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Welcome from Editors

It is our pleasure to bring to you the compiled papers from the Research Forum of the AFAC and Bushfire CRC Annual Conference, held in the Perth Exhibition and Convention Centre on the 28th of August 2012.

These papers were anonymously referred. We would like to express our gratitude to all the referees who agreed to take on this task diligently. We would also like to extend our gratitude to all those involved in the organising, and conducting of the Research Forum.

The range of papers spans many different disciplines, and really reflects the breadth of the work being undertaken, The Research Forum focuses on the delivery of research findings for emergency management personnel who need to use this knowledge for their daily work.

Not all papers presented are included in these proceedings as some authors opted to not supply full papers. However these proceedings cover the broad spectrum of work shared during this important event.

The full presentations from the Research Forum and the posters from the Bushfire CRC are available on the Bushfire CRC website www.bushfirecrc.com.

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The effects wildfire on water yield and its relationship with vegetation response

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Abstract

The response of vegetation regrowth and water yield after a wildfire is dependent on factors such as fire intensity, climate and vegetation type. Australian woody vegetation species have evolved two mechanisms for surviving fire disturbance; i) seed germination (obligate seeders) and ii) resprouting from dormant vegetative buds and/or lignotubers (obligate resprouters). The majority of post wildfire vegetation response studies have been conducted in Victoria, Australia and have been in obligate seeder dominant communities. These studies have found that there is a significant delay in vegetation regrowth as they rely on the seed bank, whilst also finding there is a significant change in water yield post-wildfire. Those studies are not representative of the vegetation in the Sydney Basin, which is dominated by obligate resprouter species. This study examines vegetation recovery and its potential effects on water yield in a burnt subcatchment of the Nattai River, which was affected by wildfire in 2001/02. The study used was designed to detect i) changes in vegetation growth during recovery and ii) establish if these changes corresponded with changes in water yield. The first approach used an 18 year time series of Landsat data to assess annual vegetation 10 years pre-wildfire and 8 years post-wildfire. Several vegetation indices were compared to assess the health and integrity of eucalypt forests and woodlands (NDVI, NDVIc and NBR). The second approach used weekly rainfall, water yield and temperature data over an 18 year time series. A generalised additive model (GAM) was used to create a water yield model and change in water yield was detected through the use of prediction intervals and error plots. Results show that there was no significant impact on vegetation or water yield following wildfire as both recovered within 8 years.

Introduction

Wildfire plays an important role in modifying vegetation communities. Vegetation communities regenerate by the production of seedlings from seeds (obligate seeders) or by vegetative buds that resprout from the stem and branches and/or lignotubers of plants (obligate resprouter). The response of vegetation communities to wildfire is dependent on many factors such as the fire intensity, burn severity, climate, light and nutrient availability, and species type (Williams, 1995; Wright and Clarke, 2007).

Many recent studies have attempted to quantify the impact of wildfire on vegetation regrowth (Diaz-Delgado et al., 2002; Hernandez-Clemente, 2009; Jacobson, 2010; Lhermitte et al., 2011). This has been achieved through the use of remote sensing data, in particularly Landsat TM imagery. Remote sensing is used to analyse vegetation recovery by implementing various vegetation indices into the analysis, including: Normalized Difference Vegetation Index (NDVI); Normalized Burn Ratio (NBR); Enhanced Vegetation index; and Leaf Area Index (LAI).

Previously, NBR has been used to determine post-wildfire burn severity (Tanaka et al., 1993) and has now been incorporated into many studies to generally determine the annual vegetation regrowth (van Leeuwen, 2008). More recent studies have also incorporated the use of NDVI which has been demonstrated to display similar spatial patterns to NBR (Epting et al, 2005; Lhermitte, 2011). Diaz-Delgado et al. (2010) studied the 1994 wildfire which occurred in the province of Barcelona, Spain using Landsat TM and MSS images. By using the NDVI it was found that there was an immediate response by shrubland and oak tree woodland due to their reprouting capabilities. Aleppo pine forests, in comparison, were found to have a slow recovery due to the limited availability of a seedbank.

