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Modelling the long term water yield impact of wildfire and other forest disturbance in Eucalypt forests

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ABSTRACT

Disturbance of forested catchments by fire, logging, or other natural or human induced events that alter the evapotranspiration regime may be a substantial threat to domestic, environmental and industrial water supplies. This paper describes the physically-based modelling of the long term changes in water yield from two wildfire affected catchments in north-eastern Victoria, Australia, and of fire and climate change scenarios in Melbourne's principal water supply catchment. The effect of scale, data availability and quality, and of forest species parameterisation are explored. The modelling demonstrates the importance of precipitation inputs, with Nash and Sutcliffe Coefficients of Efficiency of predicted versus observed monthly flows increasing from 0.5 to 0.8 with a higher density of rainfall stations, and where forest types are well parameterised. Total predicted flow volumes for the calibrations were within 1% of the observed for the Mitta Mitta River catchment and <4% for the Thomson River, but almost −10% for the less well parameterised Tambo River. Despite the issues of data availability simulations demonstrated the potential for significant impacts to water supply in SE Australia from wildfire and climate change. For example, for the catchments modelled the moderate climate change impact on water yield was more pronounced than the worst fire scenario. Both modelled cases resulted in long term water yield declines exceeding 20%, with the climate change impact nearing 30%. A simulation using observed data for the first four post-fire years at the Mitta Mitta River catchment showed Macaque was able to accurately predict total flow.

1. Introduction

In Australia, and many other countries, forested catchments yield most of the water for domestic, agricultural, industrial and environmental uses. For example, the water supply for Melbourne's over 3 million people is derived almost entirely from native eucalypt forest catchments. Disturbance of forested catchments by fire, logging, or other natural or human induced events that alter the evapotranspiration regime may be a substantial threat to water supplies. Whilst security of water supplies has always been of high importance in Australia, the recent long lived drought in south eastern Australia, climate change predictions and two major "mega fire" events in 4 years that have burnt over 2 million ha of native forest in Victoria alone, have raised major concerns for the state's water resources. Melbourne has experienced a run of 11 years of below long term median annual rainfall, which represents a statistically very unusual event estimated to have an average recurrence interval of approximately 1:1000 years (M. Peel, pers comm.).

The net result of these events and threats is that many existing forecasts of both short- and long-term yields may be redundant. Models are required that can handle spatially variable disturbances at the appropriate spatial scale. These scales may be up to 10^3 km^2. There is also a need to represent forest growth dynamics as the temporal response of some eucalypt forests is known to be highly variable.

The wildfire events of 2003 and 2006–2007 in south eastern Australia have imposed a major level of disturbance on forested catchments. A number of studies have found changes in streamflow following fire, but the majority have focussed on the short term increases following the immediate post-fire reduction in evapotranspiration (e.g. Brown, 1972; Scott, 1993, 1997; Mackay and Cornish, 1982; Helvey, 1980; Campbell et al., 1977). However long

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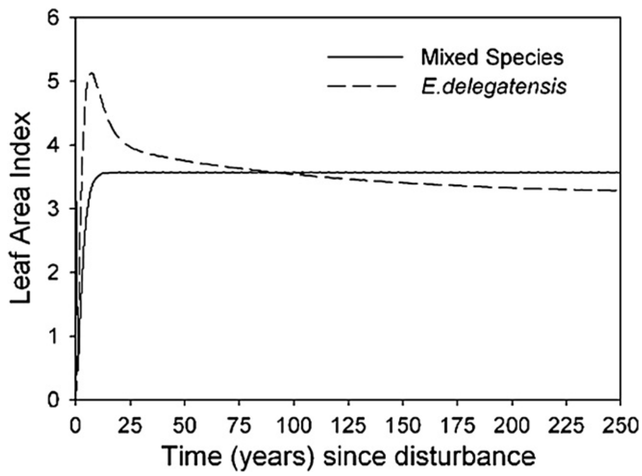

Fig. 1. Example of leaf area index–age relationships; for *E. delegatensis*.

term decreases in yield from *Eucalyptus regnans* (Mountain Ash) forests were identified by Langford (1976) and Kuczera (1987). The prime mechanism is the ecological response to fire. *E. regnans* is killed by severe fire, unlike most mixed eucalypt species. Seed is released directly after fire on to soil now exposed to direct sunlight. Hundreds of thousands of seedlings per hectare germinate. Competition for light and nutrients results in a natural thinning over time, with gaps increasingly populated with understorey species. This means a gradual shift from a very dense young forest to a mature (around 120 years) forests with large gaps in the overstorey canopy. It is the change in the density of *E. regnans* stands with age that produces a marked difference in evapotranspiration and thus streamflow (Vertessy et al., 2001). The age/streamflow relationship was generalised by Kuczera (1987) and revisited using extra data by Watson (1999) and Watson et al. (1999).

Fifteen percent of the area burnt in 2003 was *Eucalyptus delegatensis* (Alpine Ash) stands, which have the same ecological response to fire as *E. regnans*. A further 77% of the burnt area was vegetated by mixed-species eucalypts and *Eucalyptus pauciflora* (snow gum). Although most non-ash species are ecologically distinguished by their tolerance to fire, 54% of the mixed species and snow gum stands were mapped as fire severity Class 1 or 2; crown burnt or severe crown scorch (Department of Sustainability and Environment, 2003). In both instances, there is a complete loss of overstorey canopy and of understorey, shrubs and ground cover. The evapotranspiration response to fire of these species is largely unknown. Clearly evapotranspiration (ET) will be significantly diminished until leaf area recovers, as in ash forests. However the temporal recovery of ET is harder to predict. Whereas *E. delegatensis* and *E. regnans* trees are killed, mixed species survive all but the most severe fire. However, the conceptual model of a stand that is merely "interrupted" in its ET regime may not hold. Where mixed eucalypts suffer crown scorch or burn, the canopy is initially replaced by epicormic shoots rather than a fully restored canopy. The increased light availability and decreased competition for site resources, including water, may result in a scaled down ash-like response of stand growth. There has not been the same level of research into eucalypt mixed-species age/streamflow relationships as for *E. regnan*s, but studies have detected a similar, though subdued, response to clearfell logging (Cornish, 1993; Cornish and Vertessy, 2001; Lane and Mackay, 2001; Roberts et al., 2001).

If the vegetation structure of regrowing severely burnt (Class 1 or 2) mixed species stands changes sufficiently to produce an ash-like response, the potential for significant decreases in yield exists.

A key aspect of wildfire is the spatial heterogeneity of burn location and severity, and the overlay of those conditions with vegetation species, age and landscape position. It follows that a model that can deal with this spatial distribution of parameters is desirable. The Macaque forest water yield model, developed by Watson (1999) is one such model. Macaque was developed explicitly to consider the hydrologic effect of varying eucalypt species and ages within a catchment over long time periods. The model was born out of a series of studies aimed at understanding the physiological reasons for the Kuczera curve effect and to reduce the large error bands around the curves. This research demonstrated the importance of long-term vegetation dynamics on the hydrology of these systems.

