calibration results for the study catchments are shown in Table 1 and Table 3, respectively. The *NSE* results of calibration period for the three models range from 0.78 to 0.85, 0.78 to 0.85 and 0.67 to 0.83 for AWRA-L, Xinanjiang and GR4J models, respectively. The calibration *B* values range from -0.76% to 0.39% for AWRA-L, from 0.66% to 2.65% for Xinanjiang and from -0.57% to 2.29% for GR4J model. The predicted and observed annual streamflow for the entire modelling periods are shown in Fig. 3-5. There is a good agreement between the simulated and observed streamflow in the calibration period (start of flow record to 1982). The calibration results for the three models are satisfactory and are comparable with other hydrological model calibration results reported in literature (Vaze and Teng, 2011; Vaze et al., 2011). The calibration results also indicate that the model bias in simulating monthly runoff is small and non-systematic and the models used in this study are robust enough to simulate streamflow over an independent test period.

Fig. 3-5 about here

4.2 Model cross-validation

The three models are used for the parameter transposability modelling experiments. The results from the three models are similar, and Table 6 shows the model calibration and validation results for the GR4J model.

The modelling results show that the GR4J model generally performs reasonably well both in the calibration and validation periods. For all the four catchments, the NSE values obtained for the validation periods are similar to those obtained for the calibration period. The differences between the B values for the calibration and validation periods for all the four catchments are also small. First, the B values obtained in the whole validation period (1983-2009) are compared to those obtained in the calibration period (1975-1982). For the 405205 catchment, the B value obtained in the validation period is actually smaller (about 0.06) than that obtained in the calibration period and for the other three catchments, the B values obtained in the validation period are slightly larger (B increase of about 0.03-0.07) than those obtained in the calibration period. Secondly, the validation period is split into two: 1983-1998 and 1999-2009, to match the two post-bushfire periods used for bushfire impact analysis. The bias obtained in the first validation period (1983-1998) is similar to that obtained in the second validation period (1999-2004) for catchment 405205, but is about 0.03-0.12 smaller for other three catchments. The results for these four neighbouring catchments provide reasonably confidence (as discussed in Sec.4.5) in the hydrological modelling results quantifying the impacts of climate variability and vegetation change for the three study catchments.

4.3 Hydrological model simulation

The calibrated rainfall-runoff model(s) parameters combined with climatic data (*P, APET, Tmax, Tmin, Rs, and e*) are applied to simulate streamflow for the entire post-bushfire test periods (Table 1) to investigate 1983 bushfire and climate variability impact on streamflow from the three catchments. As the hydrological models are driven using observed climatic dataset for the post-bushfire period, it can be assumed that climatic difference impact between pre- and post-bushfire periods has been taken out. Therefore, the difference in observed and predicted streamflow during post-bushfire period is solely due to reductions in interception, actual transpiration and soil infiltration rates caused by bushfire.

The observed and simulated streamflow for the three catchments are shown in Fig. 3-5 (a to c). For all the three catchments, simulated annual streamflow from the three models are noticeably lower than the observed streamflow in the initial period post-bushfire (1983-1998). In the period after 1999, the three models simulated runoff is in reasonable agreement with the observed runoff.

To quantify the relative impacts of the 1983 bushfire and climate variability on streamflow during the post-bushfire test period, the simulated streamflow for the AWRA-L, Xinanjiang and GR4J models are compared with the observed streamflow (section 3.1 detailing the methodology). The difference in observed and simulated streamflow during post-bushfire periods is due to bushfire. The climate variability impact on streamflow is the difference of simulated streamflow between pre- and post-bushfire periods. Table 5 shows the simulation results for the AWRA-L model (columns 5 to 8), Xinanjiang model (columns 9 to 12) and GR4J (columns 13 to 16) when using post-bushfire climate dataset and calibrated parameters from calibration periods.