In this study Landsat imagery has been used to assess the recovery of vegetation regrowth post-wildfire. The results from the analysis of vegetation recovery were then used in the interpretation of wildfire-effects on water yield. Previous studies in Australia have examined water yield response post-wildfire and have found that a decline in water yield occurs in the first 3-5 years followed by slow recovery (Langford 1976; Kuczera, 1987). However, these studies have been located in communities influenced by obligate seeders. This study, in comparison, is located in the outer Sydney Basin which is influenced by obligate resprouter species. The aim of this study is to determine the relationship between water yield and vegetation recovery following wildfire (in a resprouter dominated forest), and establish if water yield and vegetation recover within eight years post-wildfire.

Study area and methods

Study area

This study focuses on the Nattai River subcatchment which was burnt during the 2001/2002 summer wildfire event in the outer Sydney Basin, Australia (Fig. 1). A total of 57% (47740 ha) of the subcatchment was burnt.   Nattai River subcatchment delivers water to Sydney's main water reservoir, Lake Burragorang, which supplies 80% of the drinking water to the Sydney region.

The underlying geology of the region consists of Triassic sandstone plateau with Narrabeen mudstone embedded throughout. Tenosols, Kandosols and Kurosols are the dominant soils throughout the Nattai River subcatchment (Isbell, 2002). Dry sclerophyll forests and shrubby woodlands are dominant with moist sclerophyll forest and rainforest communities present within the valleys (Keith, 2006).

The study area has a warm temperate climate with an overall average minimum summer temperature of approximately 15°C and average maximum temperature of 28°C. Summer is generally more moist than winter. Mean annual rainfall across the study area ranges from 700 - 1400 mm per annum (BOM, 2010). Twelve months before the 2001/02 wildfire the study region experienced drought conditions, associated with El Niño- Southern Oscillation (ENSO).