Two representative catchments were selected to model the 2003 fire impacts on long term water yield, the Mitta Mitta River and the Tambo River. These catchments were considered to be broadly representative of the catchments that were burnt either side of the eastern Victorian uplands. Additionally, Melbourne's principal water supply catchment, the Thomson River, was modelled for a set of potential fire scenarios.

The aim of this paper is twofold. Firstly to investigate whether fire effects can be modelled by Macaque, and secondly, what is the potential effect of wildfire on long term water supplies and how does that impact sit within climate change projections for SE Australian forests.

2. Model description

Macaque is a physically-based forest hydrologic model that operates at a daily time step. It was originally developed by Watson (1999), with summaries and applications given by Watson et al. (1999, 2001) and Peel et al. (2000, 2001). It has been successfully applied to catchments up to 500 km^2. The catchment is discretised spatially into hillslopes then into smaller areas known as elementary spatial units (ESUs). Each ESU is modelled separately, and individual ESUs are linked together by subsurface water flow pathways within a hillslope. Hillslopes are linked together by a stream network, which sums the flow from all the hillslopes to get the total catchment flow. ESUs are defined on the basis of wetness index, using the TOPMODEL (Beven et al., 1995) scheme. There is a user defined threshold value for stream delineation which acts to control the parameters of the wetness index and thus ESU size.

Within each ESU, two layers of vegetation are represented: canopy and understorey. Solar radiation is propagated through, and absorbed by these layers. Evapotranspiration (ET) is

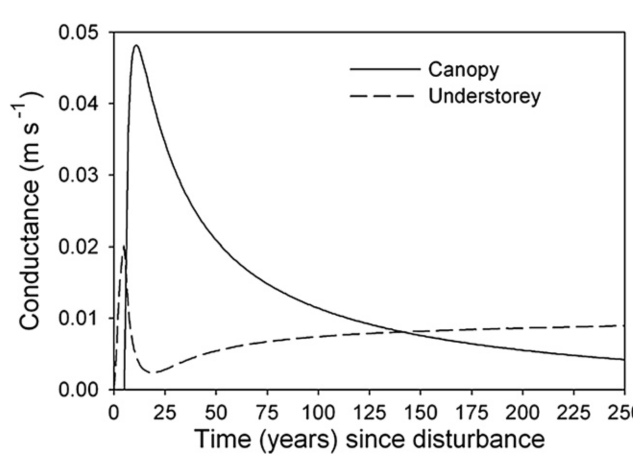

Fig. 2. Example of conductance–age relationship; for *E. delegatensis* stand over- and understorey.

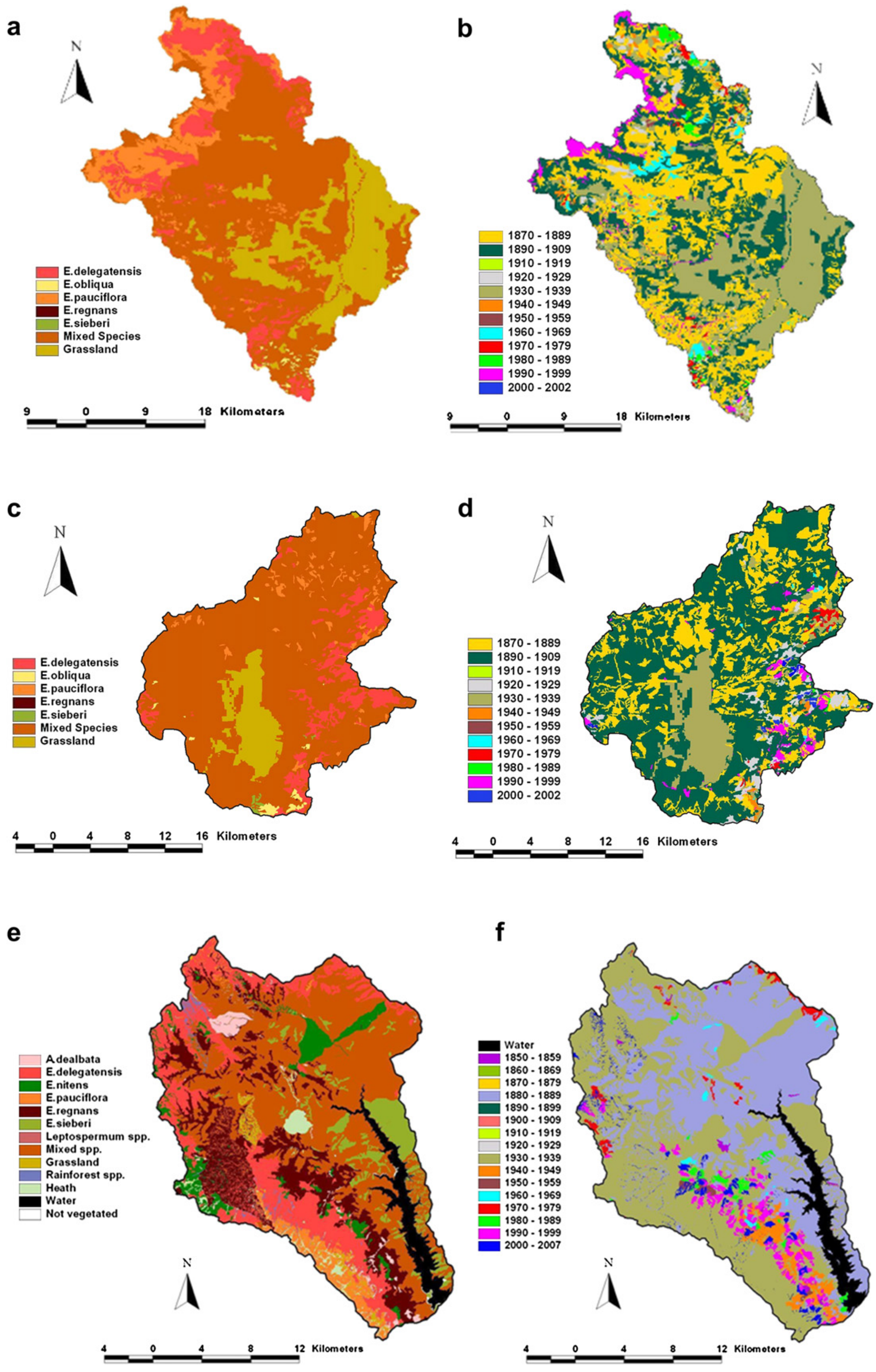

Fig. 3. a–f Species and age maps for Mitta Mitta, Tambo and Thomson catchments.