Table 5 about here

As shown in Table 5, the total streamflow change for the first 15 years post-bushfire show an increase (when compared to the pre-bushfire period) ΔQ_{tot} caused by the 1983 bushfires and climate variability for the Latrobe@Noojee, Starvation creek and Yarra River@Little Yarra catchments are 52mm, 107mm and 36mm which represent about 17%, 26% and 12% increase in streamflow respectively. Table 5 summarises the relative effects of climate variability and bushfire on streamflow from the three hydrological models. During the first 15 years post-bushfire, all the three models show that (ΔQ_{fire}) bushfire causes an increase in streamflow and the simulation results are similar in magnitude for the three catchments. When averaged over the three models, the increases in streamflow caused by bushfire are 80mm, 136mm and 30mm (26.4%, 32.6% and 9.9%) for Latrob@Noojee, Starvation Creek and Yarra River@Little Yarra catchments, respectively. Compared to the impact of bushfire, the impact of climate variability ($\Delta Q_{c\lim}$) is small for all the three catchments. When averaged over the three models, the changes in streamflow caused by climate variability are -35mm, -6mm and 2mm (-10.4%, -1.4% and 0.7% of pre-bushfire streamflow) for Latrob@Noojee, Starvation Creek and Yarra River@Little Yarra catchments, respectively. The streamflow changes caused by climate variability are similar to what we will get based on the concept of streamflow elasticity to rainfall (Chiew, 2006; see Table 2, rainfall changes of -19mm, -17mm and 20mm (-1.3%, -1.0% and 1.4%) in first 15 years post-bushfire period compared with pre-bushfire period). As shown in Figs 6 and 7, the median of the increases in streamflow due to bushfire change are 79mm, 143mm and 33mm (26%, 34% and 11% of pre-bushfire streamflow), and the corresponding changes in streamflow due to climatic differences between the pre-bushfire and the first 15 years post-bushfire periods for the three catchments are 28mm, -36mm and 3 mm (-9%, -9% and 1% of pre-bushfire streamflow). The consistency in modelling results from the three models indicates that the increase in streamflow in the first 15 years of post-bushfire period is mainly caused by reducing actual evapotranspiration and altered hydraulic properties of soil due to bushfire.

The results for the period post 1998 (after 15 years post-bushfire) show that the impact of the 1983 bushfires on streamflow for the three catchments is smaller compared to that in the first 15 years after bushfire. For Latrobe@noojee, Starvation creek and Yarra River@Little Yarra catchments, the total change in observed streamflow compared to the pre-bushfire period (ΔQ_{tot}) are -87mm, -101mm and -86mm which represent about 29%, 24% and 28% reduction in streamflow of pre-bushfire period respectively. For the post 1998 period, the reduction in streamflow due to climate variability is larger than that caused by the 1983 bushfire as the observed climate is significantly drier than that in the pre-bushfire period (and slightly drier than the climate for the first 15 years post-bushfire period) (Table 5). When averaged over the three models, the reductions in streamflow caused by climate variability for the three catchments are -91mm, -122mm and -57mm (-30%, -29% and -19% of pre-bushfire streamflow). The three models show increases in sreamflow due to bushfire for Latrobe@Noojee and Starvation Creek catchments. But the three models show a mixed response to bushfire in Yarra River@Little Yarra catchment. AWRA-L and GR4J models show reductions of -25mm and -29mm (-8.4% and -9.5% of pre-bushfire period) in streamflow, while the Xinanjiang model shows an increase of 8mm (2.7% of pre-bushfire period). The Xinanjiang model is specifically developed for humid and semi-humid catchments (Zhao et al., 1980, 1992) and so the difference between Xinanjiang and AWRA-L and GR4J models is partially due to transposability of model parameters from wet to dry periods for the Xinanjiang model (as discussed in section 4.4). When averaged over the three models, the results in streamflow change caused by bushfire compared to pre-bushfire period for the three catchments are 27mm, 32mm and -15mm (9.0%, 7.7% and -5.1% of pre-bushfire streamflow). As shown in Figs 6 and 7, the median of the increases in streamflow due to vegetation cover change are 30mm, 27mm and -25mm (10%, 7% and -8%), and the corresponding changes in streamflow caused by climatic differences between the pre-bushfire and after 15 years post-bushfire periods for the three catchments are -117mm, -129mm and -60mm (-39%, -31% and -20% of pre-bushfire streamflow). The consistency in the modelling results from the three models suggests that the impact of climate variability on streamflow is much larger than that caused by bushfire.