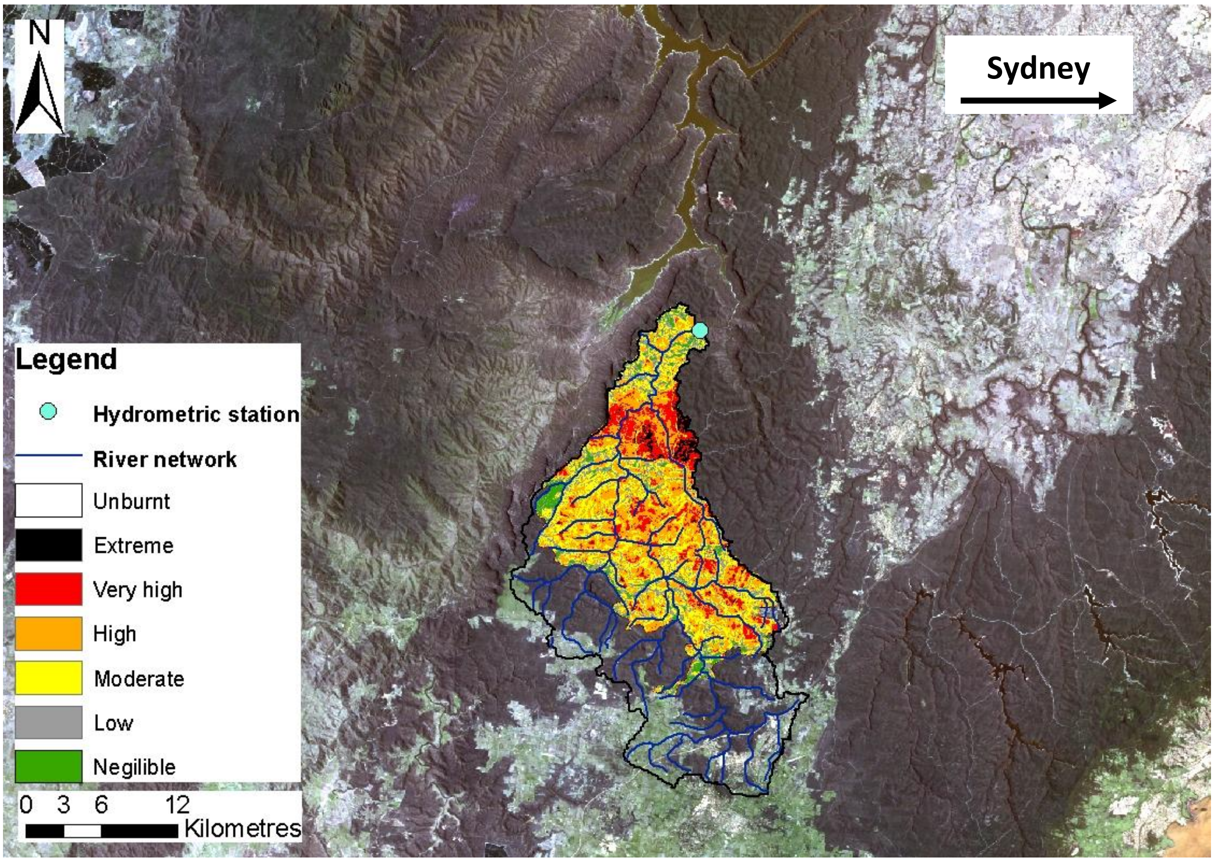

Figure 1. Nattai River subcatchment; This map also provides details on the location of the hydrometric station, river network and the different burn severity classes.

Vegetation analysis

Image processing

A wildfire severity map derived from differenced Normalised Difference Vegetation Index (dNDVI) was extracted from the work of Chafer et al (2004) (Figure 1). In order to assess the regrowth of vegetation following the summer 2001/2002 wildfire, one Landsat image for each summer between 1990/1991- 2009/2010 was obtained from either SCA or downloaded from Glovis (USGS, 2012). Spectral bands 1-5 and 7 were then stacked to form one composite image. Top of atmosphere (TOA) correction was used to create a spectral radiance. This involved a two step process.

The first step converted the digital Number (DNs) values to spectral radiance values through the use of bias and gain values for each of the Landsat scenes (equation 4):

$$L = \alpha D_n + \beta, \qquad (4)$$

where L = spectral radiance values, α is the gain and β is the recalled bias.

The second step converts the radiance to ToA reflectance (equation 5).

$$\rho_0 = \pi * L_0 * d^2 / E_0 * \cos \vartheta_z, \qquad (5)$$

where ρ_0 = Unitless plantary reflectance, L_0= spectral radiance, d = Earth-Sun distance in astronmoical units, E_0 = mean solar exoatmospheric irradiances and θ_z = solar zenith angle.

Each Landsat image was then reprojected to the correct spatial reference (GDA_1994 Mga zone 56) and clipped to a smaller area around the catchment to allow for faster processing.

Spectral indices

The Normalized Difference Vegetation Index (NDVI), the corrected Normalized Difference Vegetation Index (NDVIc) and the Normalized Burn Ratio (NBR) was calculated for each scene, as we believe these are more precises than other metrics for studying vegetation recovery.

The NDVI is the most common vegetation index used when assessing vegetation recovery post-wildfire as it is sensitive to fractional changes in vegetation cover. The NDVI is calculated by the reflectance of the red and near-infrared (IR) portions of the spectrum, which are characteristic of many common surfaces (Chen, 2011; equation 6).

$$NDVI = \frac{near\ IR - red}{near\ IR + red} \tag{6}$$

The NDVI values range from -1 to 1, with areas occupied with large vegetation canopies having higher positive values i.e. 0.75. The pixel values may be affected by the atmosphere causing a decrease in the NDVI values (Tachiiri, 2005). Therefore, NDVI can be estimated after the appropriate atmospheric correction takes place, causing the replacement of the NDVI values with NDVIc values (equation 7).

$$\mathrm{NDVI_c} = \frac{\mathrm{near\ IR - red}}{\mathrm{near\ IR + red}} * \left(1 - \frac{\mathrm{mIR - mIR_{min}}}{\mathrm{mIR_{max} - mIR_{min}}}\right) \tag{7}$$

where mIR refers to one of the middle-infrared bands (bands 5 or 7).