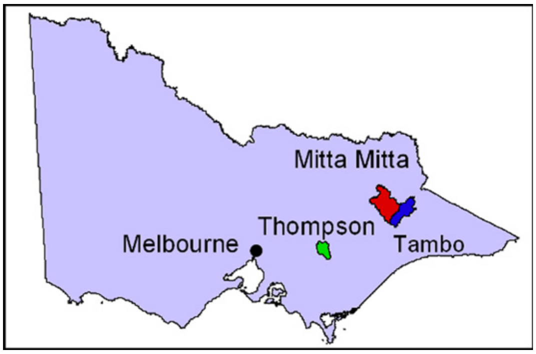

Fig. 4. Location map for modelled catchments.

calculated for these layers and the soil using the Penman–Monteith equation (Monteith and Unsworth, 1990), with detailed representation of energy balances, leaf conductance, interception storage, radiation propagation, humidity gradients and soil water extraction. Much of the complex vertical structure of the ET component is based on two other models; Topog (Vertessy et al., 1995) and RYESSys (Band et al., 1993).

The Van Genuchten (1980) model is used to calculate recharge from the unsaturated to the saturated zone. Precipitation falling on saturated soil is directly converted into runoff. Darcy's Law is used to move water laterally within hillslopes using explicit transfers of water between neighbouring ESUs, and eventually into the stream network. This last step is a development on the original model presented by Watson (1999).

A detailed climate sub-model is used to convert precipitation and temperature range inputs into required climate variables such as radiation and humidity for the estimation of evapotranspiration. Peel et al. (2000) developed a scheme whereby a precipitation surface is derived from multiple linear regression (MLR) analysis of monthly precipitation from stations in or near the catchment against a set of base precipitation stations. The regression analysis terms are then spatially interpolated by a 3-D spline and the daily surface precipitation is driven by the base stations with continuous records. This results in a number of coefficient maps (one for each base station) representing the regression coefficient at all locations. As the model runs, daily rainfall at the base stations is then related to rainfall at each ESU in the whole catchment using the coefficient maps. The MLR analysis and spline fitting is performed outside of Macaque.

Elevation-based lapse rates are used to calculate maximum and minimum temperatures at each ESU. The lapse rates can be calculated from base station data using standard equations and then input as model parameters, or can be assumed where there is not enough data. These temperatures are calculated relative to the temperature base station using the difference in elevation between the ESU and base station. The temperature at a given ESU was calculated using Equation (1).

$$T_{\mathrm{ESU}} = T_{\mathrm{BS}} + (\Gamma_{\mathrm{X}} \times \Delta_{\mathrm{Elev}}) \tag{1}$$

Where T_{ESU} represents the temperature at an ESU (°C), T_{BS} represents the temperature at the base station (°C), Γ_{X} represents the lapse rate (either for maximum or minimum temperature (°Cm^{-1}) and Δ_{Elev} represents the change in elevation (m) (Watson, 1999). This equation was applied for both maximum and minimum temperature at each ESU.

Daily maximum and minimum temperature and precipitation is used to calculate other climate variables such as vapour pressure deficit, solar and long wave radiation. Details of the models used are given in Watson (1999).

Spatial changes in climate, vegetation, soil, and topography cause changes in water yield. Changes in forest type and age are represented by changes in leaf area index (LAI) and leaf conductance to water vapour (e.g. Figs. 1 and 2). These are specified to the model as a series of LAI with age and conductance with age curves for each forest type (e.g. Alpine Ash, Mixed Species, Rainforest, Heath).

Macaque is a physically-based model. Wherever possible, model parameters are assigned values based on direct measurements of physical properties within the respective catchment, or reasonable and appropriate values taken from the literature. As is widely discussed in the literature, physically-based models frequently require calibration as all parameters cannot be measured at all necessary scales, A few parameters, particularly those relating to soil properties, remain for calibration against observed water yield. Such parameters are unlikely to change significantly in the long term with forest disturbance. Once they are calibrated for a given catchment under known disturbance regimes, they are considered to be robust. Therefore, model predictions are considered to be valid when future disturbance regimes are simulated.

2.1. Data requirements

(i) Topographic – a digital elevation model (DEM) is required for discretisation of the catchment. A 10 or 20 m DEM derived from the Victorian Corporate Geospatial Data Library was used.

(ii) Vegetation – layers of species type and age, mapped by the Victorian State Forest Resource Inventory (Fig. 3) that represent the known disturbance history. The number of layers required depends on the number of times the vegetation in a particular grid cell has been disturbed. Typically there are 2–4 species age maps required. The first layer represents the base layer, and each grid cell contains the year that vegetation type commenced growing (i.e. after the previous disturbance). For example, a grid cell with the year 1900 represents vegetation that germinated in 1900, which would be 54 years old for a model simulation starting in 1954. This areal distribution of forest type and age is then linked to the curves for the temporal distribution of leaf area index (LAI) and canopy conductance for each species (Figs. 1 and 2). Both overstorey and understorey components are represented.

(iii) Climate inputs – daily time series of precipitation and maximum and minimum temperature.

3. Catchment description

Macaque was used to model the actual 2003 fire impacts for the Mitta Mitta River at Hinnomunjie (1533 km^2) and Tambo River at

Table 1
Vegetation type for the Mitta Mitta River, Tambo River and Thomson River catchments.

Vegetation type	% (Mitta Mitta)	% (Tambo)	% Thomson
Mixed spp.	57.1	78.8	47.4
Grassland	20.3	8.9	0.7
E. delegatensis	11.4	8.2	19.9
E. obliqua	0.5	0.8	
E. pauciflora	10.7	2.7	3.9
E. sieberi		0.25	3.1
E. regnans		0.004	14.0
E. nitens			3.9
A. dealbata			1.0
Rainforest			0.36
Not vegetated			5.6
Leptospermum spp.			0.1

Bindi (551 km^2) catchments, located in north east Victoria (Fig. 4), and the Thomson River (487 km^2) in the Central Highlands. The catchment areas are largely vegetated by eucalypt forest (Table 1), and have elevations that range from 530 to 2000 m (Mitta Mitta), 285–1610 m (Tambo) and 400–1600 m in the Thomson. These changes in relief result in high precipitation gradients across all three catchments, with long term mean annual rainfall ranging from around <1000–2000 mm in the Mitta Mitta, around 700–1000 mm in the Tambo and around 850–2100 mm in the Thomson. It should be noted that rainfalls in the past 11 years have been consistently lower than the longer term values. Pre-disturbance vegetation species and age maps are shown for the three catchments in Fig. 4. There were 3 age layers required for the Mitta Mitta and Tambo catchments and 2 for the Thomson catchment.

4. Model calibration

The model was calibrated against observed streamflow for the available period of streamflow record up to 2002 for the burnt catchments. For the Mitta Mitta this was 1957–2002, for the Tambo 1974–2002. The Thomson was calibrated onflows from 1957 to 2007. The model was calibrated to maximise the Nash and Sutcliffe (1970) coefficient of efficiency (E), and to minimise the percentage difference in the mean (μ), standard deviation (SD) and coefficient of variation (CV) between observed and predicted monthly streamflow. The Nash and Sutcliffe (1970) coefficient of efficiency (E) is given by:

$$E = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \quad (2)$$

where E is the coefficient of efficiency value, O_i and P_i are the observed and predicted values respectively at each time step, and the overbar denotes the mean for the entire time period of the observed data. The coefficient of efficiency evaluates the performance between observed and model simulated means and variances. If the square of the differences between the model simulations and the observations is as large as the variability in the observed data, then $E = 0$, and if it exceeds it, then $E < 0$ (i.e. the observed mean is a better predictor than P_i). E can range from negative infinity to 1.0, where higher values indicate a better model fit. Here we adopted Chiew and McMahon's (1993) definition of satisfactory and acceptable model performance of $E > 0.6$ and $E > 0.8$, respectively. A value for E of 1.0 is considered a perfect reproduction of the observed data by the model.

