Bushfires and its implication on water supplies in Victoria, Australia

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Abstract — Australian bushfires have the ability to change the catchment landscape quickly and dramatically. These changes yet can lead to significant changes in both quantity and quality of water yielded. This investigation was conducted to determine the climatic conditions that lead to major bushfires and the response of catchments in Victoria. This was achieved by investigating the Dartmouth, Corryong and Buchan catchments that were burnt out during the 2003 Alpine bushfire.

Two main climatic patterns El Nino Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) play a major role in controlling the weather in eastern Australia. Both negative ENSO and positive IPO tend to exhibit hot drier periods and vice versa. It was found that the bulk of major bushfires occurred during periods of positive IPO and negative ENSO. However the relationship between IPO and ENSO was not strong enough to predict the occurrence of bushfire. Following bushfire the streamflow typically increases due to the reduction in evapotranspiration for 1 to 5 years, followed by a reduction as the forest regrows for 20 to 30 years, then returns to pre fire levels in 120 to 150 years. The magnitude of this reduction though varies widely depending on the type of vegetation, the age of the vegetation and severity of the fire would have profound impact. A recent model was used to predict the changes in streamflow and compared to actual changes that had occurred in the years following the fire. It was found that many measures of water quality like turbidity, nitrogen, phosphorus, suspended solids and nitrate levels have deteriorated significantly. It was found that the probability of exceedance of a critical value for the majority of the measures increased following the fires. Changes in water quality have the ability to make water supplies unfit for household purpose. Water authorities though have certain measures they can undertake measures that can be taken before, during and after the fires.Keywords—component; formatting; style; styling; insert (key words)

Keywords — bushfires, Victoria; ENSO; IPO; streamflow; water quality; stormwater.

I. INTRODUCTION

Landscape altering bushfires are common place on the east coast of Australia. Bushfires are occurring during periods of high daily temperatures, high wind and low relative humidity. The inextricable link between bushfires and climate has been shown by many researchers throughout the years including [1-3]. While the links between temperature, precipitation and humidity have been proven by all these researchers, this is of limited value if one is unable to predict when these conditions will occur. Recent research therefore has been into what weather phenomena are responsible for producing these conditions. Two climatic phenomena that are thought to increase the risk of fire are the El Nino Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). These phenomena make the Australian climate warmer and drier than average [4]. References [5-6] stated that during an ‘El Nino’ phase the inland eastern side of Australia will have temperatures higher than average with precipitation being lower than average, while a ‘La Nina’ phase will consist of temperatures lower than average with precipitation that is higher than average.

Reference [7] found a strong relationship existed between the ENSO and the calculated fire risk in Victoria. Similar research by [8] into eight sites across Australia found that at the majority of sites, with the strongest results occurring in south east Australia that a more severe season of fire danger exists, with twice as many days with high fire danger occurring, when the Southern Oscillation Index (SOI) is negative compared to when it is positive. This conclusion that a negative SOI leads to increased fire danger now appears to be the general consensus.

Reference [9] explains that when the IPO is in positive range temperatures warmer than average can be expected and vice versa in Australia. The IPO has also been found to be related to the ENSO. Reference [9] states that the IPO modulates inter-annual ENSO related climate variability over Australia due to strong link between ENSO and positive IPO events. Reference [10] similarly found that during positive IPO events the occurrence of intense El Nino events is more regular which as discussed have a high correlation with producing drought conditions leading to worse bushfire conditions. Therefore many researchers believe that a positive IPO event matched with an El Nino or positive Southern Oscillation can be an indicator that a serious risk of bushfire could occur during the summer season ahead. Reference [4] investigated this theory and found that most of the serious bushfires that have occurred in Canberra over the last century correspond with a positive IPO and positive SOI.

As can be seen above there appears to be a strong connection between the climate and certain climate phenomena and the bushfire risk and the actual occurrence of bushfires. This study will focus on the occurrence of bushfires in Victoria, and determine if there is a correlation with IPO and ENSO. If a correlation did exist this would allow authorities to introduce measures in seasons that are expected to be of high bushfire threat to protect important water resources or attempt to minimize the impacts that could result from bushfires occurring in catchments.
Recent history has shown us that these fires quite often threaten major cities with recent bushfires threatening Sydney in 2001, Canberra in 2003 and Melbourne in 2009. The effect of these bushfires on the catchments that supply water for these capital cities are of great concern for governments and water authorities alike. This concern raised by bushfires is greater when the majority of the city’s water is sourced from forested catchments. An example of this being Melbourne where almost 100% of the city’s water for more than four million people is sourced from forested catchments.

Bushfires can result in the reduction of catchment vegetation and lead to increased catchment pollution from the ash and burnt litter generated by the fire [11]. This can result in changes to the water yield that is obtained from the catchment. This usually consists of an initial increase followed by a substantial decrease in the water yielded [12]. Along with this water turbidity and ion concentrations within the water can increase [4]. This presents a major concern for the reliability and drinkability of water being supplied to cities.