The NBR integrates the use of both near infrared (NIR) and mid-infrared (SWIR) (equation 8).

$$NBR = \frac{(NIR - SWIR)}{\left((NIR + SWIR)\right)} \tag{8}$$

Similar to the NDVI/ NDVIc, NBR also has values ranging from -1 to 1.

Water yield

Data processing

In this study we used weekly discharge, rainfall and temperature data for the period January 1, 1991 to January 31, 2010. Data was excluded for the first year post-wildfire due to malfunctioning of the hydrometric station. The study therefore focused on the medium term impacts, using 10 years of pre-wildfire (1991-2001) and 7 years of post-wildfire data (2003-2010).

Hourly discharge data and rainfall data was acquired from Sydney Catchment Authority (SCA). Discharge was measured using a flow meter installed at the outlet of the subcatchment, whilst rainfall data was obtained from two rainfall gauges which were used to create a spatially weighted average of rainfall (Yoo et al., 2007). The maximum daily temperature was obtained from the Bureau of Meteorology (BOM, 2010). All data collected was aggregated into weekly total rainfall and water yield, and weekly average maximum temperature.

Modelling approach

In this section we are concerned with detecting a change in water yield. The modelling approach first involved calibrating a statistical model for the pre-wildfire period (January 31, 1991-December 16, 2001). A generalized additive model (GAM) was used in the Mixed GAM Computation Vehicle (mgcv) package in R (Wood, 2011). The model consists of four predictor variables including rainfall, maximum temperature, lagged water yield and lagged rainfall. The pre-wildfire water yield model was used to predict the post-wildfire water yield. Systematic differences in the residuals of the predicted and observed post-wildfire water yield could then be attributed to wildfire effects.

GAMs were preferred over other models due there greater flexibility when compared to standard parametric models such as the generalized linear model (GLM) (Hastie and Tibshirani, 1990) as GAM can model the non-linear relationships between rainfall and runoff. The most general form of the GAM is:

$$E(Y) = f(X_1, ..., X_p) = s_0 + s_1(X_1) + ... + s_p(X_p), \quad (1)$$

where Y is a random response variable; X_1, ... , X_p is a set of predictor variables;and $s_i(X)$, i=1, ..., s_p are smooth functions.

A log normal model (Equation 2) using thin plate splines was used (Wood, 2003). The smoothing parameters were selected using restricted maximum likelihood (REML).

$$\log(y) = \beta_0 + \sum_{i=1}^{n} s_i(X_i) \quad (2)$$

where s_i is the i^{th} thin plate smoothing spline, X_i is the i^{th} covariate.

Goodness-of- fit

The goodness-of-fit (GoF) of the pre- and post-wildfire model was tested by using the Nash-Sutcliffe coefficient (NSE) (Legates and McCabe Jr., 1999; Nash and Sutcliffe, 1970). The NSE is a normalized statistic which determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970). Due to the sensitivity of NSE to outliers and the difficulty of modelling large flow events, the modified NSE (mNSE) was also used (Legates and McCabe Jr., 1999). The efficiency test values for both the NSE and mNSE range from $-\infty$ to 1. Efficiency test values of 1 (E=1) correspond to a perfect model, while an efficiency value of less than zero (E < 0) indicates the observed mean is a better predictor than the model (Krause et al., 2005).

Change detection

A number of indicators of change due to wildfire were considered. One method of detecting change used between pre- and post-wildfire periods was to plot the modelled predictions and observations for the post-wildfire period and look for deviations. The advantage of a statistical model is that the standard error of prediction can be used to create the 95% prediction interval (PI). If many of the observed data fall outside the PI range it would indicate there is a large difference between the observed and predicted water yield.