The K-fold cross validation method described by Efron and Tibshirani (1993) was used to cross validate the calibrated models. The flow record is split into thirds, with 2 of the thirds used for calibration and the remaining third for validation. This process is repeated twice, with a different third being used for validation each time. This method is useful for assessing the consistency of the model calibration over the different periods and for assessing the adequacy of the model calibration and validation over the range of hydroclimatic conditions exhibited within the period of record.

An additional check on the model performance is through the construction of flow durations curves (FDCs), so that the distribution of flows can be evaluated. FDCs display the relationship between streamflow and the percentage of time the streamflow is exceeded as a cumulative density function (e.g. Vogel and Fennessey, 1994; Lane et al., 2005). FDCs were constructed for monthly flows. They provide both a visual and statistical aid to evaluating differences in flow regime either between catchments, or, in this case, between observed flows and those simulated using calibration parameters.

Although there are a number of parameters available for calibration, we followed the example of Peel et al. (2001) who modelled similar systems (including the Thomson), concentrating on two parameters: the precipitation scalar and the ratio of the hydraulic gradient to the surface gradient. The latter controls the internal drainage rate, and the former allows for modulating rainfall surfaces. We also varied the lapse rate and soil hydraulic conductivity and depth, but found the latter two parameters to be insensitive. Thirteen rainfall stations were available for the Mitta Mitta, and 10 for the Tambo. Three temperature stations were available for both catchments. Sixty-two rainfall stations were available to construct the rainfall surface for the Thomson. The calibration results are given in Tables 2–4.

The calibrations approached $E = 0.6$ for the Mitta Mitta (Table 2), with good agreement on total flows, little difference between CV of predicted and observed monthly streamflow, and low percentage variation from the observed mean for predicted monthly flows. The model mass balance was within 1% accuracy over the whole calibration period. The FDC (Fig. 5a) also showed good agreement for the high and median percentiles, but were a poorer fit for low flows, Macaque slightly underestimating low flows. However, the difference between the summed flows for all percentiles for the observed and predicted FDCs was only 3% overall. The E values of around 0.6 show that although the model was satisfactory, there were periods where the model could not mimic the observed flow.

The calibration for the Tambo was more problematic (Table 3). Optimising the calibration parameters proved difficult, particularly in maximising E while retaining good monthly flow statistics. These statistics are reflected by the FDCs (Fig. 5b) which show a significant divergence between observed monthly flow distribution and those predicted using the calibrated parameters. However it should be noted that this discrepancy in the distribution of lower monthly flows is less troubling for the prediction of total annual flow volumes than differences in the higher flows (lower percentiles). The discrepancy between observed and predicted percentiles is less that 5% for the 1st–50th percentiles which represent 86% of the total flow. Nevertheless, the calibration statistics indicate there are considerable uncertainties around the simulations for both catchments.

Table 2
Results for calibration and validation for the Mitta Mitta catchment. The numbers in the column headings refer to the first (1), second (2) or third (3) third. For example, Calibration 2 & 3 refers to the calibration parameters for the second and third third, Validation 1 is the corresponding first third used for validation in this case.

Parameter	Calibration 1 & 2	Validation 3	Calibration 2 & 3	Validation 1	Calibration 1 & 3	Validation 2	Calibration ALL
E	0.57	0.53	0.58	0.50	0.52	0.62	0.56
% Mean	−3.80	10.09	5.58	−9.09	0.82	1.11	0.92
% SD	−2.11	−1.20	−0.37	−6.11	−2.90	0.32	−1.63
% Cv	1.75	−10.26	−5.64	3.28	−3.69	−0.78	−2.53
PScalar	1.87		1.87		1.87		1.87
Hyd Grad	0.985		0.985		0.985		0.985

E = coefficient of efficiency; % Mean = percentage difference between the observed and predicted monthly streamflow means; % SD = percentage difference between the observed and predicted monthly streamflow standard deviations; % Cv = percentage difference between the observed and predicted monthly streamflow coefficients of variation.

Table 3
Results for calibration and validation for the Tambo at Bindi catchment. The numbers in the column headings refer to the first (1), second (2) or third (3) third. For example, Calibration 2&3 refers to the calibration parameters for the second and third third, Validation 1 is the corresponding first third used for validation in this case.

Parameter	Calibration 1 & 2	Validation 3	Calibration 2 & 3	Validation 1	Calibration 1 & 3	Validation 2	Calibration ALL
E	0.40	0.60	0.38	0.52	0.54	0.26	0.44
% Mean	−9.03	−9.86	−11.54	−4.95	−7.13	−12.79	−9.26
% SD	−0.56	−7.55	6.09	−12.84	−11.05	12.84	−1.83
% Cv	9.31	2.56	19.93	−8.30	−4.22	29.39	8.18
PScalar	1.46		1.46		1.46		1.46
Hyd Grad	0.995		0.995		0.995		0.995

E = coefficient of efficiency; % Mean = percentage difference between the observed and predicted monthly streamflow means; % SD = percentage difference between the observed and predicted monthly streamflow standard deviations; % Cv = percentage difference between the observed and predicted monthly streamflow coefficients of variation.

It was notable at both catchments there were several periods where the modelled flow was either significantly lower than the observed, or did not respond to rainfall at all. It is most likely this is a function of poorly characterised precipitation inputs as the model produces reasonable responses to precipitation for the majority of the calibration. The *E* values rise by around 0.1 if these non-response periods are not considered. A significant problem in modelling a large catchment that is sparsely instrumented is obtaining high quality continuous precipitation data that encompasses the range of rainfall gradients, particularly where there are significant elevation differences.

The calibration statistics for the Thomson (Table 4) show good agreement between observed and simulated total monthly flows with *E* values for both calibration and validation periods around 0.8. The other calibration statistics were more mixed, with greater percentage differences between observed and predicted statistics than desirable in some instances. Overall however the performance of a process model at a scale of 488 km^2 was good. The FDCs (Fig. 5c) showed excellent agreement for all but the low flows.

5. Model performance

5.1. Mitta Mitta and Tambo

The calibrations for both catchments result in some significant uncertainty around the predictions. An exploration of possible causes is warranted. It is highly likely that precipitation inputs are of a lower quality than desired. There is particularly poor rainfall station coverage in Australian upland forests, with the existing stations skewed to the few towns in these areas. Another potential issue is the species that are modelled. Watson (1999) parameterised the model with LAI–conductance–age data collected from experimental catchments in the Victorian Central Highlands. Although some of the mixed-species eucalypts are common to both the Watson (1999) catchments and those modelled here for fire impacts, there are a number of other eucalypts that are found in the drier areas of the Mitta Mitta and Tambo. It is not known if the same LAI–conductance–age relationships exist across the mixed species stands in wet and dry environments.