Reference [13] explains that Mixed Species Eucalyptus are better adapted to survive a bushfire while Eucalyptus Regnans which is more commonly known as Mountain Ash are more likely to be killed in fires. As further explained by [14] the seeds that have been released by the Mountain Ash in a fire begin growing into dense stands of seedlings. As the Mountain Ash seedlings get more mature they begin to compete with fellow seedlings for light, water and nutrients. This results in a natural thinning of trees over time. These dense stands of seedlings generate large amounts of evapotranspiration. Mixed Species in comparison can survive the majority of fires. This leads to a situation where many mature survivors can choke out the developing seedlings that have germinated from the released seeds by blocking sunlight to them. This results in the Mountain Ash forests to possess extensive even aged stands in which the trees will vary widely in age. Reference [10] explains that it is this distinct change in density with respect to the age of the Mountain Ash stand that produces vastly different levels of evapotranspiration and hence streamflow and water yielded.

One of the first to investigate the changes of water yield following bushfires in Mountain Ash forests was [15]. Reference [15] investigated the response of the Maroondah catchment in Melbourne to severe fires that occurred in 1939 where large proportions of the predominate species, Mountain Ash, was burnt out and caused to regenerate. It was found that the replacement of the largely mature Mountain Ash forest with a new regrowth forest resulted in a reduction of water yields starting from about 3-5 years after the fire and peaking around 15-20 years after the fire. Reference [15] was able to develop a simple linear formula to predict the expected reduction in runoff in a catchment based on the percentage of the forest that had been regenerated by the fire and the percentage of the fire that is mixed species. The research though has drawn some criticisms from others including [13, 16]. Reference [16] explained that the model was developed using only 4 groups of streamflow data. This results in errors occurring when the model has to extrapolate to predict results for catchments whose characteristics fall outside that of which it was developed with. Similarly under some conditions, that is when the catchment has 100% mixed species, the model predicts an increase in runoff in the short and long terms. Reference [13] explains that [15]’s research findings that some catchments while having large portions of regrowth did not have significant reductions in streamflow could be attributed to other factors like the researcher didn’t have access to a complete data set when he was conducting his investigations. Reference [13] also believed that climatic variability could also be masking the true changes that were occurring in streamflow data. These criticisms and the availability of more complete data sets were the basis for further investigations.

When further data became available, [13] believed that reassessment of earlier research was important. Reference [13] similarly to [15] focussed his study on Mountain Ash forests as against Mixed Species Eucalyptus due to the way in which they respond to fire. Reference [13] believed that the age of the Mountain Ash tree before and after the fire would have a large impact on the reductions that would occur to streamflow following the fire. Mountain Ash forests required vast amounts of water when young due to the vast amount and rapidly growing young trees increasing evapotranspiration. As the trees mature though they start to thin out as they fight for survival and growth rates decline resulting in a decrease in evapotranspiration. Reference [13] therefore believed that the linear model proposed by Reference [15] was unsatisfactory as it was unable to incorporate these changes in age. Reference [13] therefore developed a two parameter exponential model to describe the reduction in water yield. The model developed allowed for the different characteristics of the catchment to be incorporated in the model while describing streamflow as function of the forest age. The model developed though did not take into account the initial increase in water yield that is seen in forests in the years directly following a fire. This lead to criticism of the model and was to form the basis of future research.

Reference [12] developed a model that was able to overcome the shortcomings of [13] and incorporate these initial increases in streamflow that are seen following fires. These increases in streamflow are attributed to the reduction in evapotranspiration due to the removal of large amounts of foliage. The model developed by [12] was also based on the Maroondah catchments and has four terms that provide a flexible way of interpolating long term patterns of important variable such as Leaf Area Index (LAI), water yield and evapotranspiration. By combining the terms the initial increase in streamflow in the 1 to 3 years following the fire can be captured followed by the large decrease in streamflow peaking between 20 to 30 years after the fire. Some criticisms though have been raised of the model due to the large number of parameters that are incorporated and the fact that at times the parameters can have arbitrary or inconsistent values in order to fit the data set. Even though it has been criticised it is widely accepted and used due to its ability to accurately model the changes seen in Mountain Ash forests following bushfires.

As seen above much literature has been devoted to the impacts that bushfires have on the yield of water from forests of Mountain Ash. The effects that bushfires have on the water yield of Mountain Ash have been refined over the years and are
now widely accepted as being correct. The same though cannot be said for other forests such as those largely made up of Mixed Species Eucalyptus. The literature relating to changes in Mixed Species Eucalyptus has found mixed results and will be investigated below.