4.4 Comparisons between different models

The box and whisker plots in Figs. 6 and 7 show the change in streamflow in the two periods (the first 15 years after the 1983 bushfires and after 15 years post-bushfire) estimated by the three hydrological models (AWRA-L, Xinanjiang and GR4J model) for the three catchments (Latrobe@noojee, Starvation Creek and Yarra River @Little Yarra) in mm and percentage change respectively. The horizontal line in each box shows the median of the modelling results over the three models, the upper and lower envelops show the 75th and 25th percentile values and the upper and lower whiskers show the 95th and 5th percentile values.

Fig. 6 and 7 about here

There are some differences in bushfire and climate variability impacts estimated by the three models for the three study catchments (Figs 6 and 7). The maximum difference between the modelling results during the first 15 years due to bushfire for the three models are 29mm (95mm to 66mm), 44mm (155mm to 110mm) and 18mm (38mm to 20mm) for Latrobe@noojee, Starvation Creek and Yarra River @Little Yarra catchments respectively. This maximum difference is equivalent to 9.5%, 10.7% and 5.9% relative to pre-bushfire period streamflow for the three catchments, respectively. After 15 years post-bushfire, the maximum difference between the modelling results for the three models is 43mm (48mm to 4mm), 27mm (48mm to 21mm) and 37mm (8mm to -29mm).

This is equivalent to 14.3%, 6.6% and 12.2% relative to pre-bushfire period streamflow for the three catchments, respectively. The differences between the results from the three hydrological models can be attributed to differences in the conceptual complexity, structure, parameter numbers and transposability of model parameters. This is further discussed in Sect. 4.5.

All results from the three models show reasonable agreement with each other. In first 15 years after bushfires (1983-1998), bushfire causes substantial increase in streamflow and its impact on streamflow are much larger than that of climate variability. Streamflow in Starvation Creek catchment show much larger increase than that in Latrobe@Noojee catchment which in turn shows larger increase than in Yarra River @Little Yarra catchment. It seems to be inversely related to percentage of ash disturbance. Yarra River @Little Yarra catchment with the highest percentage of ash disturbance (shown in Fig.2 (a)) has the lowest increase in streamflow.

After 15 years post-bushfire, bushfire impacts on streamflow are negligible for the post 1999 period (after 15 years post-bushfire), when compared to the impacts in the first 15 years post-bushfire. During this period, there is a large reduction in streamflow due to substantial reduction in mean annual rainfall of 217mm, 221mm and 150mm (15.4%, 13.6% and 10.2%) compared to the pre-bushfire period for Latrobe@Noojee, Starvation Creek and Yarra River@Little Yarra catchments, respectively. The differences in the results from the three models are partially due to the uncertainties in hydrological model structure and parameterisation.

4.5 Discussion

The applicability of hydrological modelling to quantify vegetation change and climate variability impacts on streamflow mainly depends on how the model parameters are calibrated and how they are transferred from calibration period to simulation period. It is important to investigate the transposability of model parameters in time (i.e., to make sure that their estimation is not dependent on climate characteristics of the calibration periods). This can provide us with a better understanding of uncertainty associated with using hydrological models for quantifying bushfire and climatic variability impacts on streamflow. To investigate the model transposability, four median-size catchments close to the three study catchments shown in Table 6 were selected. As shown in Table 6, the differences in B between the calibration period and the first validation period range between 0.01-0.06 and the differences in B between the calibration period and the second validation period range between 0.07-0.11. The slightly higher B values in the second validation period can be partly caused due to the larger climatic differences between the two periods (the 1999-2009 period is about 15% drier than the 1975-1982 period for these four catchments). This is in agreement with the finding of some recent papers which indicate that there can be a reduction in model predictive capability when transferring calibrated model parameters from wet to dry periods (Vaze et al., 2010; Merz et al., 2011; Coron et al., 2012). The modelling experiments carried out in this study suggest that the uncertainty of transferring model parameters from the calibration period to the first test period (the first 15 years post-bushfire) is very small (difference in B values between calibration and validation periods of 0.01-0.06) and it increases slightly when transferring the calibrated parameters from the calibration period to the second test period (after the first 15 years post-bushfire). The 0.01-0.06 changes in B from the calibration period to the first test period are much smaller than the impacts of the 1983 bushfire impact on streamflow and the 0.07-0.11 changes in B from the calibration period to the second test period are also smaller than the climate change impact on streamflow in the second period (Table 5). These results provide confidence in the climate variability and vegetation change impact assessments based on hydrological modelling.