An alternative method is to plot a residual error model through time. A systematic pattern in the error plots would suggest a systematic change in water yield. Based on previous Victorian studies, it would be expected that a pattern may form to resemble that of the Kuczera curve, where by a sudden decline in water yield occurs post-wildfire and then begins to recover from about 25 years post-wildfire to pre-wildfire conditions (Kuczera, 1987). Modelled error showing a random scatter would indicate that wildfire had no impact on the post-wildfire water yield. A smooth spline was fitted to the error in order to aid in identifying whether there was a trend in the model error.

Results

Vegetation recovery

The reason for analysing vegetation response post-wildfire is to establish if the vegetation has recovered according to the regrowth of the vegetation canopy. Pre-wildfire data was required to determine the time frame it took for burnt vegetation to return near its pre-wildfire conditions. This study used Landsat imagery from the summer of 1990/1991 to the summer of 2009/2010. Three vegetation indices were implemented to assess the regrowth of vegetation in this period (NDVI, NDVIc, and NBR; Figure 2). The NDVI graph shows values in the pre-wildfire period ranging from 0.77 to 0.85% (Figure 2a). Once the 2001/2002 wildfire event took place, the NDVI declined to 0.64%. Within 6-12 months post-wildfire the NDVI graph suggests vegetation recovered rapidly with a NDVI of 0.71 %. After two years post-wildfire the vegetation had returned to pre-wildfire conditions with a NDVI of 0.81%.

The NDVIc and NBR have lower vegetation indices values during this period when compared to the NDVI values, and display a slightly different trend in the post-wildfire period (Figures 4b and 4c). Both NDVIc and NBR displayed vegetation indices above 0.4 % in the pre-wildfire period and increased to 0.49 % and 0.74 for NDVIc and NBR, respectively. Both indices show an obvious decline in vegetation for the 2001/2002 summer (with a value of 0.35% for NDVIc and 0.32% for NBR). Both indices indicate that it takes up to five years for vegetation to reach pre-wildfire levels.

Water yield

The key point of the water yield test was to determine if there was a change in subcatchment hydrology post-wildfire. The goodness of fit between the models was produced and observed values were investigated. In the case of Nattai River, the model was the better predictor over the mean of the observed data as the NSE value is > 0. Within the pre-wildfire period, Nattai River had a NSE value of 0.16 and a mNSE value of 0.41, whilst in the post-wildfire period there was less variation (NSE value of 0.40 and mNSE value of 0.35). Since the NSE and mNSE remained high in the post-wildfire period, there was no substantial change in the quality of the model predictions.