Research conducted by [17] into the regeneration of State Forests in New South Wales was based on results taken from research done by [18-21] into the effect of clear fell logging. Reference [17] therefore believed that the response of the Mixed Species Eucalyptus would be appropriate for developing response curves for the effect of a fire that results in mortality of the Mixed Species Eucalyptus. Reference [17] found that when Mixed Species Eucalyptus was totally killed by the fire the response in terms of water yielded from the catchment was similar to that of Mountain Ash but somewhat smaller. It attributed these changes in response to differences in evapotranspiration between the different species. Similar research into clear fell logging by [22] has found similar responses by Mixed Species Eucalyptus under regeneration. Other researchers though have undertaken studies that find results that contradict those found above. Reference [23] conducted research into the Licking Hole catchment in Canberra following bushfires in 1983. It found that there was a discernible increase in yield in the 36 months following the fire, similar to Mountain Ash catchments. After those first 36 months though there was no long term decrease in water yielded from the catchment. It attributed this to the fact that the majority of the mature Mixed Species Eucalyptus trees in the catchment had survived the fire and had regenerated by epicormic growth; this resulted in an initial decrease in evapotranspiration and reduction in interception but returned to normal levels following the regrowth. Similar research conducted by [4] in the Gingera Catchment in Canberra following 2003 bushfires found no statistical evidence to suggest that runoff had changed following the bushfire. The bushfires that had burnt the Gingera catchment had similarly to the bushfire in the Licking Hole catchment been of an intensity to not kill the trees but just remove all vegetative layers. Reference [14] therefore believes the response of Mixed Species Eucalyptus is largely dependent on the severity of bushfire that burns the vegetation.

If the response of Mixed Species Eucalyptus is largely dependent on the severity of the bushfire it is important to understand the different classes of fires that can occur in forests. These different classes of bushfire intensity in eucalyptus forests have been classified by [24] and can be seen in Table 1. The fire intensity and flame height have been related to the effects that are had on a eucalyptus forest was documented by [25]. It is only in the Very High rating fire intensity where Mixed Species Eucalyptus are killed and in lesser fires only the canopy is removed and the trees scorched. These ratings are therefore very important in determining the effect a bushfire will have on the response of a Mixed Species Eucalyptus forest.

As can be seen above there is some disagreement between how a Mixed Species Eucalyptus Forest will react following a bushfire. The research following will focus on the 2003 bushfires in catchments in Victoria’s north east to try and determine the impacts of the bushfires on the quantity of water yielded from the catchment. This information will then be combined with the information gathered above to determine what possible impacts bushfires could have on Victorian water catchments and supplies into the future.

The effect of bushfires on the quality of water taken from catchments is also an important consideration. If water quality degrades too significantly extra treatment of the water may become necessary or the water may have to be left to settle and other sources utilised. Bushfires are able to change many processes that could affect water quality including the amount of runoff generated, the level of erosion occurring and the release of nutrients and metals. Increased runoff and erosion leads to degraded water quality as it allows the deliverance of more sediment to streams while the release of nutrients and metals changes the chemical balance in the water which may require further treatment as stated by [26].

Reference [27] found that bushfires have the ability to decrease the infiltration capacity of the soil. This is thought to occur in several ways including the fire increasing the water repellence of the soil and also ash sealing soil pores. Another way in which the runoff is increased following a bushfire as discussed by [28, 29] is the removal of vegetation. Bushfires can also increase the amount of erosion that occurs in a catchment. Bushfires have the ability to change the soil structure which can lead to increased soil erosion as explained by [30].

The most common impact on water quality following a bushfire is an increase in suspended sediment as highlighted by [26]. Studies by [31] found that increases in suspended sediment in terms of yield in tonnes per hectare per year rose anywhere from 1.3 times to 1459 times. The reasons behind these large variations are attributed to various factors by [26] including the post fire rainfall patterns, the area and severity of the catchment burnt, changes to erosion processes and the location of sediment sources. Reference [32] explains these sediment yields decline in the years following the fire as vegetation cover is restored throughout the catchment and impacts on the soil reduce and return to pre fire levels. Turbidity following bushfires has also found that dramatic increases have occurred following bushfires. Research by [11] into the Bendoora Reservoir following the 2003 bushfires in Canberra found that a turbidity level 30 times the previously recorded maximum occurred. This affected the entire depth of the reservoir and resulted in the water supply being declared unfit for consumption. Similar research into Lake Glenmaggie in eastern Victoria following the 2003 and the 2006/7 bushfires found similar results with large increases in turbidity (up to 1398 NTU) resulting in the water being declared unfit for domestic consumption. Not all research though has come to the same conclusion. Reference [31] found that the Dartmouth Reservoir in north-eastern Victoria showed only small changes in turbidity despite the 2003 bushfires burning over 95% of the catchment. Similarly [33] found that no water quality impacts occurred in the Mount Bold Reservoir following bushfires in 2007. Reference [26] believes these differences in impacts may be largely based on the reservoir themselves and their capacity and size and their attenuating capacity.
The level of chemical constituents in soils and their availability may also be changed by bushfires. As explained by [34] this can include large quantities of salts (including calcium, magnesium, chloride), nutrients (nitrogen and phosphorous) and trace metals that are deposited in ash beds following the fires. Research by [35] into the East Kiewa River in north east Victoria found that nitrogen and phosphorus levels increased by six times following bushfires and that the highest mean and median concentrations occurred in the first three to six months. Similar research by [31] in Victoria’s south east found that nitrogen and phosphorus levels increased anywhere from double to over one hundred times greater following fires. Studies by [36] though resulted in different findings. It found no significant increase in nitrogen or phosphorus following bushfires in northern Australia. Several factors have been highlighted that can explain the variability that is seen in the increases. Reference [37] explains that variability can occur due to differences in the area of forest burnt, the severity of the fire responsible for the burn, differing soil and forest vegetation types and the way in which the fire changes the soil structure.