As there have been several years of data since the 2003 fire, we ran the calibrated model for the Mitta Mitta catchment until the end of 2006 with observed rainfall and temperature inputs and compared the predicted flows with the observed flows. Fig. 6 shows the monthly and daily observed and predicted flows for the period after the 2003 fire. We truncated the time series to December 2006 as there was more fire disturbance from the 2006/07 fires in the catchment, and the reliability of gauging data post 2006 is poor. Despite the uncertainty in the spatial distribution of rainfall inputs and forest type responses the model performs reasonably well, albeit with some considerably lagged responses for some periods. The data returned an *E* value of 0.58 for monthly flows. However, perhaps more importantly, the predicted total flow for 2003–2006 was 97.5% of the observed flow, giving a mean annual difference of less than 1%. These data suggest that although there are uncertainties arising from the calibrations, the model was able to broadly simulate the impact of the fire on flow in the short term.

5.2. Thomson

The Thomson calibration results also suggest Macaque can be used to explore disturbance scenarios with some confidence where the input data is of reasonable quality. Further, the species mix is less varied than found in the Mitta Mitta and Tambo catchments. There is a greater proportion of *E. regnans* and *E. delegatensis* which have the best hydrologic characterisation, and the mixed-species eucalypts are in higher rainfall areas than much of the Mitta Mitta. They are more likely to conform to the default LAI–conductance–age relationships. The prediction of total flows over the calibration period within 4% of the observed is good for a catchment of this size and vegetation complexity.

Table 4
Results for calibration and validation for the Thomson catchment. The numbers in the column headings refer to the first (1), second (2) or third (3) third of the whole period of record. For example, Calibration 2&3 refers to the calibration parameters for the second and third third, Validation 1 is the corresponding first third used for validation in this case.

Parameter	Calibration 1 & 2	Validation 3	Calibration 2 & 3	Validation 1	Calibration 1 & 3	Validation 2	Calibration ALL
E	0.799	0.763	0.750	0.847	0.810	0.736	0.788
% Mean	0.64	−12.1	−5.27	−0.48	−6.19	1.85	−3.61
% SD	6.16	−11.5	−0.46	3.66	−2.32	9.48	1.30
% Cv	5.48	0.73	5.08	4.16	4.13	7.50	5.10
PScalar	1.43		1.43		1.43		1.43
Hyd Grad	0.99		0.99		0.99		0.99

E = coefficient of efficiency; % Mean = percentage difference between the observed and predicted monthly streamflow means; % SD = percentage difference between the observed and predicted monthly streamflow standard deviations; % Cv = percentage difference between the observed and predicted monthly streamflow coefficients of variation, PScalar = precipitation scalar; Hyd Grad = hydraulic gradient.

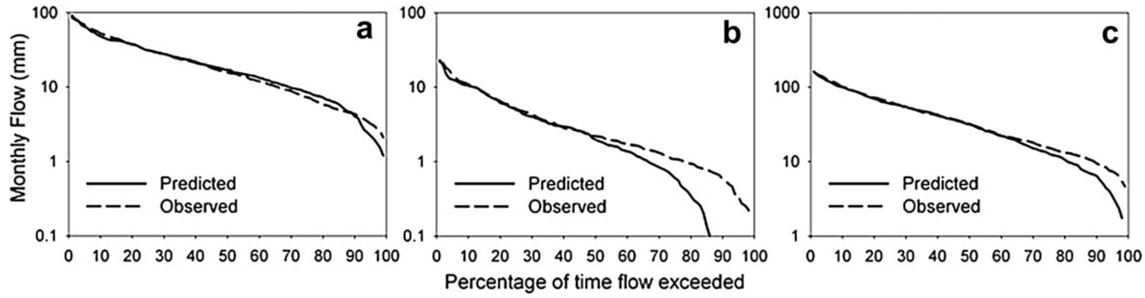

Fig. 5. Observed and predicted flow duration curves for (a) Mitta Mitta River, (b) Tambo River and (c) Thomson River.

6. Simulation of fire impacts

6.1. Input layers

6.1.1. Mitta Mitta and Tambo

An additional vegetation disturbance layer was produced to represent the post-2003 fire period, based on fire severity mapping (Fig. 7a–d). There were a number of issues to be resolved. The most important was related to the ecological response of eucalypts to fire. This response is not uniform, but is crucial hydrologically (see Eamus et al., 2006). A key issue was assigning the mixed-species eucalypts to either recovered or regrowth categories. Following some qualitative analysis of remotely sensed recovery data, all mixed species stands within Class 1 severely (crown burnt) and 60% in Class 2 (severe crown scorch) were considered to be regrowth stands. All *E. delegatensis* stands exposed to Class 1 and 2 were deemed to be dead (Fig. 6). Table 5 gives the resultant percentages of modelled regrowth. This distinction between recovered and regrowing forest means that the recovered stands are modelled as undisturbed, and regrowing stands are regarded as a single age stand regenerating from seed. This classification of "recovered" and "regrowth" and subsequent modelling as unchanged or regrowing was a pragmatic approach to a complex and poorly researched issue.

6.1.2. Thomson simulations and inputs

A set of simulations to explore fire and climate change scenarios for the Thomson were run as part of a study on potential threats to Melbourne's water supply. For the fire simulations, three scenarios were used (Fig. 7e,f); a subset of the 1939 fire comprising *E. regnans* and mixed-species eucalypts giving an 18% mortality(Fig. 7e), the 1939 fire mortality area and species distribution which resulted in 47% of the forest in the catchment classed as killed (Fig. 7f), and a 100% tree mortality scenario. As for the Mitta Mitta and Tambo fire scenarios, a single year representative climate was used for the 250 year runs. This time frame was used as it matches the forest life cycle represented in the conceptual curves of flow–age relationships for ash forests (Kuczera, 1987; Watson et al., 1999). For water resource considerations the first 50 years is the salient period.

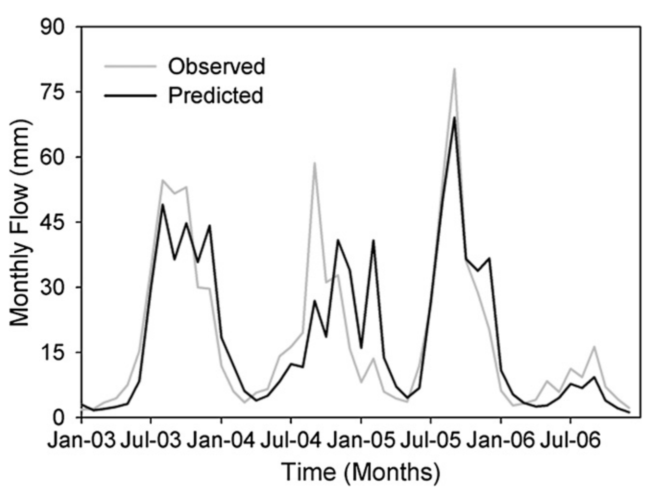

Fig. 6. Observed and predicted post-fire monthly streamflow for Mitta Mitta River.