The hydrological modelling results for all the three catchments indicate that there is a substantial increase in streamflow in the first 15 years after the 1983 bushfires that is not attributable to climate alone. An increase in streamflow in the early years is consistent with conceptual models of leaf area loss/ET decrease, as nearly 19% to 84% of the forest cover in the three catchments was burnt in the 1983 bushfires. However, we cannot be sure how much canopy area was affected due to lack of detailed information about the fire intensities for the 1983 bushfire. The Bosch and Hewlett (1982) review of forest cover change and streamflow found that streamflow response to cover changes of <20% of catchment area could not be verified statistically.

The only hypothesis that supports the persistence of such increases after the first 3-5 years is disturbance by subsequent logging activities (Fig. 1(IV)), which almost doubles the fire kill area for the Latrobe and Yarra catchments, and results in the largest area of ash disturbance at Starvation Creek. Removal of more ash through logging effectively increases the fire mortality and consequently magnifies the hydrologic effect. Given that there would be some soil moisture deficits, a lag in response to lowered ET is likely. However, the large streamflow increases for Starvation Creek that can be attributed to the fire appear to be highly disproportionate to the fire-related mortality area of only 3%, and even once logging begins at this catchment the response apportioned to vegetation change appears to be quite high for the area affected.

There are two issues that require consideration if we are to accept the modelling results as representing real effects. Firstly, what processes could drive such large flow increase at Starvation Creek with a 3% mortality area, and secondly, how would the balance of disturbance/regrowth over two decades play out in streamflow changes for all catchments?

For Starvation Creek, the only plausible explanation for the early post-fire years is that there was a significant impact in the non-ash species that resulted in high canopy loss and low ET immediately after the fire. Rainfall in 1983 and 1984 was 1453 and 1541 mm, respectively (long term SILO mean is 1565 mm), which means there was a significant supply of potential water for streamflow. The catchment received 979 mm of rainfall between the fire (16 February) and 30 September 1983. Little ET could be expected from burnt areas during this period. An increase of this magnitude is less than that measured by Lane et al. (2006) for stands with almost complete canopy loss (but extensive alpine ash mortality). It is also consistent with early increases predicted and observed by Lane et al. (2010) using physically-based modelling for the 1533 km^2 Mitta Mitta catchment after the 2003 fires. Further, the dry period that preceded the Ash Wednesday fire was relatively short (rainfall in 1981 was 1515 mm and in 1982 it was 1243 mm), suggesting that soil moisture deficits were not extreme.

There is current unpublished research into the ecohydrology of recovering mixed species eucalypt stands that suggests early post fire water use may vary as a function of fire severity (Nolan et al. submitted). Moderate burns appear to produce higher water use once seedling recruitment and leaf area recovery begins. Conversely, severe burns may retard the re-development of canopy for some years, leading to lower water use for a few years. If the fire was severe at Starvation Creek then it could drive the flow increases at Starvation Creek after 1984, but it also may be that the post-fire rainfall (almost 1000 mm) recharged deep stores that fed the streamflow for some years. The low ash mortality also means there would be little effect in subsequent years of high water-using regrowth with an origin in 1983 or 1984. This may in part explain the scale of flow increases in the late 1990s.

The water gain/loss over time is the balance between lower and higher rates of ET relative to the pre-disturbance values as the ash stands recover. The conceptual model for ash ET is a decrease for 1-5 years followed by an increase until age 25-30, then a return toward equilibrium rates over many decades. The fire disturbance followed by logging would result in different areas of the catchments in varying states of ET. It is notable that the three models show either flow decreases or (for Latrobe) a very small increase for the post 1998 period. This accords (at least relatively) with a trend toward high water use in the latter part of the record. However, the modelling suggests in some instances that the streamflow changes are due to climate rather than vegetation dynamics.

There is a background vegetation-hydrologic dynamic that may or may not have been dealt with by the calibration. The ash that was not subject to fire or logging is ageing, and according to the Kuczera and Watson curves, is on a trajectory of increasing streamflow. Over the period of interest (1983-2000, 2004, 2007) we could expect flow increases in the order of 4% for 1983-1998 for Latrobe and Yarra catchments and 8% for Starvation Creek from the remaining ash stands, plus further increases for the post 1998 period. It could be argued that the good calibration results reflect the models' ability to deal with this issue. If this is not the case then some of the flow increases may have been inflated in the first post-fire period, and perhaps decreases masked subsequently.