Research into the effect bushfires have on the level of metals in catchments is sparse and the results varied. Research by [36] determined that metal levels (iron and manganese) changed negligibly following a bushfire in northern Australia. On the other hand [12] found a noticeable increase in metal (iron and manganese) concentrations following the 2003 bushfires in Canberra. Similar research by [38] found significant increases in metal concentrations (iron, copper, zinc, chromium, arsenic and lead) in the Ovens River in north east Victoria following the 2003 bushfires. Overall most researchers believe there will be an increase in metal concentrations but further research is required to determine the factors that affect the degree to which concentrations increase.

Other impacts on water quality that can occur following bushfires can include increased chloride and sulfates, increased cyanide and decreases in dissolved oxygen. Limited research has occurred in Australia into changes in chlorides and sulfates following bushfires. Research overseas has had mixed results with research by [39] finding significant increases while research by [40] found no significant increases following fires. Similarly limited research has been conducted into the effect of bushfires on cyanide levels. Reference [41] found that impacts are most likely to be felt in small catchments where dilution is limited and that any increases will be short lived and related to rainfall events directly after the bushfire. The level of dissolved oxygen following bushfires is also limited. The studies that has carried, including [42, 43], has found that dissolved oxygen can reduce significantly in rainfall events following bushfires due to sediment passing down the stream.

Changes in water quality following bushfires can affect many of the differing uses of water. Drinking water is negatively affected by most of the impacts that have been discussed above. This can lead to the need to build new treatment plants, cart water or impose water restrictions to ensure that citizen’s health is not affected by the water. An example of this occurred in Canberra following the 2003 bushfires where water restrictions had to be enforced due to turbidity levels [11]. Aquatic ecosystems can also be affected by bushfires. Aquatic ecosystems are most affected by high turbidity levels and low dissolved oxygen concentrations. This can lead to a decline in fish and other aquatic creatures as was found following bushfires in the north-east of Victoria in 2003 [42]. Bushfires can also impact on the use of water for agriculture. Increased nitrogen, phosphorus and metal levels in water can lead to the water being unfit for stock consumption [44]. This can once again lead to the need to transport water. Finally industrial users of water can also be affected by changes in the quality of water. Many industries such as food processing and manufacturing have strict guidelines on water quality that can be exceeded following bushfires [26]. Overall it can be seen that many different end users of water can be affected from changes in water quality following bushfires.

The potential to reduce bushfires in forested catchments appears to be limited. While some measures can be implemented such as fuel reduction burns, making catchment restricted areas and having fire fighters ready to be implemented, if the right circumstances present themselves nothing can be done to stop these fires [8]. Plans therefore have to be developed to guide the response of the relevant parties in the wake of a major bushfire in a forested catchment. These plans are used to ensure that sufficient potable water will be available for use by the residents living in fire affected cities. This involves ways of mitigating the effects of reduce yield and decreased quality following bushfires. One of the most effective ways of developing plans can be to analyze the effects of previous bushfires on catchments.

This paper will therefore analyze the effects of the 2003 Eastern Victorian Alpine Bushfires on several catchments in Victoria’s north east. As the fires only occurred few years ago

<table>
<thead>
<tr>
<th>Class</th>
<th>Fire intensity, KW/m²</th>
<th>Max. flame height, m</th>
<th>Remarks</th>
<th>Severity effects in Eucalypt forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt;500</td>
<td>1.5</td>
<td>Upper limit for fuel reduction burning.</td>
<td>Partial removal of litter and ground cover layer. Scorch or partial removal of low shrub canopy.</td>
</tr>
<tr>
<td>Moderate</td>
<td>501-3000</td>
<td>6</td>
<td>Scorch of complete crown in most forest.</td>
<td>More complete removal of litter layer. Low and medium shrub layer canopy consumed. Partial canopy scorch depending on tree height.</td>
</tr>
<tr>
<td>High</td>
<td>3000-7000</td>
<td>15</td>
<td>Crown fires in low forest types - spotting &gt; 2 km.</td>
<td>Litter layer removed down to mineral soil. 100% canopy scorch of tree layer.</td>
</tr>
<tr>
<td>V. high</td>
<td>7000-70,000</td>
<td>&gt;15</td>
<td>Crown fire in most forest types - fire storm condition at upper intensities.</td>
<td>Litter and top of soil layer completely burnt. All vegetation layers completely removed.</td>
</tr>
</tbody>
</table>

TABLE I. RANGE OF FIRE INTENSITIES AND FLAME HEIGHTS [24, 25]
the long term impacts are not yet known but will be predicted from previous researches including [12, 13, 26].