Three climate change scenarios were also run (Fig. 8a,b). These were based on the rainfall (Fig. 8a) and temperature projections (Fig. 8b) produced by Howe et al. (2005) for the year 2050. Climate change projections for the Greater Melbourne Region were developed by CSIRO Atmospheric Research from Global Climate Models (GCMs) developed in-house and by international modelling groups and in-house Regional Climate Models (RCMs). The full methodology is given by Jones et al. (2004). The climate change scenarios were developed in consultation with the agencies principally concerned with water supply planning in Victoria and were deemed to be appropriate given the uncertainties around climate change projections (Feikema et al., 2007). The context of these climate inputs is to compare two "step changes" in streamflow forcings; fire and an altered climate. It is not to predict the effect of climate change on streamflow *per se*.

Briefly, the regionalised output from 11 GCMs was incorporated in the OzClim climate scenario generator (Page and Jones, 2001) and monthly climate patterns calculated from linear regression of each variable (e.g. rainfall, maximum, minimum and average temperature) from each grid square against mean global warming. These patterns were then linearly interpolated on to a 0.05° grid, generating monthly ranges of change as a function of global warming. The climate change projections had been developed using greenhouse gas emission projections and climate science as described in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (2001).

The projections represent the average reductions in rainfall, and increases in temperature that would be expected at 2050. It should be kept in mind that the climate sequences represented in the simulations in this study are not transient, and that they essentially are a 250 year period with "as at 2050 climate". For our simulations we used the predicted monthly changes in precipitation and temperature as scalars for daily model inputs; i.e. if January mean precipitation for the "Moderate" case is $-x\%$, then each daily rainfall total in January was scaled by $-x\%$.

The climate scenarios consisted of the slight (average annual reduction of 1.6%), moderate (average annual reduction of 7.1%) and extreme (average annual reduction of 13.8%) rainfall projections, each combined with the moderate temperature projection (+1.5 °C change in annual average temperature by 2050).

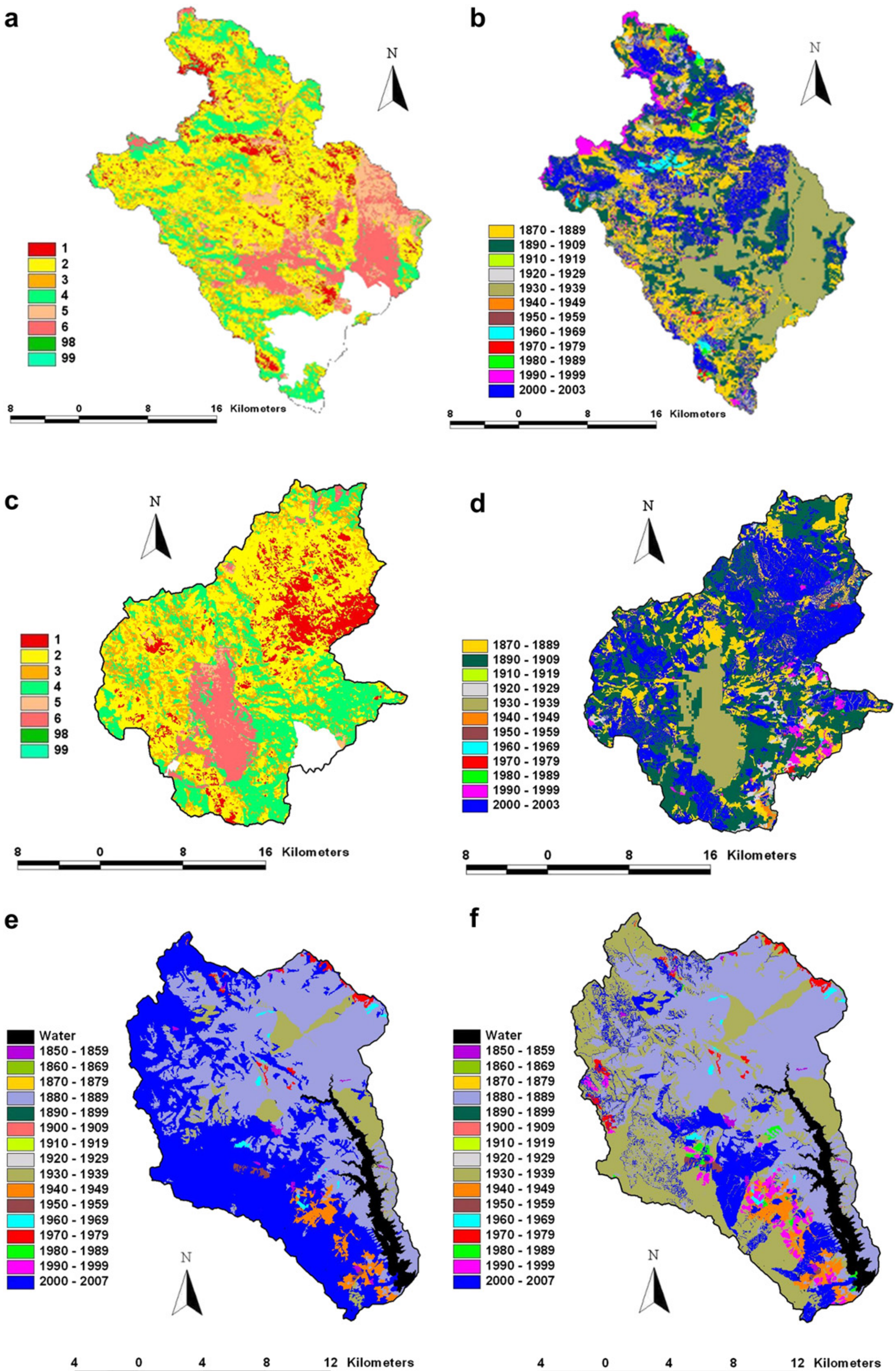

Fig. 7. (a, c) Maps of fire severity classes for Mitta Mitta and Tambo catchments, respectively and, (b, d) resultant age distribution for Mitta Mitta, and Tambo catchments, respectively. Fig. 6e,f is the age distribution for the 18% mortality and the 47% mortality scenarios for the Thomson catchment.

Table 5
Percentage area and species modeled as regrowth forest.