Finally, the other fire-related hydrologic processes that should be considered in modelling are changes to soil hydraulic properties and consequent runoff generation. Increases in surface runoff generation after fire have been widely reported in the literature (eg. White and Wells, 1979; Prosser and Williams, 1998; Moody and Martin, 2001; Robichaud, 2000, Johanson et al., 2001; Benavides-Solorio and MacDonald 2001; Onda et al., 2008). Development or enhancement of water repellency (eg.; Shakesby et al., 1993; Robichaud, 2000, Doerr et al., 2000; Martin and Moody, 2001), the effect of ash on infiltration (Campbell et al., 1977, Cerdà and Doerr, 2008; Onda et al., 2008; Woods and Balfour 2010; Ebel et al., 2012) or loss of roughness/detention storage from plant immolation (eg. Lavee et al., 1995 Scott, 1997; Inbar et al., 1998) have been invoked as the agent driving the process change. The implication is water is more efficiently routed to the stream network via infiltration-excess overland flow, and that peak flows in particular may increase markedly (eg. Campbell et al., 1977; Scott, 1993, Moody and Martin, 2001; Moody et al., 2009, Soulis et al, 2012). Some of these runoff generation studies have been at plot or small experimental catchment scales where scale effects may not be captured.

Recent studies into post-fire soil hydraulic responses to fire in similar environments to the wet eucalypt catchments modelled here (Lane et al. 2004; Lane et al. 2006; Sheridan et al. 2007; Nyman et al. 2010) have found that although there is enhancement of water repellency (which is naturally occurring in summer) and generation of surface runoff, this does not translate into broadscale overland flow. The principal reason is the spatial heterogeneity in infiltration properties mainly controlled by macropore distribution and their suction characteristics (Nyman et al., 2010). As the background hydraulic conductivities can be in the order of metres per day, small patches of non-repellent soil can capture any generated flow. Lane et al. (2006) found all flow percentiles increased after fire, but no evidence of altered runoff generation processes. The net result is that it is unlikely these soil factors are important for streamflow analysis on an annual scale in the modelled catchments. However it is emerging that soils in drier eucalypt forests may respond differently (Nyman et al., 2011).

The streamflow response to bushfire for the first couple of years, shown in Figs 3-5, is not as large as expected (Soulis, et al., 2012; Lane, et al., 2010; Cornish and Vertessy, 2001). First, the interaction of vegetation dynamic and hydrologic response may or may not be considered in the calibration. Second, hydrological response to bushfire is greatly related to fire severity. The more severely the catchments are burnt, the more significantly the vegetation and soil properties are disturbed. The severe destruction of vegetation cover can reduce catchment evapotranspiration rates in early post-bushfire period and changes in soil properties affect runoff generation mechanism (Scott et al., 1998). As discussed previously, we are not sure about the fire severity and the quantity of direct bushfire impact on streamflow using rainfall-runoff modelling. All of these factors contribute uncertainties to explain the modelling results.

Overall, the modelling results are plausible from a process perspective for the Latrobe and Yarra catchments, but explaining the large effect at Starvation Creek is contingent on significant (and unknown) loss of canopy from non-ash species. Generalising these results for bushfire impacts is difficult. As stated, the lack of information on fire severity and canopy loss is limited for this fire event, so the exact vegetation impact is not known. There were two quite distinct patterns of rainfall over the period of interest, with a relatively wet period coinciding with the first analysis period (1983-1998) followed by a sequence of dry years. Finally, the issue of soil moisture deficits at the time of the fire and the subsequent rainfall in the next 6-9 months before significant vegetation recovery is likely to be a large lever on flow responses.

5. Conclusions

The hydrological modelling results for all the three catchments suggest that there was a substantial increase in streamflow in the first 15 years after the 1983 bushfires that could not be accounted for by climate effects. There is a reasonable agreement between the bushfire and climate variability impacts on streamflow results for this first post-fire period from the three hydrological models for the Latrobe@Noojee, Starvation Creek and Yarra River@Little Yarra catchments. We hypothesise the flow increases were mainly caused by the loss of leaf area and tree morality because of the bushfires and associated reductions in interception, actual transpiration and soil infiltration rates. These increases are in agreement with the general pattern of significant annual water yield increases following forest disturbance reported in the literature, but the persistence of the inflow increases appears to be related to logging in the 1990s and early 2000s. The modelled flow responses for the post-1998 period are attributed to a combination of vegetation recovery after disturbance and climate factors as the lengthy drought developed. Flow decreases driven by vegetation are plausible for areas of regenerating mountain ash.