II. MATERIALS AND METHODS

The investigation involved with the links between the climate and the occurrence of bushfires was undertaken by analysis of data related to the El Nino Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO) and bushfire occurrence in Victoria. The IPO and Southern Oscillation Index (SOI - used to define the ENSO) were plotted for each year since the 1880’s. Overlaid on this was the occurrence of major bushfires in Victoria. From this it could be determined whether bushfires occurred in the majority of years where peaks in the two indexes coincide or if the majority of these years passed without bushfires. If the majority of these years where the peaks coincide were to have bushfires, authorities would be able to take pre-emptive actions to secure water supplies before the summer season and possible bushfires occur. Data relating to the indexes was sourced from the Australian Bureau of Meteorology [45] that monitor the SOI and the Meteorology Office Hadley Centre for Climate Change in the United Kingdom (2008) [46] who monitor the IPO and its effects on the climate. IPO data was only available up until the year 2008. This has resulted in not being able to define the relationship with bushfire up unto 2012. Data relating to the occurrence of bushfires in Victoria was sourced from the Department of Sustainability and Environment (DSE) [47] who is responsible to monitor and control bushfires that occur in national parks in Victoria. The bushfires selected were based on the area burnt and not fatalities or structures burnt.

The next investigation involved with predicting, calculating and comparing the effect bushfires have on the volume of water yielded from catchments. Three different catchments: Dartmouth (3579 km$^2$, 90% burnt), Corryong (299 km$^2$, 75% burnt) and Buchan (822 km$^2$, 77% burnt) were utilized to analyze the effects of bushfires on water yield. These catchments can be seen in Fig. 1 and are located in Victoria’s north east. The estimation of the impacts that bushfires have on water catchments was done using methods developed by [12, 13]. These methods require some aspects of the catchment to be known including the different types of vegetation, the age of the vegetation and the severity of fire that burnt the vegetation. These inputs can be acquired from the DSE. The next step was to determine the actual impacts of the bushfires on the catchments. This involved developing a curve representing the runoff generated from the catchment to the rainfall that fell in the catchment. A curve was developed based on the data available in the years prior to the fire. The years following the bushfire were then plotted on the graph to try and determine if the runoff in the catchment had changed based on the amount of rain that was falling. Following this the runoff coefficient was calculated and plotted on a yearly basis and then an eight year rolling average. This was undertaken to highlight any changes that had been identified in the above graphs. This required data relating to the daily streamflows and inflows that were occurring in the streams and reservoirs under investigation and data relating to the rainfall that was falling in the catchments. Streamflow and reservoir data was acquired from several different sources including government data archives, Victorian Water Resources Data Warehouse (2012) [48, 49] setup specifically to store data relating to water statistics and from the Murray-Darling Basin Authority [50] that was established to investigate and maintain the health of the Murray-Darling River system. Rainfall data relating to the catchments was accessed from the Bureau of Meteorology [45] who is responsible for weather forecasting and data collection in Australia.

Finally the effect of bushfires on the quality of the water that is yielded from catchments has been investigated. Two catchments: Corryong and Buchan were utilized to analyze the effects of bushfires on the quality of water yielded from catchments. The impacts of the bushfires on water quality were investigated by analyzing five different water quality parameters: turbidity, total nitrogen, total phosphorus, suspended solids and nitrates. These parameters were investigated by plotting their levels for periods of time prior and following to the fire. This allowed for any changes in the quality of the water to be identified and the problems associated with this discussed. This required data relating to these different aspects of quality under investigation to be obtained. This water quality data was acquired from the above stated sources [48-50]. There were some incomplete data available resulted in only two catchments instead of three being able to be investigated.

III. DATA ANALYSIS AND RESULTS

A. Climate Data

As discussed above the SOI was plotted along with the IPO and the occurrence of major bushfires in Victoria. This graph can be seen in Fig 2. There appears to be five main phases in the IPO during the 20th century. That is a positive phase at the turn of the century (1896 -1911), a negative phase (1913-1924), a moderate positive phase (1926 -1944), another negative phase (1946 -1977) and another positive phase (1978 -1999). It also appears that a return to neutral will be followed by a positive phase. The state of Victoria generally experiences drier periods when the IPO is positive.
From Fig. 2 it can also be seen that the SOI oscillates more regularly than the IPO. It can also be seen that there is a relationship between positive IPO events and the occurrence of El Nino or negative SOI events. During positive IPO events the occurrence of negative SOI events or El Nino events are more frequent or more intense than during neutral or negative IPO periods. El Nino events are highly correlated with the occurrence of droughts in the Eastern States of Australia including Victoria [10]. Drought conditions result in reduced rainfall and higher temperature resulting in an increase in the availability of dry fuel. This in turn increases the likeliness of the occurrence of serious bushfires.