Catchment	Species				
	E. delegatensis	Mixed Sp	*E. pauciflora*	Other	Total
Mitta Mitta	5.20	20.90	5.02	0.11	31.24
Tambo	3.88	32.35	0.05	0	36.28

6.2. Mitta Mitta and Tambo simulations

The long-term fire impact was modelled by running a No-Fire and a Fire scenario for 250 years. A constant climate was imposed by repeating the precipitation and temperature from a single year for the 250 year sequence. The climate data were selected from the calibration period as the year in which the three climate base stations were all closest to the calibration period average. This single-year sequence means the modelled water balances are purely a function of vegetation. However it masks any impact of inter-annual climatic variability. Ideally the average climate based simulations would be replaced by a series of model runs driven by stochastic climate replicates, which could be averaged to determine the impact on water yield of vegetation disturbance. However, the significant time required to run such an analysis was beyond the scope of the paper, given that single model runs can exceed 5 h.

7. Simulation results

7.1. Mitta Mitta

Fig. 9 is the predicted yield for Fire and No-Fire scenarios for the Mitta Mitta. The maximum decrease in yield, reached 15 years after the fire, was 17% relative to the no-fire predicted yield. A 41% increase is predicted for the immediate post-fire year, declining rapidly to no-fire levels by year 4. The cumulative predicted decrease in yield is 10965 GL over the 250 year scenario, which is a 7% decrease overall. Perhaps more relevant is the 12% cumulative decrease in the first 50 years. A notable aspect of the simulated yield is the increasing yield from the No-Fire scenario. This is due to the decline in LAI and conductance as the forest ages. Interestingly, after 33 years the fire curve equals the No-Fire yield at year 1.

7.2. Tambo

The predicted response from the Tambo at Bindi (Fig. 10) is slightly greater than for the Mitta Mitta. The peak decrease is 21% 53 years after the fire, while the change over the full 250 year series is similar to the Mitta Mitta. The difference between the two catchments may be partly explained by the larger proportion of the catchment assigned regrowth forest in the Tambo. There is also the possibility that the calibrated parameters are unable to adequately represent the system, and the model is over sensitive to the scale of disturbance. A notable difference between the two catchments in both the observed and predicted curves is the very low initial flows, relative to the long term average, from the Tambo. The very dry conditions preceding the fire resulted in very low soil moisture stores. These stores were the initial conditions for the simulations and produced the early decrease in the No Fire curve. These results clearly have considerable uncertainty around them given the calibration performance.

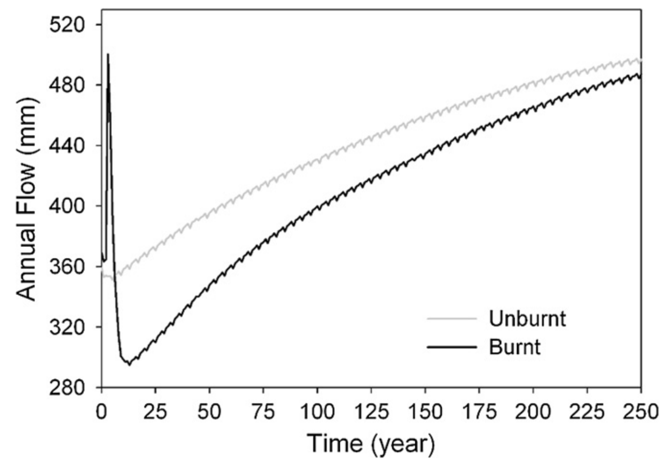

Fig. 9. Predicted long-term flow for Fire and No-Fire scenarios for the Mitta Mitta catchment.

7.3. Thomson

The results of the fire and climate change simulations were combined and shown in Fig. 11 as a cumulative percentage change from a no disturbance, no climate change case. That is, percentage increase or decrease in flow relative to a no disturbance/no climate change scenario. The simulations suggest that the very real threats of wildfire and of climate change pose potentially significant risks to long term water supplies in south eastern Australia. Cumulative impacts due to the simulated fire areas peak at −14% and −22% around year 34 after fire for the 47% and 100% mortality simulations, respectively. The 18% mortality simulation produced only a 4% maximum yield decrease. Fig. 10 suggests that climate change could, under the model inputs used, have a greater impact than

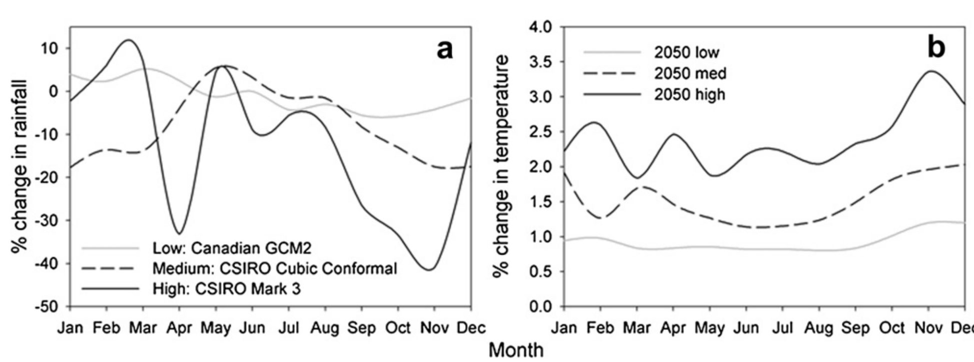

Fig. 8. (a) Estimated monthly percentage changes from long term rainfall for slight (least reduction), moderate and extreme projections under climate change in 2050, and (b) Estimated monthly percentage changes from long term temperature (degrees Celsius) for slight (coolest), moderate and extreme projections under climate change in 2050.

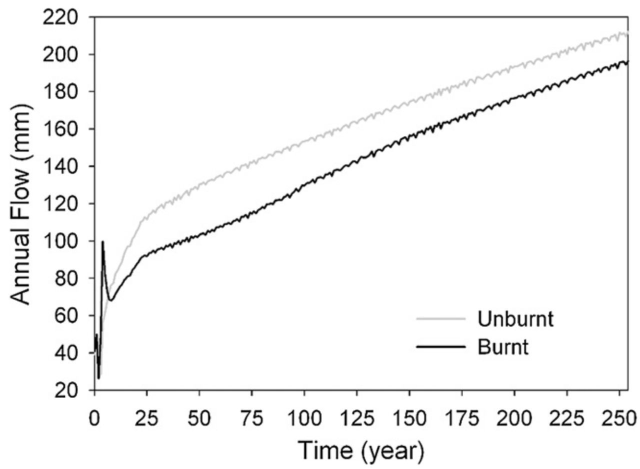

Fig. 10. Predicted long-term flow for Fire and No-Fire scenarios for the Tambo catchment.

even the most serious of wildfires, due largely to the diminution of rainfall. Whilst the first few decades exhibit the most divergence between the modelled scenarios, by continuing the simulations out to 250 years we can see the disturbance effect of the fire corrects gradually as the forest develops from young to mature. In contrast the climate simulations are on a different aged forest (mostly 70 years old at year 1) which means there is no initial flow increases to buffer the yield declines. The climate change simulations do not include the possible effect of rising CO_2 levels, which may lead to reductions in stomatal conductance and increases in water use efficiency (Arora, 2002).