Uncertainties in this study arise from transferring of model parameters from calibration to test periods, imprecise knowledge on fire severity and associated impact on non-ash species, the interplay of fire recovery, logging effects and a background vegetation-flow dynamic in these forests, and from distinct climate regimes over the period of the study. However the modelling has produced some interesting insights into fire and logging effects in SE Australian forests.

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Table 1 Catchments attributes and calibration and test periods

Catchment Code	Catchment Names	Burnt Area Percentage (%)	Catchment Area (km^2)	Area Burnt (km^2)	Period of record	Calibration Period	Test period
226205	Latrobe at Noojee	18.52	292.9	54.25	1966-2007	1967-1982	1983-2007
229109	Starvation Creek	84.12	31.5	26.47	1973-2004	1974-1982	1983-2004
229214	Yarra River at Little Yarra	45.58	149.4	68.1	1971-2000	1972-1982	1983-2000
405205	Murrindindi River at Murrindindi Above Colwells	-	108.2	-	1975–2009	1975–1982	1983-2009
405227	Big River at Jamieson	-	626.3	-	1975–2009	1975–1982	1983-2009
405209	Acheron River at Taggerty	-	627.6	-	1975–2009	1975–1982	1983-2009
227202	Tarwin at Meeiyan	-	1066.7	-	1975–2009	1975–1982	1983-2009

Table 2 Mean annual streamflow, rainfall and areal potential evapotranspiration (*APET*) for different periods for the three catchments

Catchments	Streamflow (mm/yr)				Rainfall (mm/yr)				*APET* (mm/yr)			
	Start year-1982	1983-1998	1999-end year	1983-end year	Start year-1982	1983-1998	1999-end year	1983-end year	Start year-1982	1983-1998	1999-end year	1983-end year
Latrobe@noojee	304	356	217	306	1413	1394	1196	1322	1119	1101	1108	1103
Starvation Creek	417	523	315	464	1621	1604	1400	1549	1092	1073	1079	1075
Yarra River @ Little Yarra	305	341	219	328	1477	1497	1327	1478	1136	1113	1119	1113

‘start year’ is the calibration start year of streamflow record.

‘end year’ is the end year of streamflow record.

Table 3 Hydrological model calibration results for the three catchments

Catchment Code	Catchment Names	AWRA-L		XAJ		GR4J	
		NSE	B (%)	NSE	B (%)	NSE	B (%)
226205	Latrobe@noojee	0.78	-0.76	0.78	0.66	0.71	-0.57
229109	Starvation Creek	0.84	-0.20	0.80	2.65	0.67	2.29
229214	Yarra River @ Little Yarra	0.85	0.39	0.85	1.80	0.83	-0.31

Table 4 Overview of the characteristics for the three hydrological models

Characteristics	AWRA-L	XAJ	GR4J
Number of free parameters	17	14	4
Interception	An interception store	No interception store	A zero capacity interception store
Evapotranspiration	Rainfall interception evaporation; Soil evaporation; Open water evaporation; Groundwater evaporation; Transpiration	Three-layer evapotranspiration	One layer soil evaporation
Runoff production	Three layers soil moisture accounting store; Infiltration excess surface runoff and saturation excess runoff; Two hydrological response units	A soil moisture accounting store; Saturation excess runoff;	A soil moisture accounting store; Infiltration excess surface runoff and saturation excess runoff
Routing	No routing store	lag-and-route routing; A nonlinear routing store	Two unit hydrographs; A nonlinear routing store
Source	Van Dijk [2010]	Zhao [1992]	Perrin et al. [2003]

Table 5 Effects of bushfire and climate variability on the mean annual streamflow for the three catchments