![SOI, IPO and Fire Occurrence](image)

**Fig. 2.** SOI, IPO and major fire occurrence in Victoria.

Fig. 2 also shows that most of the major bushfires that have occurred in Victoria have coincided with a positive IPO period. This includes fires in 1898, 1939, 1944, 1983 and 2003. The only major fire that didn’t occur in a positive IPO period is the 1965 which did occur during a period where the IPO had increased significantly following an extremely strong negative period. While this shows that a relationship exists between the occurrence of major bushfires and the changes in the IPO, however it is not strong enough to use in predicting the occurrence of bushfires in Victoria. Similarly the relationship between the SOI and the occurrence of major bushfires isn’t strong enough to use to predict bushfire occurrence. Nevertheless, the use of the SOI to predict the probability of temperature and rainfall within the state of Victoria to be significantly above or below the median can be used by authorities to warn dangerous bushfire conditions during certain seasons. This is largely due to the fact that other interactions that have an impact on the weather. This includes ocean/atmospheric systems including the Madden-Julian Oscillation and Indian Ocean surface temperatures that impact Australia’s climate [52].

**B. Water Yield Data**

This paper will investigate the Dartmouth, Corryong and Buchan catchments and analyze the impacts the 2003 bushfires had on them. This will include predicting the impacts using previously developed methods and comparing this to the data currently available for the catchments.

### 1) Prediction of changes

The predictions of the changes in water yield were based on the function developed by [12] that models the changes in evapotranspiration of vegetation while regrowing following the fires. The variables in the equation are set depending on the type of vegetation that is present and also the mean annual rainfall for the catchment. To predict the changes in water yield that occurred following the bushfires several other parameters also need to be known. One important parameter is the severity of the fire. The fire severity needs to be known as the response of different kinds of vegetation is dependent on how severe the fire is. The response of Mixed Species Eucalyptus and Mountain Ash can be seen below in Table II. Other important parameters include the mean annual rainfall for the catchment, the mean annual runoff, and the different types of vegetation present in the catchment and the areas of vegetation that was burnt out in the fire along with other parameters can be seen in Table III.

<table>
<thead>
<tr>
<th>Severity</th>
<th>Mountain Ash</th>
<th>Mixed Species Eucalyptus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severity One</td>
<td>Regrowth</td>
<td>Regrowth</td>
</tr>
<tr>
<td>Severity Two</td>
<td>Regrowth</td>
<td>60% Regrowth, 40% Recover</td>
</tr>
<tr>
<td>Severity Three</td>
<td>Recover</td>
<td>Recover</td>
</tr>
</tbody>
</table>

**TABLE II. VEGETATION RESPONSE TO DIFFERENT FIRE SEVERITY**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dartmouth</th>
<th>Corryong</th>
<th>Buchan</th>
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<tbody>
<tr>
<td>Catchment area, Km$^2$</td>
<td>3579</td>
<td>299</td>
<td>822</td>
</tr>
<tr>
<td>% Mixed Species</td>
<td>75</td>
<td>75</td>
<td>85</td>
</tr>
<tr>
<td>% recovered (severity 2-3)</td>
<td>44.41</td>
<td>47.2</td>
<td>39.0</td>
</tr>
<tr>
<td>% regrowth (severity 1-2)</td>
<td>23.09</td>
<td>9.8</td>
<td>26.5</td>
</tr>
<tr>
<td>% unburnt</td>
<td>7.5</td>
<td>18</td>
<td>19.5</td>
</tr>
<tr>
<td>% Mountain Ash</td>
<td>25</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>% recovered (severity 3)</td>
<td>10.57</td>
<td>13.7</td>
<td>5.5</td>
</tr>
<tr>
<td>% regrowth (severity 1-2)</td>
<td>11.93</td>
<td>5.3</td>
<td>6</td>
</tr>
<tr>
<td>% unburnt</td>
<td>2.5</td>
<td>6</td>
<td>3.5</td>
</tr>
<tr>
<td>Mean annual rainfall, mm</td>
<td>1040</td>
<td>1070</td>
<td>1020</td>
</tr>
<tr>
<td>Mean Annual Runoff, mm</td>
<td>221</td>
<td>376</td>
<td>277</td>
</tr>
</tbody>
</table>

**TABLE III. CATCHMENT CHARACTERISTICS**

These data were then used to calculate the evapotranspiration that was expected to take place in the years following the fire using the equation developed by [12]. An example of how the level of evapotranspiration changes in the years following the fire can be seen below in Fig. 3 for the Dartmouth Reservoir in the Dartmouth Catchment. Once the evapotranspiration levels were known the changes in streamflow were calculated based on the mean average rainfall, the mean average runoff and systems losses that had been calculated on base data. The basic equation can be seen below.

\[
\Delta \text{Stream Flow} = \Delta \text{Rainfall} - \Delta \text{ET} - \Delta \text{Runoff} - \Delta \text{Losses}
\]

This change in streamflow has been plotted for the Dartmouth (Dartmouth Reservoir), Corryong (Nariel Creek) and Buchan (Buchan River) catchments in Figs. 4, 5 and 6 respectively. The streamflow in each of the catchments is
expected to initially increase for 4 – 5 years followed by a significant decrease which peaks between 20 and 30 years following the fires. Following this decrease the streamflow begins to slowly increase again but is not expected to return to pre fire levels until over 150 years after the fire event. The predicted streamflow changes investigated above will be compared to the actual streamflow changes that have occurred.