8. Discussion

Macaque has the potential to be widely used in catchment management and water supply planning in Victoria. There is a vigorous community debate about forest management which includes harvesting and fire management. Currently much of the debate is ill-informed, and has been to some extent based on inappropriate use of the empirical "Kuczera curve" (Kuczera, 1987) that describes the catchment average age–water yield relationship for *E. regnans*. This curve described the 250 year age-yield relationship, showing a distinct yield decline as regenerating stands use more water than mature stands. The yield decline approaches 50% at around 25–30 years, relative to mature stands. This figure has often been invoked as the effect of any disturbance of any scale in forested catchments. A 50% reduction is highly unlikely for three reasons. First, the Kuczera data was from mature catchments which yield more water than the current 70 year old 1939 fire regrowth, which means the difference between the regenerating and the unburnt forest is much less. Second, the increase in flow that may be expected for some years after the fire has not been factored in to the total streamflow. Third, it is unlikely that 100% of a catchment will be Ash species that are entirely killed by the fire. Additionally it is not well known that there is not one, but a family of Kuczera curves.

However the modelling presented in this paper has demonstrated some shortcomings. Macaque was originally developed to model small (<100 km^2) catchments within a relatively limited climatic region. Application at far greater spatial scales where there is substantial variation in precipitation and related variation in vegetation may be pushing the limits of the model. The calibration results for the Mitta Mitta and Tambo may reflect these issues. The availability of precipitation data sets in remote mountainous areas is particularly problematic. The improvement in calibration-validation statistics with a 4-fold increase in rainfall station density strongly suggests this to be an important input parameter. Where such data are poor, a corresponding model performance is likely. The representation of fixed LAI and conductance curves for the various tree species is practical but crude (although still gives a better representation of eucalypt forest growth/ET dynamics at relatively large scales than other current models). Any spatial variation in these parameters is not captured. The assumption of similar LAI and conductance curves for a wide range of mixed species in also questionable, although pragmatic. Further, Macaque is not a coupled carbon-water model and as such does not describe the many possible interactions between climate parameters, forest growth, and water use. Consequently, the climate change scenarios are limited to biophysical interaction under current CO_2 levels. This can be regarded as a shortcoming, but the research that would enable the full biophysical representation of CO_2 effects and feedbacks for a range of species and environments is not yet available. Sensitivity analyses on conductance suggested that a 10% reduction led to a 7% increase in streamflow, relative to the modelled scenarios. The lack of knowledge on the ecohydrologic response of the majority of mixed eucalypt species to fire is of concern. This is a problem for any modelling of fire effects, not only for Macaque. Finally there are some questions around the timing of the LAI peak and the consequent modelled streamflow decline in the early post-disturbance years. There may be a lag in the streamflow response relative to the LAI peak that is not reproduced by Macaque (Watson et al., 1999; Bren et al., in press), although the model test on the Mitta Mitta was encouraging in this respect. This issue is less problematic for longer term yield predictions.

Despite these caveats we contend the modelling gives a credible prediction of the scale of yield impacts that may be expected under the modelling assumptions. The post fire "test" on the Mitta Mitta gave excellent results in terms of total flow for the few years that could be modelled However the longer term impacts cannot yet be explored. The simulations suggest there are potentially significant threats to water supplies under the modelled scenarios. Although the absolute values presented are subject to the model assumptions and uncertainty in input parameters, and the age of the forest at disturbance, the orders of magnitude are credible. The areas that can be affected by fire far outweigh other disturbances or landuse changes, and the ecological responses of the "ash" species in particular mean a substantial hydrologic impact is highly likely. Repeated fire events have been suggested as a likely outcome of a warming, drying climate (Bates et al., 2008). The effect of multiple events is to reset the vegetation "clock", potentially resulting in

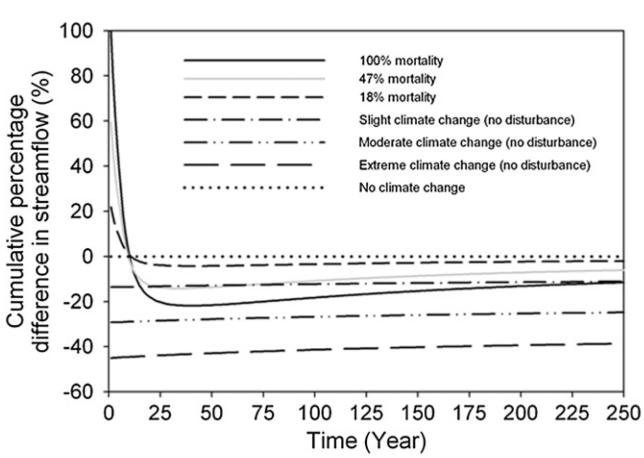

Fig. 11. Predicted cumulative differences in annual yield from an undisturbed condition for fire and climate change scenarios for the Thomson catchment.

a perpetually regenerating, high water using forest (unless the events are so close together that the forest is unable to reach canopy closure). The climate change scenarios suggest the impact of reduced rainfall and higher temperature could be of the same order as large fires. As the climate change responses are less driven by changes in ET than decreased rainfall, any additional disturbance such as fire that do result in relatively large increases in ET would compound the water yield declines. We did not simulate the combined effect of climate change and fire. The ecological response of forests to a combination of these impacts may be complex.

The impact on streamflows predicted by Macaque can be contrasted with "assumed" impacts of fire. While simulated values are not as catastrophic as a 50% reduction, streamflow declines of 20% in coming decades are not trivial. Even with errors around the predicted values, the simulations provide water managers with some guidance for future planning. The sources of uncertainty in Macaque highlight the difficulties in modelling complex mosaics of vegetation age, species, climate, soil and topography, and disturbances. However demands for spatially explicit models are increasing as water and forest managers deal with the new set of challenges brought by drought, fire climate change, and community concerns with logging. More research into the ecohydrologic response of a greater range of mixed-species eucalypts is urgently required to refine modelling of disturbances. Also required are tools for accurate remotely sensed estimation of LAI in complex forests.

The disturbance scenarios explored in this study can be extended to timber harvesting, or other vegetation changes in forests, providing there are adequate species–age parameters. An advantage over empirical models is the ability to spatially distribute the disturbance. This may be important where there are large rainfall gradients within the catchment. However Macaque requires significant time and familiarity to run, and may not be necessarily superior to simple models where input parameters are questionable.

9. Conclusions

The results from applying Macaque to large forested catchments were varied. Calibrations for the Mitta Mitta and Tambo were just satisfactory at best, while the model proved to be a good predictor of streamflow for the Thomson. In general the model performed better in terms of total flow than monthly flows. The better quality of rainfall input data and greater confidence in vegetation parameters in the Thomson are likely to have played a significant part in the improved model performance. Despite the calibration results, the model accurately predicted total flow in the Mitta Mitta catchment for the first 4 years after the fire. Simulations of actual and synthetic fire impacts suggest serious yield decreases in the first few decades after a large fire event. The coarse climate change scenarios for the Thomson indicated changes in rainfall and temperature could prove more deleterious to water supply than severe fire.

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