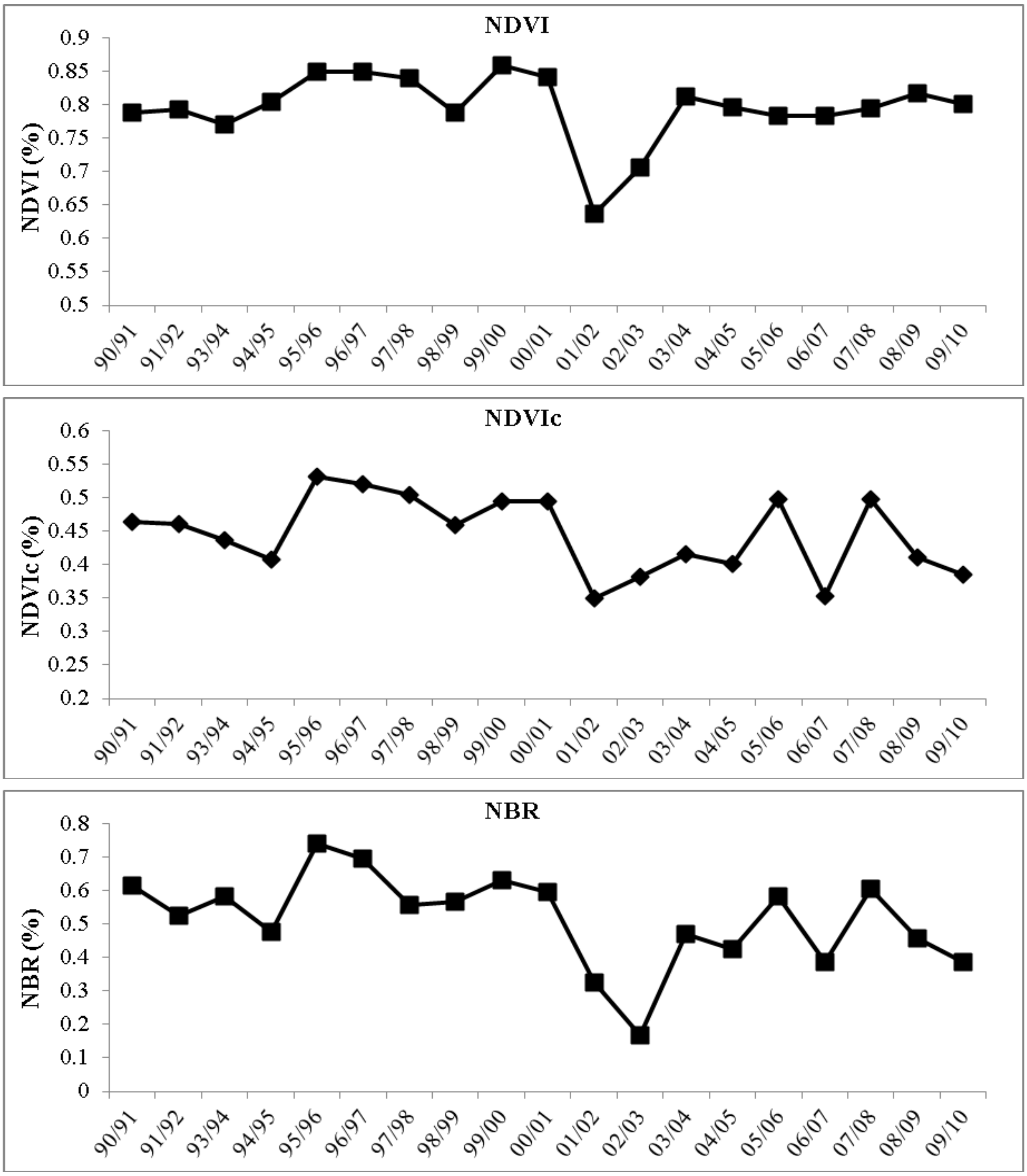

Figure 2. Vegetation growth from summer 1990/1991-2009/2010 using four different vegetation indices including a) NDVI; b) NDVIcand c) NBR.

The 95% prediction interval graphs were used to detect change in hydrology in the post-wildfire period (Fig. 3). In this case, the Nattai River showed some variation between the observed and predicted water yield in the 95% PI graphs. The median error value on the log scale for the Nattai River was -0.87, whilst the exponent of this was 0.42 meaning observed data matches predicted data was within 42% on average predictions, indicating water yield was generally over predicted. Variations between the two occurred primarily in dry years when flow flows occurred or the model predicted flow when the observed water yield was zero. For instance, in 2006, 21.6% of the data fell outside the lower 95% PI range. This is mainly due to zero flow being recorded as indicated by the flat observed line being situated below the lower 95% line.