2) Actual changes: The actual changes that had occurred in the water yielded from the catchments in the years following the fire were also investigated. This was achieved by getting daily streamflow (ML/day) and rainfall data (mm/day) for each of the catchments for over 30 years prior to the bushfire. The streamflow and rainfall data for each of the catchments was then condensed into monthly data and also annual data. The monthly and annual streamflow data was then converted from ML into mm by dividing it by the area of the catchment so that a relationship between the rainfall and streamflow data could be established. The comparison of rainfall and streamflow and the line of best fit and associated equation and goodness of fit were calculated for each catchment prior to the bushfires. The rainfall and runoff for each year following the fire was plotted individually to allow for comparison. The rainfall and runoff comparison can be seen in Figs. 7, 8 and 9 for the Dartmouth Catchment (Dartmouth Reservoir), Corryong (Nariel Creek) and Buchan (Buchan River) catchments respectively.

It can be seen in Figs. 7, 8 and 9 that while there is a slight increase in the water yielded from the catchment in the years directly after the fire followed by a decrease in the water yielded, there doesn’t appear to be any significant change in the yield of water that as expected. From the literature review it was expected that a significant increase in the runoff would be seen directly following the bushfires followed by a significant decrease. This was similar to what was seen in the predictions conducted above. Therefore further investigation was required to see if any changes had in fact occurred. This was done by assessing the changes that were occurring in the runoff coefficient. The runoff coefficient is calculated by dividing the runoff by the rainfall that is occurring. It represents the amount of rainfall that is being converted into runoff. This was calculated for each individual year and also on an 8 year moving average to assess any changes that were occurring. The graph of the runoff coefficients can be seen in Figs. 10, 11 and 12 for the catchment respectively.

It can be seen in Figs. 10, 11 and 12 that following the bushfires there was a slight increase in the runoff coefficient in all of the catchments. Following this slight initial increase a decrease in the runoff coefficient can be seen particularly in the...
Dartmouth Reservoir and the Nariel Creek. It appears though the changes in runoff have been more pronounced but the periods before and after the bushfires were characterized by drought. This decrease in rainfalls has resulted in the true effect of the bushfires being somewhat masked as less rain has been falling and the rain that has been falling has been used in wetting the catchment which have become quite dry. This has resulted in the catchment not producing the initial increase in runoff as expected.

Overall it can be seen that the runoff in the catchments under investigation, have changed in regards to the amount of water yield in the period following the fires. These impacts in small amounts are expected to remain for up to 150 years following the fire with a peak impact being experienced between 20 and 30 years after the fire. These reductions have the ability to reduce the total amount of water available for use from the catchment and could lead to serious impacts for end users. The impacts these decreases could have and the way in which they could be mitigated will be discussed later.

C. Water Yield Data

The impact that bushfires has on the quality of water yielded from catchments has been studied by numerous with conflicting answers. As discussed earlier this study will investigate the Corryong and Buchan catchments and analyze the impacts the 2003 bushfires had on them. This will include investigating the impacts of the bushfires on turbidity, nitrogen, phosphorus, suspended solids and nitrate concentrations.

The turbidity levels for the Buchan River and the Nariel Creek can be seen in Figs. 13 and 14 respectively. As can be seen in both the figures the turbidity had been relatively stable prior to the fires with only minor peaks occurring following intense rainfall events. Before the fire the average turbidity level in the Buchan River was 3.95 NTU and in Nariel Creek 1.95 NTU. Following the fires though it can be seen that the turbidity level begins to fluctuate much more, the average level of turbidity increase and larger peaks occur more often than they did prior to the fire. Following the fire the average turbidity level rose to 28.00 NTU in the Buchan River and 11.20 NTU in the Nariel Creek.
This is supported by comparing the pre and post 2003 fire turbidity exceedance values in the streams. The exceedance probability graphs pre and post fire for the Buchan River and the Nariel Creek can be seen in Figs. 15 and 16 respectively. Taking the guideline level of problem turbidity as 5 NTU it can be seen in Figure 15a that prior to the fires the probability of exceedance of the problem turbidity level was 18.5% in the Buchan River. Following the fire though this probability exceedance rose to 46.5% as seen in Fig. 15b. Similarly in the Nariel Creek it can be seen in Fig. 16a that prior to the fire the probability of exceedance of the problem turbidity level was 7.8%. Following the fire this probability level increased to 19.8% as seen in Fig. 16b.