Catchment	Periods (post-bushfire)	ΔQ_{tot} (relative to pre-bushfire)		AWRA_L				XAJ				GR4J			
				ΔQ_{fire}		ΔQ_{clim}		ΔQ_{fire}		ΔQ_{clim}		ΔQ_{fire}		ΔQ_{clim}	
		mm/yr	%	mm/yr	%	mm/yr	%	mm/yr	%	mm/yr	%	mm/yr	%	mm/yr	%
latrobe@noojee	1983-1998	52	17	95	31	-44	-14	79	26	-28	-9	66	22	-15	-5
Starvation Creek	1983-1998	107	26	155	37	-48	-12	110	26	-4	-1	143	34	-36	-9
Yarra River @Little Yarra	1983-1998	36	12	38	12	-2	-1	20	7	16	5	33	11	3	1
latrobe@noojee	1999-2007	-87	-29	30	10	-117	-39	48	16	-135	-44	4	1	-91	-30
Starvation Creek	1999-2004	-101	-24	48	12	-149	-36	27	7	-129	-31	21	5	-122	-29
Yarra River @Little Yarra	1999-2000	-86	-28	-25	-8	-60	-20	8	3	-94	-31	-29	-10	-57	-19

ΔQ_{tot} is the difference in observed streamflow between post- and pre- bushfire periods; ΔQ_{clim} is the impact of climate variability on streamflow, calculated from the difference in simulated streamflow between the post- and pre- bushfire periods (Eq. (3)); ΔQ_{fire} is the impact of bushfireon streamflow, calculated from the difference between ΔQ_{tot} and ΔQ_{clim}.

Table 6 Calibration and validation results for the GR4J model in four undisturbed catchments

Catchment code	Area (km^2)	Calibration NSE (1975-1982)	Validation NSE			Calibration B	Validation B			B Difference (validation - calibration)		
			1983-2009	1983-1998	1999-2009		1983-2009	1983-1998	1999-2009	1983-2009	1983-1998	1999-2009
405205	109	0.58	0.73	0.72	0.58	0.13	0.07	0.07	0.06	-0.06	-0.06	-0.07
405227	632	0.83	0.84	0.85	0.77	0.07	0.11	0.08	0.16	0.04	0.01	0.09
405209	633	0.82	0.85	0.85	0.82	0.09	0.12	0.08	0.20	0.03	-0.01	0.11
227202	1080	0.85	0.78	0.76	0.83	-0.01	-0.08	-0.07	-0.10	-0.07	-0.06	-0.09

Figure captions

Fig.1. Location for the three study catchments and four validation catchments (Ⅰ and Ⅱ), bushfire extent (Ⅲ) and logging extent (Ⅳ) for the three study catchments

Fig.2. Cumulative percent of mortality/regrowth for three catchments: (a) mortality/regrowth for ash; (b) mortality/regrowth for all species

Fig.3. Variation of annual rainfall, observed and simulated annual streamflow at the three catchments for AWRA-L model: Latrobe@noojee (a), Starvation Creek (b), Yarra River @ Little Yarra (c). Two dash lines are for years of 1983 and 1998, respectively

Fig.4. Variation of annual rainfall, observed and simulated annual streamflow at the three catchments for XAJ model: Latrobe@noojee (a), Starvation Creek (b), Yarra River @ Little Yarra (c). Two dash lines are for years of 1983 and 1998, respectively

Fig.5. Variation of annual rainfall, observed and simulated annual streamflow at the three catchments for GR4J model Latrobe@noojee (a), Starvation Creek (b), Yarra River @ Little Yarra (c). Two dash lines are for years of 1983 and 1998, respectively

Fig.6. Summary of bushfire impact on annual streamflow in mm from the year 1983 to the end year of streamflow record for the three catchments. White boxplots are bushfire impact from the year 1983 to 1998, and gray ones are from the year 1999 to the end year of record. For each catchment, the three white/gray boxplots represent total streamflow change in mm relative to pre-bushfire period (horizontal line), vegetation change impact on streamflow in mm (without notch), climate change impact on streamflow in mm (with notch), respectively.

Fig.7. Summary of bushfire impact on annual streamflow from the year 1983 to the end year of record in percentage for the three catchments. White boxplots are bushfire impact from the year 1983 to 1998, and gray ones are from the year 1999 to the end year of record. For each catchment, the three white/gray boxplots represent total streamflow change relative to pre-bushfire period in percentage (horizontal line),

vegetation change impact on streamflow in percentage (without notch), and climate change impact on streamflow in percentage (with notch), respectively