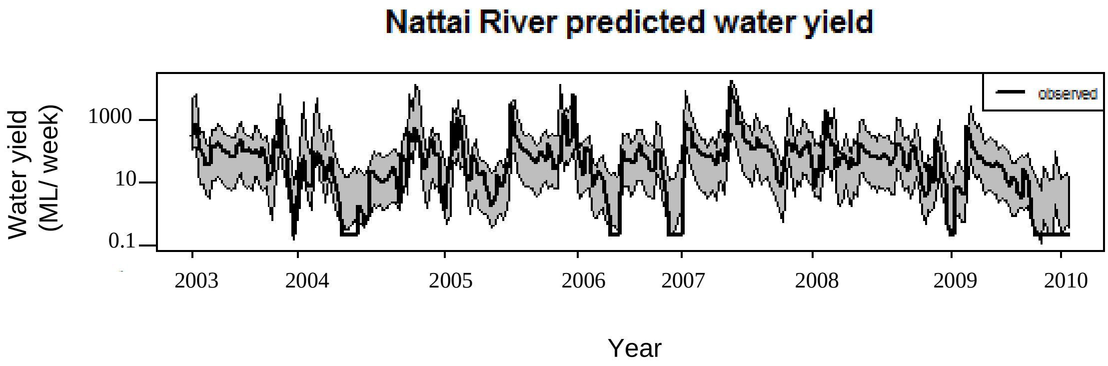

Figure 3. Nattai River 95% prediction interval for water yield post-wildfire

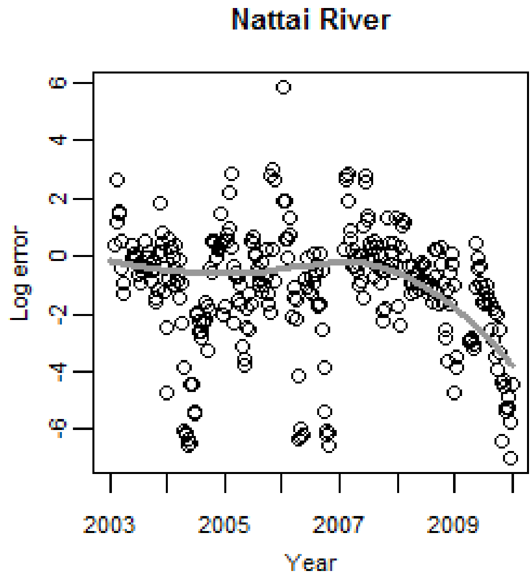

Figure 4. Nattai River error plot, displaying the overall trend in error post-wildfire.

In this instance, a small systematic shift in water yield data is seen to occur post-wildfire as the smooth line curve is less than zero on the log error axis (Fig.4). Such a shift could be a result of the model being parameterised for non-drought years, whilst the post-wildfire period underwent drought conditions due to the presence of El Nino. This would have caused a change in water yield and therefore a change in the smooth line. The smooth line is flat until the end of 2007, where it then begins to steeply decline. This decline suggests that the model is over predicting water yield and becomes higher the closer to 2010.

Discussion

Wildfire is evident throughout previous worldwide studies to have a detrimental effect on the different environmental values within a catchment (Certini, 2005; Wilkinson et al, 2006), through changes in soil chemical, physical and biological properties, change in water yield and destruction of vegetation. However, each of these values has only generally been studied individually, and the impact of wildfire on each value has only been investigated immediately post-wildfire (Doerr et al., 2004). In comparison, this study measured change vegetation regrowth post-wildfire through remotely sensed data and examined change in water yield post-wildfire, over an 18-year period to determine if both have a similar response to wildfire, hence have some form of a relationship.

The study developed a Generalized Additive Model (GAM) of water yield to predict the expected water yield of the burnt catchment during the post-wildfire period. The use of the GAM to examine the response of the Nattai River subcatchment has proven to be a practical method to use when forecasting a catchments normal water yield regime within eastern Australian. As water yield is constantly being influenced by external factors, limitations occurred when establishing a model. Villarini et al. (2009) found similar limitations in their GAM based model when attempting to predict high flow events in the Little Sugar Creek watershed located in North Carolina. In Nattai River, the water yield was could have been influenced by El Niño conditions in the post-wildfire period. This process would have continued until 2007 when El Nino conditions weakened, slowly being replaced by a La Nina event. Most of the error which occurred in model was due to extreme water yield values being predicted in response to high rainfall events. Therefore, as we are interested in the medium term changes in water yield, a NSE and mNSE value greater than 0.35 in the post-wildfire period displays a good fitted model.