This is supported by comparing the pre and post 2003 fire turbidity exceedance values in the streams. The exceedance probability graphs pre and post fire for the Buchan River and the Nariel Creek can be seen in Figs. 15 and 16 respectively. Taking the guideline level of problem turbidity as 5 NTU it can be seen in Figure 15a that prior to the fires the probability of exceedance of the problem turbidity level was 18.5% in the Buchan River. Following the fire though this probability exceedance rose to 46.5% as seen in Fig. 15b. Similarly in the Nariel Creek it can be seen in Fig. 16a that prior to the fire the probability of exceedance of the problem turbidity level was 7.8%. Following the fire this probability level increased to 19.8% as seen in Fig. 16b.

**TABLE IV. WATER QUALITY PARAMETERS BEFORE AND AFTER BUSHFIRES**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Buchan River</th>
<th>Nariel Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg before fires</td>
<td>Avg after fires</td>
</tr>
<tr>
<td>Turbidity, (CL: 5 NTU)</td>
<td>3.95</td>
<td>28.0</td>
</tr>
<tr>
<td>Nitrogen (CL: 0.375 mg/L)</td>
<td>0.29</td>
<td>0.53</td>
</tr>
<tr>
<td>Phosphorus (CL: 0.031 mg/L)</td>
<td>0.019</td>
<td>0.088</td>
</tr>
<tr>
<td>Suspended solids (CL: 20 mg/L)</td>
<td>3.95</td>
<td>28.7</td>
</tr>
<tr>
<td>Nitrate (CL: 0.03 mg/L)</td>
<td>0.038</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Note: CL: critical level

### IV. MITIGATORY STRATEGY

There are several steps water management authorities and governments can take to attempt to mitigate the effect that bushfires have on the quality of water that is sourced from catchments. This includes steps that can be taken before the bushfire season, during and following the bushfire. Mitigation measures for each time will be investigated below.

The major mitigation measure that can be taken before the bushfire season is those that relate to reducing the likelihood of bushfires. This includes the undertaking of fuel reduction burns. Fuel reduction burns reduce the amount of litter that is present in the catchment and lowers the risk of bushfires during the following season [47]. Care has to though during these burns to ensure that the same negative effects of bushfires on water quality aren’t produced from the burn off. This is usually avoided due to the low intensity of fuel reduction burns. Other measures that can be taken by management authorities before the bushfire season is a risk assessment of their catchments and determine which of their catchments are most susceptible to bushfires [26]. This would allow for a more rapid response to occur during and after the bushfires to try and attempt mitigating the effects of the bushfire. Some of the measures that could be taken during and after the bushfire will be investigated further.

During bushfires it is important that sensitive catchment areas are known to fire-fighters and that codes of practices (such as those specified by the Department of Sustainability and Environment) are adhered to during the firefighting efforts. This includes not using fire retardant foams in catchment areas.
and not constructing fire breaks in stream and riparian zones [53]. Other measures that can be taken include minimizing the use of heavy equipment in catchments and instead use foot crews that are given access via the air as opposed to land. Also when the use of heavy equipment cannot be avoided using GPS tracking to monitor the areas that they access so that reconstruction can be undertaken following the fire [26].

Following bushfire management authorities need to undertake several actions to ensure negative impacts on water quality can be minimized. This includes the rapid assessment of the impacts of the fires before intense rains occur. This includes the changes to the soil profiles, vegetation cover, and where disturbances from heavy equipment have occurred. This allows for the worst affected areas to be prioritized and treated first. Measures undertaken can include the establishment of erosion control structures such as mulching, vegetation and soil stabilization and the establishment of sediment control devices such as silt fences, straw bales and barriers [43]. Another measure that can be taken includes the removal of debris from streams and creeks to ensure the flow isn’t obstructed during intense rainfall events. Constant water quality monitoring should also be undertaken to ensure any changes are quickly picked up. If some instances though no measures will be successful in preventing negative impacts to water quality and alternate water sources may be required or further treatment of the water supply required to return it to a level suitable for use.

V. CONCLUSIONS
Overall the investigation has shown that the relationships between climatic events including the El Nino Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) aren’t strong enough to use to predict the occurrence of bushfires in Victoria but are suitable to predict when seasons of below or above average temperature and rainfall will occur and possible high fire danger. The investigation also showed that the 2003 bushfires in Victoria’s Alpine region had changed the amount of water that was being yielded from the catchments. This included an initial decrease in the first 3 to 4 years following a fire followed by a substantial decrease peaking around 20 to 30 years after a fire and returning to pre fire levels approximately 120 to 150 years after the fire. The importance of suitable planning by water authorities including the use of water restrictions and finding other sources of water was determined to be critical to ensure that the required amount of water is continually available. Finally the report found that the water quality in the catchments was also affected. The investigation found following the fires greater peaks in water quality than those predicted or has responded in a different fashion. Also further research could be conducted into the effect of bushfires on different measures of water quality including dissolved oxygen levels and metal concentrations including iron, magnesium and lead.

REFERENCES