The removal of vegetation within a catchment can have adverse impacts on water yield (Brown, 1972; Langford, 1976; Cornish and Vertessy, 2001). Bailey and Copeland (1961) show that with ground coverage of about 37%, 14% of rainfall contributes to runoff. With only 10% ground cover, 73% of rainfall contributes to runoff, suggesting that less ground cover causes an increase in water yield levels. According to the Kuczera curve (Kuczera, 1987), once vegetation re-growth begins, a decline in water yield should occur as immature vegetation requires a higher water intake. However, within the Nattai River there was no evidence of changes in water yield due to wildfire.

The changes in water yield which occurred post-wildfire could be strongly influenced by the quick recovery of the vegetation communities within the Nattai River subcatchment.

According to Chafter et al. (2004) and Chafer (2008) the initial shrub understory which contributes to ~80% of fuel within a eucalypt community (Chafer et al 2004, Chafer, 2008) would have rapidly regrown within months post-wildfire allowing for a short recovery period. This is evident in Figure 4a-c, as vegetation recovers to pre-wildfire levels within 2-5 years post-wildfire. The minimized impact on water yield is a result of the vegetation recovery method. The dominant species in this catchment are classed as obligate resprouters. These species rely on the growth of their vegetative buds, which resprout on the stem and branches of the plants within weeks to months post-wildfire, to recover. Such immediate regrowth means water is consumed by vegetation immediately post-wildfire, but not in significant amounts as mature vegetation only requires water for new leaf development. This is different to the studies conducted within the Melbourne water catchments as they are classed as obligate seeders and rely on the seedbank to produce new seedlings (Langford, 1976). This can take months to years for seedlings to occur as they rely on the right climatic conditions. Furthermore, as the seedlings grow they require more water than mature plants resulting in more water being taken out of the catchment for vegetation growth. This would cause a larger change in water yield to occur within the Melbourne catchments in comparison to the Sydney Basin water supply catchments.

A change in both water yield and vegetation took place by the 2007/2008 summer which is influenced by the change in climatic conditions as the transition from El Nino to La Nina conditions took 10 months arriving in early-mid spring 2007 (Hope and Watkins, 2007). By November, eastern Australia received above average total rainfall. La Nina event dominated summer 2007-2008, peaking in February 2008 (Wheeler, 2008). However, El Niño followed in winter 2009 but was only present until August 2009, leaving Australia with serious rainfall deficiencies (Jakob, 2010). This clearly had an impact on the Nattai River subatchment as water yield began to be overestimated in the GAM model due to its decline (especially at zero flow). This is evident in both the PI graph (Figure 3) and in the error plot as the smooth line drastically declines (Figure 4). This change in climate also impacted the catchment vegetation as all vegetation indices values declined for summers of 2008/2009 and 2009/2010. Therefore, such changes are not due to the wildfire event, but the environment responding to external climatic factors.

To further develop a better relationship between water yield and vegetation additional studies need to be conducted to compare other burnt catchments and unburnt catchments within the Sydney Basin to determine if a similar response is found. However, due to the limitations of the availability of Landsat data, statistical analysis to assess the relationship between water yield and vegetation is complicated. Therefore, another option could be to assess Moderate Resolution Imaging Spectroradiometer (MODIS) imagery over the same period as it is more readily available. From this possible statistical methods could be implemented to assess this relationship. Findings from such studies could provide environmental agencies and stakeholders with significant information about the response of catchments post-wildfire, which could help develop and plan future strategies in post-wildfire events.

Conclusion

In conclusion, the Nattai River subcatchment did not produce a smooth spline curve which had a similar trend to the Kuczera curve, suggesting it had very short recovery period. Further to this, the vegetation indices used in this study demonstrate that a significant degree of modifications within vegetation communities occurred immediately post-wildfire and was further exacerbated by the effects of El Niño. However, a steady increase in vegetation indices suggests a quick recovery of vegetation, achieving close to pre-wildfire values within 3-5 years. This in effect shows that the Sydney Basin water supply catchments obligate resprouter species have a much faster recovery time than the Melbourne water supply catchments obligate seeder species (Langford, 1976; Kuczera, 1987). Therefore, information provided from such a study can help catchment management agencies and stakeholders understand the response of a catchment after a wildfire event and help further develop new strategies for future wildfire events.

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